

UNIVERSITY OF BREMEN
CHAIR OF LOGISTICS

PHD THESIS

**Concepts, Mechanisms, and Algorithms
to Measure the Potential of Container
Sharing in Seaport Hinterland
Transportation**

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Abbreviations

AEO	Authorized Economic Operator
am-TSPTW	Asymmetric Multiple Traveling Salesman Problem with Time Windows
C-TPAT	Custom-Trade Partnership Against Terrorism
CBP	Customs and Border Protection
CTTP	Container Truck Transportation Problem with Time Windows
DCP	Distinct Container Problem
FEU	Forty-foot Equivalent Unit
FTPDPWTW	Full Truckload Pickup and Delivery Problem with Time Windows
ICT	Inland Container Transportation Problem
IE	Inbound Empty
IF	Inbound Full
MC-CTTP	Multi-Company Container Truck Transportation Problem
MC-CTTP-CS	Multi-Company Container Truck Transportation Problem with Container Sharing
MIP	Mixed Integer Programming
OD-CTTP	One-Depot Container Truck Transportation Problem with Time Windows
OE	Outbound Empty
OF	Outbound Full
PDPTW	Pickup and Delivery Problem with Time Windows
RTS	Reactive Tabu Search
SCP	Shared Container Problem
TEU	Twenty-foot Equivalent Unit
VCY	Virtual Container Yard
VRP	Vehicle Routing Problem
VRPFC	Vehicle Routing Problem with Full Containers
VRPTW	Vehicle Routing Problem with Time Windows
WPB	Window-Partition Based
WTO	World Trade Organization

1 Introduction

The increasing industrialization and liberalization of the world economy have led to remarkable growth rates in container transportation, especially in the last decades. Accompanied by ever-increasing customer expectations and speed requirements, international container operators are faced with a complex and dynamic transport system that comprises ocean-going services, as well as transport-services on land. In order to maintain their position in a highly competitive market, operating companies in the global maritime industry are forced to improve efficiency and to reduce costs.

Coping with possible cost savings, the reduction of empty container movements is a major issue in sea and hinterland transportation. Due to natural imbalances in international trade, shipping companies have to deal with hinterland regions of seaports that report either a surplus or a lack of empty containers. With regard to future transportation requests, empty containers have to be allocated between these regions. Bearing in mind that the movements of empty boxes do not create any revenues, the repositioning of empty containers causes remarkable expenses due to the fact that the costs for moving a full container are almost as high as the costs for moving an empty container (Exler, 1996). Drewry Shipping Consultants (2011) state that the global expense for empty container repositioning amounted to 30.3 billion dollars in 2009. This is a substantial problem since these costs account for 19% of the global maritime industry income and, hence, form a major part of the industry cost structure (UNCTAD, 2011). Although empty container movements cannot be avoided completely, minimizing these costs can considerably reduce the general expenses of operating companies. The need to improve efficiency leads to empty container management as an important field of activity in container transportation.

In the past, cost saving possibilities for container transport chains have mainly been investigated by focusing on acquisitions and strategic alliances for sea transport only. Given the decline in the potential to find remaining methods for the reduction of expenses at sea, the pressure rises to decrease costs in areas of international container transportation still remaining. Remarkably, the research for cost saving possibilities in the hinterland of seaports has received limited attention within the last decades, although the proportion of inland costs in the total

costs of container shipping ranges from 40% to 80% (Notteboom and Rodrigue, 2005). This is even more noticeable when analyzing the potential of empty container management in a seaport's hinterland. While 40-50% of the total container movements in hinterland transportation are required for the transport of empty boxes, this share is only at around 20% in sea transportation (Branch (2006) and Drewry Shipping Consultants (2011)).

The high share of empty container movements in hinterland regions is due to the fact that most of the routes are actually pendulum tours between terminals, import (receivers) and export customers (shippers), and the container depots. Solutions to reduce this amount focus on the realization of street turns, i.e. available empty containers are moved directly between customer locations without frequenting a container depot as an intermediate return. Hence, a recently emptied container at a receiver's location is integrated into a successional transport chain by moving the empty container directly to a shipper where it can be loaded with export cargo. In practice, only a small amount of street turns can be realized in hinterland container transportation. For instance, in the hinterland region of the ports of Los Angeles and Long Beach, only two percent of the empty import containers handled by receiver customers in 2000 were directly moved to shipper customers (The Tioga Group, 2002). The main limits of establishing street turns are, for instance, timing of import and export requests, location mismatches of requests, and wrong container types (e.g. size).

A further key complicating factor is the fact that containers belong to different shipping companies. Therefore, customers - although located next to each other - cannot be "street turned" since they are served by different companies that refuse to exchange their containers. In the past, there have been a few attempts to overcome this drawback by establishing coalitions between shipping companies. Members of these initiatives cooperate with each other by allowing the common use of their containers. In doing so, empty containers of foreign shipping companies can be integrated into routes of other companies. Due to this *container sharing* idea, the probability to increase the number of street turns should increase significantly since the probability of location mismatches of transportation requests decreases, while the probability of the timing of import and export requests simultaneously increases. Consequently, the high amount of empty container movements of a hinterland region is reduced and trucking companies improve their profit by decreasing transportation costs in return. Unfortunately, most of the attempts to establish coalitions between shipping companies have failed due to the fact that too few shipping companies want to participate. A main barrier for putting these

coalitions into practice lays in the fact that companies can hardly weigh the risks against the benefits. While the risks are various and provide a deterrent effect for companies to participate¹, the quantitative benefits regarding the transportation cost savings have barely been investigated in practice or in the literature. Yet knowing the approximate benefit of joining such coalitions is of crucial importance to increase the willingness of companies to take chances and to raise the incentive of participating in a container sharing coalition.

1.1 Scope of the Research

This thesis analyzes how trucking companies of a hinterland region can improve their routes if shipping companies allow the mutual exchange of their containers. In this case, trucking companies that are assigned by shipping companies cooperate by sharing information regarding which locations empty containers are currently stacked. These containers can then be integrated into a vehicle's route of any operating trucking company in the hinterland. The investigation aims at measuring the quantitative potential of the container sharing idea by means of problem settings illustrating realistic hinterland regions of a seaport. As a first step, the impact of street turns on the transportation costs of a trucking company should be measured. By forbidding or allowing the use of street turns for a single trucking company, the potential of the container sharing idea can be indicated, and the interrelation of empty container movements and transportation costs can be shown. As a further step, the benefit of exchanging empty containers between several trucking companies needs to be analyzed. In doing so, it is possible to investigate the potential and realistic limits of container sharing.

Mathematical models should be formulated to specify and solve the optimization problems. Unfortunately, modeling these settings is a difficult task since two interdependent transportation levels need to be considered for an exact mixed integer programming (MIP) formulation that illustrates a hinterland container transportation problem comprehensively. Besides the consideration of the vehicles' routes, the models should also include the allocation of containers. Due to the consideration of the container as a passive transportation entity and the vehicle as an active transportation entity, it is possible to solve the underlying problems sequentially and simultaneously by means of a commercial solver software.

¹For example, companies fear to reveal sensitive data concerning the demand and requirements of their customers (Notteboom and Rodrigue, 2007) or they fear the risk of receiving equipment from cooperating companies which is not in a good condition (Pawlik, 1999).

The best performing solution approach in terms of efficiency and effectiveness can then be used to solve small test instances for the proposed problem settings. Due to the complexity of the underlying problems, the MIP models cannot be applied for instances of practical size. Therefore, heuristic solution approaches must be developed. On the basis of computational experiments, the performance of the solution methods should be assessed. Subsequently, realistic-sized data sets can be solved in order to measure the potential of a container sharing coalition. On the basis of data sets with different characteristics, such as the number of trucking companies or time conditions, possible benefits in different hinterland settings can be calculated.

1.2 Structure of the Thesis

The relevancy of empty container repositioning as a global and regional problem is discussed in Chapter 2. For a deeper understanding of this problem, the most important actors and their tasks in maritime container transportation are introduced. Afterwards, a brief description of the developments in sea and hinterland transportation during the last decades is given. Due to the presented economic environment, the need for companies to optimize their empty container management becomes obvious and is described. A special focus lays on empty container logistics for transport services in hinterland regions. The importance and difficulties of rationalizing empty container movements, as well as prior approaches in the literature to achieve a decrease of empty container movements, are specified.

Chapter 3 presents the container sharing idea as an opportunity to reduce transportation costs in hinterland container transportation. Initially, a description of the container sharing concept is given. Subsequently, the arising benefits of container sharing, as well as challenges to put this idea into practice, are discussed. Due to the fact that the concept of container sharing is not a completely new idea, prior approaches that are similar to this concept and have been investigated in the literature and/or in practice are surveyed.

A first indication of the potential of container sharing in the hinterland of seaports is given in Chapter 4. By means of two basic scenarios which are based on a comprehensive truck container transportation problem known from the literature, it is investigated to what extent container sharing induces cost saving possibilities for trucking companies in seaport hinterlands. For the sake of simplicity, both scenarios consider only one trucking company. In the first basic scenario (distinct

container problem (DCP)), the operating company only has access to its own containers. Thereby, the possibilities to allocate empty containers between locations is partly restrained by forbidding empty container movements like street turns. The second basic scenario (shared container problem (SCP)) illustrates the situation of a company participating in a container sharing coalition, i.e. empty containers can be assigned to transportation tasks which seem to be most appropriate for the company. In this scenario, street turns can be applied. Exact MIP formulations are given for both scenarios. By means of the SCP, the performance of a sequential method compared to a simultaneous solution approach is measured. Finally, it is investigated how container sharing affects a reduction in a trucking company's transportation costs

Chapter 5 extends the problem setting of the previous chapter by including more than one trucking company. The consideration of several trucking companies enables the opportunity to analyze precisely the effects of container sharing on container movements and transportation costs. Once again two scenarios are introduced: while the first scenario (multi-company container truck transportation problem (MC-CTTP)) forbids the exchange of empty containers between trucking companies, empty containers are allowed to be interchanged among several owners in the second scenario (multi-company container truck transportation problem with container sharing (MC-CTTP-CS)). The resulting advantages of the MC-CTTP-CS compared to the MC-CTTP are shown by a simple example. Furthermore, MIP models are given for both scenarios. On the basis of small-sized instances, computational experiments are performed to give results for the advantages of a container sharing coalition.

In order to solve realistic-sized instances, a tabu search heuristic for the MC-CTTP and the MC-CTTP-CS is presented in Chapter 6. The performance of the heuristic is tested by adapting it to a similar problem known from the literature. Subsequently, several large-sized instances with different characteristics according to the number of trucking companies and time conditions are generated. Finally, the instances are solved by means of the tabu search heuristic.

Chapter 7 analyzes the obtained findings of the previous chapters. Amongst others, the dependency of street turns, empty container movements, and the transportation costs are analyzed. Based on the generated results, possible challenges of putting the container sharing idea into practice are mentioned.

The main findings of this thesis are summarized in Chapter 8, concluding with an outline of further research directions for the container sharing idea.

2 Empty Container Repositioning

Guaranteeing the balance of empty containers between import and export-dominated regions, the repositioning of empty containers marks one of the ongoing issues for the operating actors in sea and land transportation. Bearing in mind that the allocation process of empty containers constitutes a non-revenue generating, undesirable and, therefore, expensive field of activity in container transportation, empty container repositioning has become one of the most important problems in the shipping industry over the last years. First noticed as a necessary evil required for moving full containers, empty container repositioning nowadays marks an integral part of an efficient global transportation system (Di Francesco, 2009).

This chapter provides an introduction to empty container repositioning as a problem on the global and regional levels. Initially, Section 2.1 introduces the main actors in maritime container transportation. Afterwards, the developments in the shipping industry during the last decades are briefly described in Section 2.2. The reasons and the relevancy of empty container management in maritime container transportation are summarized in Section 2.3. Section 2.4 gives a survey of empty container logistics for transport services in hinterland regions. Finally, Section 2.5 provides a literature review focusing on operational research articles that produce ideas or present approaches to decrease the amount of empty container movements in intermodal door-to-door services and especially in hinterland container transportation.

2.1 Main Actors and Operations in Intermodal Door-to-Door Services

Intermodal door-to-door services define the transport chain from a shipper to a receiver. Thereby, “intermodality is a characteristic of a transport system, that allows at least two different modes [(road, rail and water)] to be used in an integrated manner in a door-to-door transport chain” (Commission of the European Communities, 1997). In maritime container transport, these activities are generally defined by hinterland transportation and sea transportation. Figure 2.1

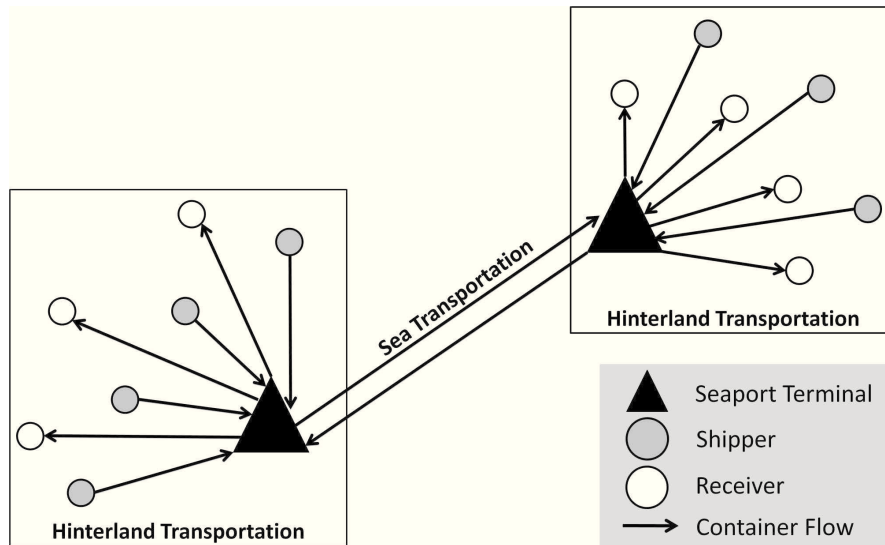


Figure 2.1: *Intermodal Door-to-Door Services*

shows the segments considered within a transport chain. The route segments are subdivided into the pre- and end-haulage at land, as well as the main haulage at sea. The pre-haulage is characterized by a customer-terminal connection. Along this connection a container is carried from a *shipper* to the seaport terminal by train, barge, or truck. At the seaport, the transport mode is changed and the main haulage describing a terminal to terminal transport begins. The main haulage is carried out by a container vessel and describes the longest traveling distance in the transport chain. When the vessel arrives at the destination terminal, the container is transshipped again from the vessel to a train, barge, or truck and moved to its final destination which is defined as a *receiver*. This thesis focuses on trucks as the transportation mode in the pre- and end-haulage.

Based on the transport demand of a shipper and a receiver, a *carrier* is assigned to organize a smooth container flow from one hinterland region to another. Thereby, the carrier is free to perform the container transportation by itself if it is in possession of the necessary resources. Alternatively, it can subcontract the transport to adequate *transport operators*. Transport operators take care of active container movements in sea or hinterland transportation. Regarding hinterland transportation in pre- and end-haulage, the transport operator is defined by a *trucking company* who is responsible for serving customer-terminal and terminal-customer connections. In sea transportation, the transport operator is represented by a *shipping company* who takes care of the main haulage. For reasons of convenience, one of the transport operators usually takes over the job of the carrier and subcontracts the other required transports to trusted transport

operators. The situation where a transport operator offers complete door-to-door services for a shipper is called carrier haulage. In the majority of cases, the shipping company is assigned to organize the transport chain since it represents the biggest player in this chain (Hildebrand, 2008)¹. Accordingly, merchant haulage describes the situation where an autonomous carrier² or the receiver is in control of the transport chain design (Veenstra, 2005). Due to this situation, a clear distinction between carriers, transport operators, and customers is partly difficult since the borders are blurred.

The average share of carrier haulage is about 30% in Europe. However, there exist large differences between regions, carriers, and routes. For instance, P&O Nedlloyd had a carrier haulage percentage in Europe of 49% in 2002, while other carriers only controlled 10% of inland container movements. Carriers have very little room to raise the benefit in hinterland transportation. If the carrier haulage tariffs are above the open market rates, merchant haulage becomes more attractive for the carriers. According to (Notteboom, 2004, p. 94) “the resulting competitive pressures partly explain the weak level of price contention between carrier and customer when it comes to charge in inland leg”. In consequence, carriers need to detect possible cost savings if the income cannot be increased significantly.

Basically, there are two main groups of container owners: the shipping companies and the *container leasing companies*. The container leasing industry mainly developed in the 1970’s due to the need to compensate the growing imbalance of international trading (Theofanis and Boilé, 2009). The goal of these companies is to guarantee the supply of equipment at locations where there is a demand for it (Konings, 2005). A small number of containers are owned by other transport operators, such as trucking companies or container depot operators, who are located in the hinterland and handle, store, and repair containers. Overall, shipping companies and other transport operators own 59% of the global container fleet, while leasing companies own 41% (Theofanis and Boilé, 2009). During the transportation process the carrier needs to take care of a container which is used for the freight. The carrier can either use its own container, if available, or it hires a container from a container leasing company and returns it after the freight is unloaded at the receiver location, making it possible to hire containers short-term or long-term. Considering long range contracts, containers are used for months

¹In the following, carrier haulage describes the situation where the shipping company takes over the job of the carrier.

²An autonomous carrier defines a player who is independent from one of the transport operators in the transport chain.

and even years. Treated as normal containers that are owned by the shipping company, long-term leased containers feature the same decision options and flexibility. The main motive for shipping companies to close a short-term contract with a container leasing company is because of acute demands for equipment. In this case, lease prices are very volatile. Leasing companies can usually provide a more efficient way to position empty containers than shipping companies since they have agreements with a number of shipping companies who operate in different branches of trade that partly complement the supply of, and demand for, empty containers in and between regions (Theubert, 2010). Shipping companies and leasing companies have essentially different and conflicting goals. Shipping companies require containers as transportation equipment. Thus, management decision-making is focused on minimizing transportation and handling costs. Besides, leasing companies consider containers as their core assets: so, they seek to make profit out of their leasing and try to cover depreciation (Theofanis and Boilé, 2009).

Container depots mark important locations for the transport operators in hinterland regions since they constitute transshipment centers and storage points for containers. Further functions include maintenance and repair, inspection as well as the cleaning of the containers (Vojdani and Lootz, 2011). Container depots should be located at a well-chosen position that is advantageously connected to the transportation infrastructure in order to enable an efficient distribution to the surrounding hinterland region. Nevertheless, empty container depots are often situated unfavorably in a port's premises. This is mainly due to the fact that shipping companies like to see their empty boxes near their home bases in order to stay in control of their inventory (Veenstra (2005) and Islam et al (2010)). Furthermore, containers which shall be positioned globally are stored in the port area due to a fast transshipment. Besides, container depots located in the hinterland shall be used for the storage of containers which need to be moved to shippers in order to discharge port areas and to minimize the distance to the customer.

For reasons of clarity, only the actors which are relevant for this thesis have been mentioned in this section. For a comprehensive survey of further actors and their corresponding actions, the interested reader is referred to The Tioga Group (2002) and Hildebrand (2008).

2.2 Developments in Maritime Container Transportation

Over recent decades, the market environment of maritime transportation has changed substantially. The globalization process and the large-scale adoption of the container since its introduction in the 1960's mark the main driving forces of change (Notteboom, 2004). The innovation of the container simplified and accelerated the stevedoring services of the vessels and decreased labor costs and berth dues in port business. Due to the fact that the containerization has led to a loading and unloading which is fully mechanized, nowadays the costs for stevedoring services have been remarkably reduced compared to the loading and unloading of conventional cargo vessels (Exler, 1996). At the same time a steady enlargement of container vessels has been causing an enormous decrease of transportation costs since more containers can jointly be moved (Lun et al, 2010).

Today the container represents the standard unit load concept in maritime transportation. Especially in the last two decades, the worldwide container port throughput has increased tremendously. The early 1990's marked a phase of acceleration of containerization particularly due to the increasing international division of labor and the growing liberalization of world trade. This development continued in the 2000's e.g. through China's World Trade Organization (WTO) accession in 2001 (Notteboom and Rodrigue, 2009). Between 1990 and 2008 the global container throughput rose by an annual average rate of more than 10%. While the total number of full containers shipped on worldwide trade routes (excluding transshipment) amounted to 28.7 million TEU in 1990 (UNESCAP, 2005), the container throughput before the financial crises reached 508.4 million TEU moves in 2008 (UNCTAD, 2010).

Obviously, the growing importance of container transportation goes along with the expanding global trade. The market liberalization appears to enhance the development of logistics. International supply chains have become much more complex through the expansion into new markets, mass customization, and due to product and market segmentation. While shipping companies in the past mainly focused on port-to-port business, today they expand their field of activities along the supply chain of intermodal door-to-door services. This is due to the trend of shipping companies gaining greater control over the logistic chain (Heaver et al, 2001), which comprises the activities that are required to establish door-to-door services. Consequently, shipping companies seek to not only organize the transport on sea, but also the services on land.

The development of ever-increasing customer expectations and speed require-

ments on the one hand and an intensified competition between the actors in intermodal door-to-door services on the other hand, has required the improvement of efficiency along a company's supply chain (Cheung et al, 2008). During the 1990's this pressure lead to an increase in alliances formed by shipping lines. As Notteboom (1997) stated, "the ambitions of some megacarriers to offer door-to-door services will partially shift the decision power from freight forwarders and stevedoring companies towards these shipping companies." These coalitions had the chief objective of maintaining freight rates in order to realize possible cost savings and to guarantee investment profitability (Evangelista and Morvillo, 1999).

In the last decades, the shipping industry has mainly been trying to exploit cost saving possibilities in sea transport. According to Van der Horst and De Langen (2008) and the Bundesamt für Güterverkehr (2007), the lack of attention paid to hinterland transport systems is mainly caused by the complicated relations between the different actors operating in the hinterland. While the coordination in sea transportation is mainly limited to the operating shipping companies, the coordination in hinterland transportation systems comprises actors such as shipping companies, terminal operating companies, and hinterland transport providers. Optimizing the integration and coordination in hinterland regions requires adequate mechanisms and the decrease of transaction costs (Panayides, 2002).

The reduction of empty container movements has become a major issue in maritime container transportation, especially during the last ten years (Theofanis and Boilé, 2009). Empty container repositioning causes remarkable expenses because they do not create any revenues, while the costs for the transport are almost as high as the costs for moving full containers (Exler, 1996). Drewry Shipping Consultants (2011) state that the global expense for empty container repositioning amounted to 30.3 billion dollars in 2009. Two-thirds of this amount is caused by seaside repositioning, while the rest is due to landside repositioning. This is a substantial problem since these costs constitute one-fifth of the global maritime industry income (UNCTAD, 2011). The need to improve efficiency leads to empty container management as an important field of activity in sea and hinterland transportation.

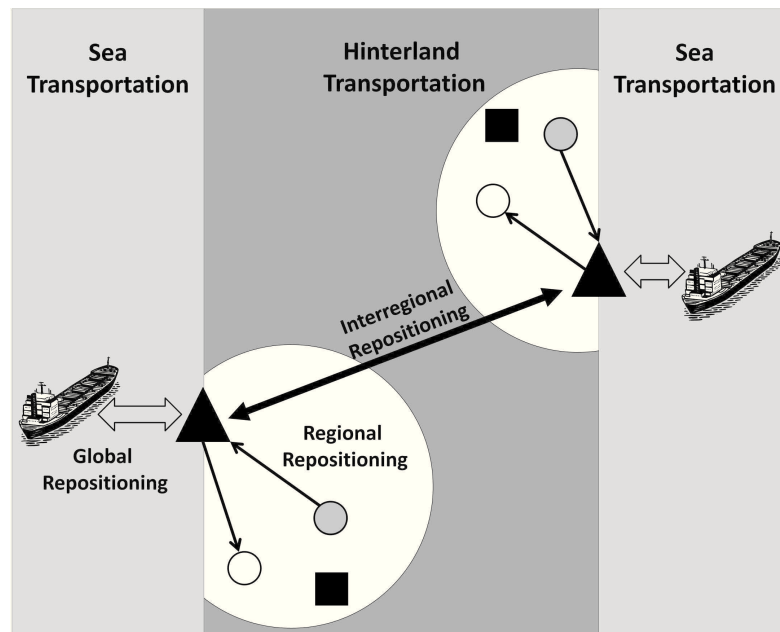


Figure 2.2: *Empty Container Repositioning in Sea and Hinterland Transportation (Based on Theofanis and Boilé (2009))*

2.3 Empty Container Management

Managing empty container flows is about handling the movements, storage, and distribution of empty containers. The process starts just after a container is unloaded at a receiver location and ends with the supply of the empty container at a shipper location where an empty container is required for loading. Thereby, the goal is on providing empty containers at minimum transportation costs and at maximum containers use (Furió et al, 2009).

Just like the transportation in intermodal door-to-door services, empty container management distinguishes between the allocation of containers on the sea and in the hinterland. Three geographical levels of empty container repositioning are considered: global, regional, and interregional (see Figure 2). On the international level, empty container management deals with the movement of empty containers at global scale to reverse the imbalance problem in international trading. Empty container logistics in the hinterland takes place at the regional and interregional levels (Boilé et al, 2008).

This thesis is focused on empty container logistics at the regional level. Nevertheless, empty container management in sea transportation significantly affects hinterland container transportation. Due to international trade, a general direction in traffic flows is imposed which is completely outside the level of intervention of the hinterland's actors (Notteboom and Rodrigue, 2007). Hence, international

container flows are an exogenous force for hinterland container transportation. Traffic flows define hinterland regions as import- or export-dominated areas in which either a surplus or a lack of empty containers is obtained. In the following, a short overview of the reasons for empty container management in sea transportation and its resultant importance is given. Subsequently, the challenges of empty container repositioning for hinterland container transportation are explained more comprehensively in the next section.

The importance of empty container management in port-to-port business has increased significantly since the Asian economic crises in 1997/1998 at the latest. Due to the devaluation of the Asian currencies, goods from these regions have become cheaper for European and North American customers, while goods from Western civilization have become more expensive for the Asian countries. As a result, the exports from Asia increased and the imports in Europe and North America decreased. A remarkable surplus of empty containers in the West civilization and a shortage of empty boxes in the Far East have been the consequence (Olivo et al, 2005). This case is exemplary for trade imbalances as the main reason for empty container repositioning on the global level. Due to the imbalance of international trading, there are areas which are export- or import-dominant. An illustration showing the global imbalances in port-to-port business according to the trade volumes can be seen in Figure 2.3. These asymmetrical trade volumes are due to various economic basic conditions, such as the imbalance of economic development between different countries and regions, different orientations of economies, and the sudden variation of cargo volumes (Wang et al, 2008). Although the Asian economic crisis has been overcome, the biggest disparity in trade flows is still mainly caused by the Asian countries as the manufacturing region of the world. This development is caused by the rising economic strength of export-dominated countries such as China or the Republic of Korea. Hence, in 2010 the outbound flows from Asian regions to Europe and North America were more than twice as high as the inbound flows from these regions.

Besides the asymmetrical trade volumes, a further cause of the trade imbalance is the different types of containers (Pawlik, 1999). In maritime container transportation there exist mainly two sizes of containers: the 20-foot container (1 Twenty-foot Equivalent Unit (TEU)) and the 40-foot container (2 TEU or Forty-foot Equivalent Unit (FEU)). TEUs are allowed to have a maximum load weight of 21,600 kg, while FEUs have a maximum 32,210 kg load weight (Branch, 2006). Due to these sizes, there are regions which require TEUs and others which demand FEUs. The Asian countries, for instance, mainly export goods which

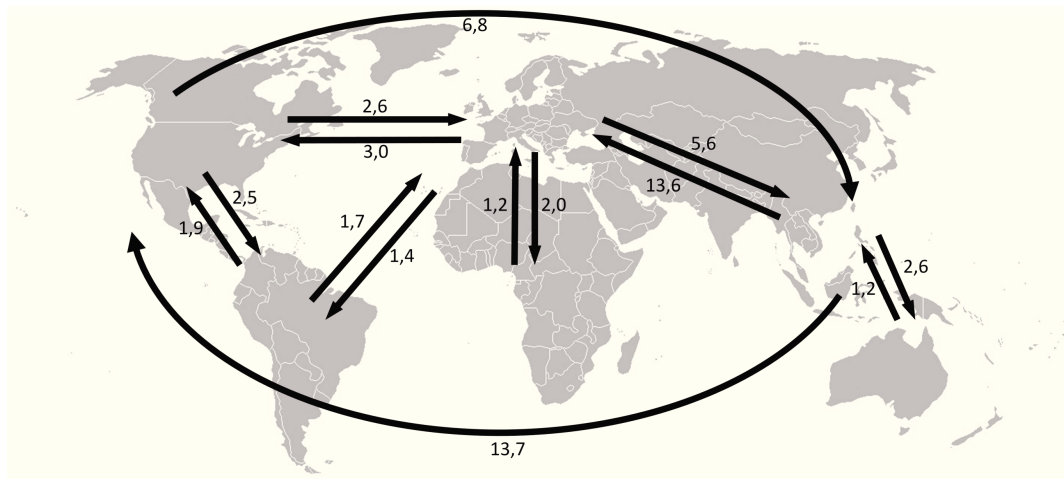


Figure 2.3: *Global Container Imbalances on Selected Trade Routes in 2010 (in Million TEU; Based on Hautau and Hüttmann (2009) with Actualized Data from Drewry Shipping Consultants (2011))*

are relatively lightweight and have a large volume. In contrast, the European industry predominantly supplies goods which are heavier on average. In many cases these goods do not possess the volume to fill a FEU so that Europe focuses to a greater extent on the usage of TEUs, while the Asian countries export FEUs (Konings and Thijs, 2001). A further example for trade imbalance caused by container types is the utilization of refrigerated containers, which are predominantly demanded by countries in South America or Africa. For instance, in African countries, mainly finished products are imported in standard containers, while African agricultural companies require a huge number of refrigerated containers to export fruits (Theubert, 2010).

In recent years, a third main cause of the imbalance in containers has been detected. The focus is on fluctuating steel prices which influence the container fleet and the repositioning of boxes. Boilé (2006) reports that in May 2004 repositioning empty containers from the US East Coast to Asia cost \$1,200 for leasing companies. At the same time, new containers could be built at a cost of \$1,300 in China. As a result, shipping and leasing companies tended to build containers in Asia and to recycle old containers in Europe and North America instead of moving “fresh air” to Asia. During 2004, steel prices have risen abruptly and unexpectedly. In July 2005, prices for a new TEU reached \$2,250. Hence, shipping and leasing companies concentrated once again on the repositioning of their empty containers from import-dominated regions to export-dominated regions. Accompanying the ongoing manufacturing of containers, especially in China where 95% of the containers worldwide are built, a surplus of containers in Asian countries

Table 2.1: *Development of Global Empty Container Handling*

Year	Total Port Handling (million TEU)	Full Container Handling (million TEU)	Empty Container Handling (million TEU)	Empty Incidence
1980	38.7	30.3	8.4	21.7%
1985	57.4	44.0	13.4	23.3%
1990	88.1	70.3	17.8	20.2%
1995	145.5	118.7	26.8	18.4%
2000	236.7	186.4	50.3	21.2%
2005	399.2	316.6	82.6	20.7%
2010	548.5	431.6	116.9	21.3%

Source: Drewry Shipping Consultants (2011)

was obtained for the first time. The decreasing demand for new containers led to several closings of container manufacturing companies in China. Accompanied by the financial crisis and the ongoing recycling of old containers in the West the global container fleet declined in 2009. After the crisis, the need for new containers increased once again in 2010. However, since many factories in China closed, a growing equipment shortage has been detected since 2010, which has consequently led to an increasing importance of empty container management (Foxcroft, 2010).

The above-mentioned factors are the main reasons for empty container repositioning in sea transportation, in general and in recent years. More detailed information on these factors and further explanations can be found in Lun et al (2010), Wang et al (2008), Boilé (2006), Song and Carter (2009), or Vojdani and Lootz (2011).

The global transshipment volumes which can be seen in Table 2.1 show that the empty incidences have not changed substantially since 1980. The amount of empty containers has been settling down into a narrow band around 21% in the years since 2000. Even the financial crisis in 2009, which initially increased the East-West imbalance, has not shifted the global assessment to any significant degree. This development is an indicator that carriers seem to have reached their limits of effectiveness in managing the route imbalances between Asia as the “manufacturing and export centre of the world” (Drewry Shipping Consultants, 2011) and the other regions. The days of empty incidences below 20% are unlikely to return any time soon. But at the same time, developments in the past years indicate that historic highs of 23% and greater are unlikely to occur in the future.

Due to the cost pressure in maritime container transportation, carriers can simply not afford to deal with these high rates of empty incidents and need to guarantee an efficient empty container management (Drewry Shipping Consultants, 2011).

2.4 Empty Container Repositioning in Hinterland Container Transportation

As previously mentioned, the allocation of empty containers in a port's hinterland is significantly affected by trade imbalances in port-to-port business which are outside the hinterland's actors' level of intervention (Notteboom and Rodrigue, 2007). Besides this exogenous force for hinterland container transportation, regional container repositioning is much more complex than container allocation in port-to-port business. This is due to the fact that the repositioning of empty containers requires the coordination between several actors, as well as the allocation of containers between considerably more location types. The different container movement patterns which can be applied in hinterland container transportation are illustrated in Section 2.4.1. Afterwards, Section 2.4.2 describes the need to reduce empty container movements. The difficulties of putting the most efficient container movement pattern (*street turn*) into practice are surveyed in Section 2.4.3.

2.4.1 Container Movement Patterns

The repositioning of empty containers in hinterland regions takes place at two geographical levels: interregional and regional. At an interregional level, empty containers are repositioned between two regions overland. This transport becomes necessary if a region, for instance, is not an import- and consumption-area at the same time. Provided that a full container addressed to a receiver in region B is imported through sea transportation in region A, then an interregional transport from region A to region B is indispensable. For instance, in the United States a large percentage of full containers for the greater New York region is imported at Los Angeles-Long Beach in California and moved to the New York region intermodally overland. The obtained empty containers - after the containers are unloaded in this region - are then moved back to California for the most part (Boilé et al, 2008). Hence, interregional empty container management can help to balance the number of empty containers between import- and export-dominated regions inside a wide geographical area such as North America, Asia,

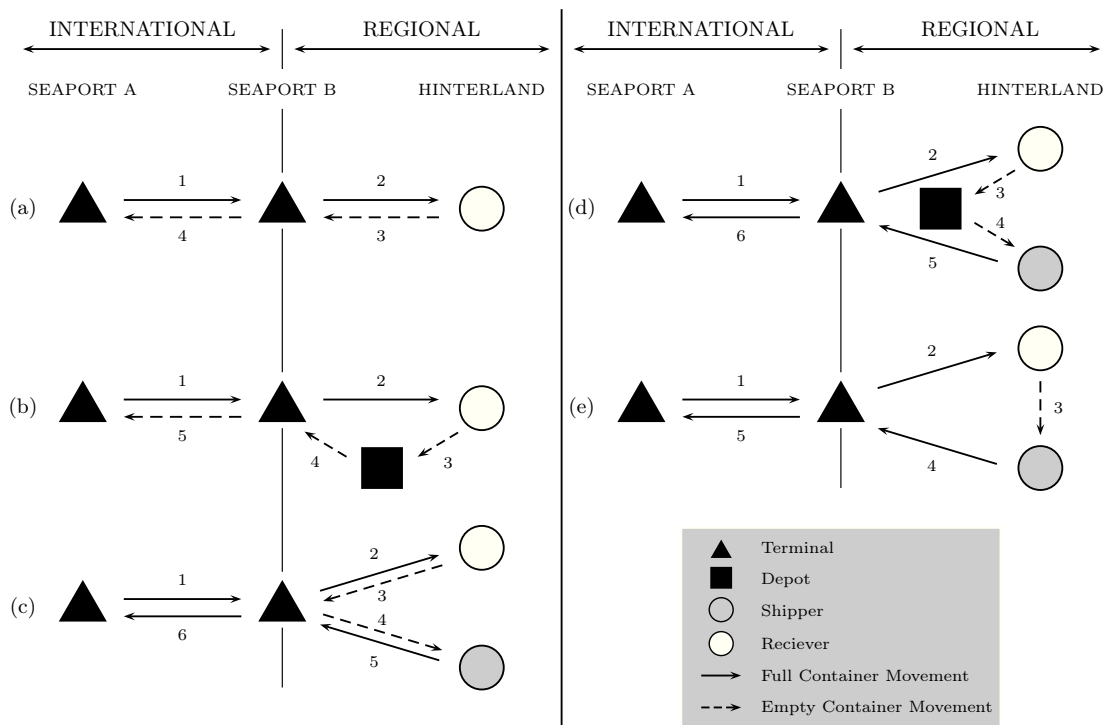


Figure 2.4: Container Movement Patterns (Based on Furió et al (2009))

or Europe. Carriers therefore mainly make use of intermodal transportation. For the most part, barges or trains are used to move containers since they guarantee a more cost effective way for transportation than container movements by trucks. The change of modes is performed at the seaport terminal or at a nearby inland terminal (Macharis and Bontekoning, 2004).

As can be seen in Figure 2.4, the allocation of containers in regional container transportation is substantially different from the global, as well as the interregional, container transportation. While the allocation of containers in global and interregional transport involves only terminals where in between container flows are applied, regional container repositioning is much more complex since it is about the allocation of containers between considerably more location types. These location types include terminals, empty container depots, as well as a number of shipper and receiver customers (Veenstra, 2005).

Different from loaded containers, empty containers usually do not have fixed origin and destination locations. Hence, there exists a need to meet future transportation opportunities (Di Francesco, 2007). Figure 2.4 shows the different container movement patterns that can occur in regional container repositioning. In addition and for a comprehensive survey, the international flows representing the port-to-port business are illustrated. Certainly, the global flows are carried out by

container vessels. The regional transport is guaranteed by making use of trucks.

The pattern of Figure 2.4(a) is defined as the “*repositioning*” of empty containers (Hanh, 2003). A loaded container arrives at the seaport terminal illustrated by movement 1. Afterwards, the shipment is picked up and delivered by a truck to a receiver customer (movement 2). The container is then emptied and it is moved back to the seaport terminal (movement 3), from where it is sent back to its origin region for the next cycle (movement 4). Pattern B also defines a “*repositioning*” operation. But instead of moving the container from the receiver directly back to the seaport terminal, the empty box is stocked in an empty container depot before it is moved to the terminal.

The “*match back*” operations are illustrated by Figure 2.4(c) and Figure 2.4(d). Here, the empty container obtained at the receiver location is not directly used for a global empty repositioning move. Instead, the container remains in the region and is moved via the seaport terminal or the empty container depot (movement 3) to the shipper (movement 4).

A special case of the “*match back*” operation is defined as the “*street turn*” pattern (see Figure 2.4(e)) since the empty container from the receiver is directly moved to the shipper location. Hence, empty trips are rationalized since an empty container is reused without an intermediate return.

2.4.2 Importance of Rationalizing Empty Container Movements

The obvious motive to ration empty container distances is that the movements of empty containers generate substantial costs for the companies in intermodal door-to-door services. This is because the transport of these boxes do not generate any revenues. In addition, empty container repositioning ties up plenty of resources, such as transport and storage capacities. Therefore, the movements of empty boxes has a negative and harming impact on the business of transport operators (Wolff et al, 2011). In 2009, 6% to 7% of the global maritime income was dedicated to landside positioning of empty containers (UNCTAD, 2011).

The need to improve efficiency in regional and interregional container transportation becomes even more important as most bottlenecks in door-to-door chains are in the hinterland. Through the enormous growth rates of container throughputs at the ports, congestions in the port areas have become a big problem. Jula et al (2006) and Hanh (2003) state that empty containers have the

highest average dwell time³ at the terminal (anywhere from 14 to 50 days) and are, therefore, the largest contributor to the congestion at and around the port. As a consequence, this inefficient container handling tends to restrict the overall terminal capacity so that the operating capacity of terminal gates is diminished (Hanh, 2003). Usually, truck drivers that arrive at the port area expect an average waiting time of two to three hours (Barber and Grobar (2001) and Jula et al (2005)). The problem of congestion goes along with long waiting times for truck drivers, as well as large CO₂-emissions and noise disturbance for the surrounding population (Vojdani and Lootz, 2011). Therefore, the reduction of empty container movements in regional repositioning has become an import field of activity for actors in hinterland transportation, not only due to economic reasons, but also because of environmental and sustainability reasons (Song and Carter, 2009)

The problem of inefficient container transport becomes obvious if one has a look at the share of empty container movements overland. In most cases, at least 50% of the movements between the port and its hinterland concerns empty containers (see Figure 2.4(a)-(d)). For instance, Figure 2.4(d) comprises two full container movements (movements 2 and 5) and two empty container movements (movements 3 and 4). Characteristically, patterns (a) and (c) only comprise pendulum container movements between the customers and the terminal. For instance, a full container leaving the port to a customer is moved directly back from this location to the seaport terminal after it is unloaded. In pattern (b), even two-thirds of the movements are characterized by empty moves. The statistics confirm this analysis since the share of empty container flows for transport-services on land is at least 40% and, therefore, even twice as high as the portion in sea transportation (Konings (2005) and Crainic et al (1993b)). In Europe, the situation is even worse, as Branch (2006) states that over 50% of the container movements are empty.

Hence, empty container repositioning constitutes a major cost driver for the operating actors in hinterland transportation. Solutions to shrink the amount of empty container movements mainly focus on *street turn* operations where empty containers available at some customer locations are directly moved to places where they will be needed next (Veenstra, 2005). Thereby, only one-third of the container moves are required to position empty containers, as can be seen in Figure 2.4(e). The ideal situation for the *street turn* pattern occurs when the receiver-customer is also shipper. In this case, the receiver can unload the full container

³The dwell time is defined as the time a container has to be parked on the terminal until it is picked up (Hartmann, 2004).

and use the empty box for exporting goods. Since empty repositioning moves are omitted, only profitable container movements are performed. The second best case for the *street turn* pattern occurs if a shipper and a receiver are located geographically close to each other (Hanh, 2003). Then, only a short empty repositioning move has to be performed.

2.4.3 Challenges of Making Use of Street Turns

The direct reuse of empty containers without an intermediate return of the box to the container depot plays an important role for trucking companies in the hinterland of seaports in achieving high performance levels in the management of a company's equipment (Di Francesco, 2007). Unfortunately, it is hard to find data on the relative frequency of street turns in hinterland transportation. The report of The Tioga Group (2002) surveying the Southern California region, indicates that it is not applied very often in hinterland transportation. It is stated that 1.1 million import containers were emptied at receiver locations in 2000. At the same time, 500,000 shippers needed an empty container for export. It is estimated that only 25,000 containers were used for street turn patterns. Wolff et al (2012) mentions that the street turn share ranges from 5% to 10% in the hinterland of the port of Hamburg. At the same time, the authors state that for other European regions this container movement pattern is "even more seldom or almost non-existent".

The reasons for the small amount of street turns vary. According to Hanh (2003), actors in hinterland regions are aware of the big potential of this reuse operation but fail to implement this container movement pattern due to the following institutional and informational barriers (Furió et al (2009) and Vojdani et al (2009)):

- Usually, a hinterland region is import- or export-dominated so that there exists a surplus or a lack of empty containers. Thus, there are more customers who either receive goods or customers who want to ship goods.
- A coincidence of an import and export operation at the same time is required.
- The type of container for the shipper and for the receiver has to be the same.
- The contract of a leased container has expired.

- The shipper and the receiver have to be served by the same shipping company (as the possessing actor of the underlying container). For instance, two different shipping companies A and B, who are responsible to take care of a shipper (shipping company A) and a receiver (shipping company B), usually do not exchange their containers with each other (see Section 3.3).

Hanh (2003) states that the locations of shippers and receivers are rather dispersed in the United States. Hence, a street turn between these customers is unlikely to appear due to matching problems of the time windows or due to the fact that the distance from the receiver to the shipper is almost as long as for a match back operation. Even if this is not the case, import and export customers mainly operate with different carriers who are not eager to exchange their containers. In Europe, the conditions for street turns are more often found than in the United States. For certain branches, such as the electronic and car industry, the import and export companies are often run by the same corporation and, therefore, favor the direct reuse strategy. Nevertheless, the potential of the street turn patterns remains high. Overcoming these drawbacks and increasing the use of this pattern requires addressing these barriers and finding tactical and strategic approaches in order “to create a fast, reliable, efficient and seamless system for empty container reuse outside the terminals” (Jula et al, 2006, p. 47).

2.5 Approaches to Reduce Empty Container Repositioning Costs

In the foregoing sections the main reasons for the requirement of an efficient handling of the repositioning of empty containers in sea and hinterland transportation have been stated. Although the reduction of empty container flows in intermodal door-to-door services has been constituted, an important matter for many decades, the literature on the allocation of empty container in maritime transportation is relatively scarce (Lai et al (1995), Choong et al (2002) and Li et al (2007)). The following section provides a literature review that focuses on operational research articles which produce ideas or present approaches to improve the situation in hinterland container transportation. Thereby, only approaches that take explicitly empty container repositioning into account are discussed. Since sea transportation highly influences the transport systems overland, Section 2.5.1 firstly investigates the relevant literature of empty container management in intermodal door-to-door services in general. Thus, approaches

concerning the minimization of empty container flows in sea *and* in hinterland transportation are discussed. Afterwards, Section 2.5.2 gives a survey of articles which consider concepts, methods, and algorithms for the minimization of empty container flows only in hinterland container transportation.

2.5.1 Intermodal Door-to-Door Services

Early descriptions of network models examining the allocation of empty containers can be found in White (1972). The author describes and defines a transportation system for goods which shall be moved from supply to demand locations by means of different transportation modes. Thereby, an algorithm is illustrated which considers explicitly the distribution of empty containers. Crainic et al (1993b) describe a dynamic deterministic scenario which handles the allocation of empty containers according to current and future customer demands. The authors propose a general modeling framework reflecting the operational and planning complexity between land transportation and maritime shipping transportation. The importance of the length of the planning horizon is stated. Since the number of decision variables rises with the number of considered periods, the planning horizon should be determined carefully. The article is focused on technical aspects and does not include any experimental results. Based on this framework, Abrache et al (1999) propose a decomposition algorithm, concentrating on a multi-commodity case and generating a deterministic model. Lai et al (1995) present a simulation model for a shipping company which handles the leasing, storage pick-up, and drop-off of the containers. The authors stress the difficulty in forecasting future export container movements and the demand for empty containers since these movements fluctuate continually. A heuristic search is employed which seeks to minimize the operational costs for the company. Cheung and Chen (1998) try to improve the repositioning of loaded and empty containers for liner operators in sea transportation by modeling the container allocation as a two-stage stochastic model. They aim to determine the number of leased containers needed to meet customers' demands over time. The problem is solved by means of a single-commodity stochastic network. In the first stage, all parameters are deterministic whereas in the second stage, some parameters are stochastic. By using a stochastic linearization method the two-stage stochastic network is solved. Recently, Li et al (2007) dealt with the problem of shipping companies in positioning empty containers from supply ports to demand ports. The authors include company-owned and leasing containers and define policies for the allocation of containers at the right amounts to the right

ports at the right time. A heuristic algorithm is implemented in order to solve numerical examples. Shintani et al (2007) address the design of service networks for shipping companies by taking explicitly into account empty container repositioning. Different from other studies, the authors simultaneously consider not only the allocation of containers but also the deployment of ships. The problem is defined as two-staged and solved by a genetic algorithm. Computational results show the potential of the proposed method to save costs in the shipping network if both problems are considered. Finally, Dong and Song (2009) jointly optimize the container fleet size, as well as the empty container repositioning, in liner shipping systems. By considering dynamic and imbalanced customer demands, the total costs are minimized. As a solution approach the authors use a genetic algorithm.

2.5.2 Hinterland Container Transportation

The operational planning of empty container repositioning in the hinterland of seaports can be divided into two subproblems: container allocation and vehicle routing. Crainic et al (1993b) note that ideally a single mathematical comprising both problems should be developed since the independent consideration of these subproblems neglects possible positive emergences. Due to its complexity, the simultaneous consideration of both subproblems within one single MIP model has been neglected for many years. A literature review concerning this emerging field of integrated routing solution approaches can be found in Section 4.2.1. Nevertheless, in the past, planning concepts in hinterland container transportation have mainly focused on vehicle routing or on empty flow management (Dejax and Crainic (1987) and Braekers et al (2011c)). The objective of vehicle routing in hinterland transportation is to minimize overall transportation costs of loaded and empty movements which are to be executed in the next period. Additionally, the field of container allocation seeks to minimize the distribution of empty containers due to known and forecast demand. An overview of corresponding articles focusing on vehicle routing problems with full truckload restrictions can be found in Section 6.1.1. In the following, a literature review concerning container allocation problems in the hinterland of seaports is given.

In 1987, Dejax and Crainic were the first authors who noted that very little effort has been made to develop models that focus on container transportation issues. In their work, therefore, they offer a survey of the literature on container fleet management models in freight transportation. Dejax and Crainic (1987)

discuss the advantages of a hierarchically integrated approach of simultaneously managing empty and loaded freight vehicle movements. Crainic et al (1993a) develop a multi-commodity network model for the assignment of customers to container depots in hinterland transportation. The problem comes to a location-allocation problem where the right container depots have to be selected. An interdepot traffic is considered in order to balance the number of containers between supply and demand regions. The right number and the right places of the depots, as well as the consideration of full and empty container flows, is handled by means of a tabu search heuristic. Chu (1995) examines the allocation of empty containers between customers, ports, and depots in anticipation of future demand. To cope with uncertainty he develops a multi-stage stochastic mathematical model. Chu firstly decomposes the problem by using Lagrangian relaxation techniques. Subsequently, he implements an algorithm and solves each subproblem. The computational experiments indicate that the stochastic model provides better solutions than the deterministic model in terms of total costs. Choong et al (2002) define an integer formulation for a broader hinterland in which empty containers can be moved by barges at very low costs. By means of a case study in the Mississippi River, the effects of planning horizon length on the selection of transportation modes are shown, where a longer planning horizon encourages the use of cheap but slow modes. As in Choong et al (2002), Olivo et al (2005) also examine empty container management on a continental or interregional level and formulate a two-commodity model. The model comprises decisions concerning service routes, inventory links, and decisions regarding time and place to lease containers. During a weekly rolling horizon planning period, the authors consider small hourly time steps in order to allow a more detailed representation of transportation systems. Although the authors consider two types of containers, substitution options are not included. Based on this work, Di Francesco et al (2006) propose a dynamic model which also addresses a heterogeneous fleet of containers, but as opposed to Olivo et al (2005), allows the substitution of container types. A mathematical model which offers a decision support system for shipping companies is proposed. Numerical experiments show that the substitution of containers leads to significantly improved solutions.

Based on their work from 2003, Jula et al (2006) analyzed the impact of two empty container reuse methodologies (“depot-direct” and “street turn”) on the reduction of number and cost of truck trips in the Los Angeles port area. The authors assume the maritime terminal as the only container depot in the underlying region, i.e. empty containers cannot be stacked at the trucking companies’

depots. The objective is to reduce the congestion at the port area by evaluating the possible benefits of constituting further off-dock container depots to reduce the required number of empty trips (“depot-direct”). The authors also analyze the idea of the “street turn”-strategy. By implementing a two-phase optimization technique which seeks to find the best match between supply and demand of empty containers over a number of periods, it is concluded that the reuse strategies can reduce the traffic around the ports significantly. Since the focus is on avoiding congestion, savings regarding the companies’ transportation costs are not considered. Based on these contributions, Chang et al (2008) analyzes whether the substitution between empty containers of different types leads to a reduction of empty container interchange costs. Computational tests show that container substitution may result in a reduction of empty container movements. Deidda et al (2008) proposes a decision support tool which quickly determines truck routes in order to implement the street turn strategy. Based on an optimization model, several daily distribution problems of a real-world shipping company are solved and compared to the decisions made by the company. Results show that the solution approach is able to determine truck routes with significant distance reduction.

3 Reducing Hinterland Transportation Costs through Container Sharing

The reduction of hinterland transportation costs goes inherently along with an efficient allocation of empty containers. Dealing with container movement patterns, which include up to two-thirds of moves needed to transport empty containers, transport operators try to increase the number of street turns. However, in reality the amount of direct transports of empty containers from receiver to shipper locations is relatively low due to the stated reasons in the foregoing chapter. A promising idea that can help to overcome these difficulties and enable an efficient transport for container operators in hinterland regions is container sharing. Thereby, trucking companies exchange their empty containers with each other in order to increase the number of street turns and to decrease hinterland transportation costs.

The following chapter initially provides a description of the container sharing idea in Section 3.1. While Section 3.2 gives an overview of the benefits of container sharing, Section 3.3 illustrates the challenges of putting container sharing into practice. Finally, Section 3.4 surveys prior approaches that are similar to the container sharing concept.

3.1 Concept of Container Sharing

Analyzing the institutional and informational barriers of realizing street turns, it can be noticed that one of the most important drawbacks is the fact that regions are either import- or export-dominated. Providing the same number of shippers and receivers in a hinterland region would certainly raise the chance to realize additional street turns since it increases the coincidence probability of import and export operations which can be served by a truck at the same time. Unfortunately, this barrier is exogenous and, thus, cannot be influenced by the operating carriers and trucking companies. Dealing with this situation, the above mentioned coincidence probability is even decreased by the fact that the number of shippers and receivers of one region are served by different trucking companies. These transport operators are urged to only take possession of the containers

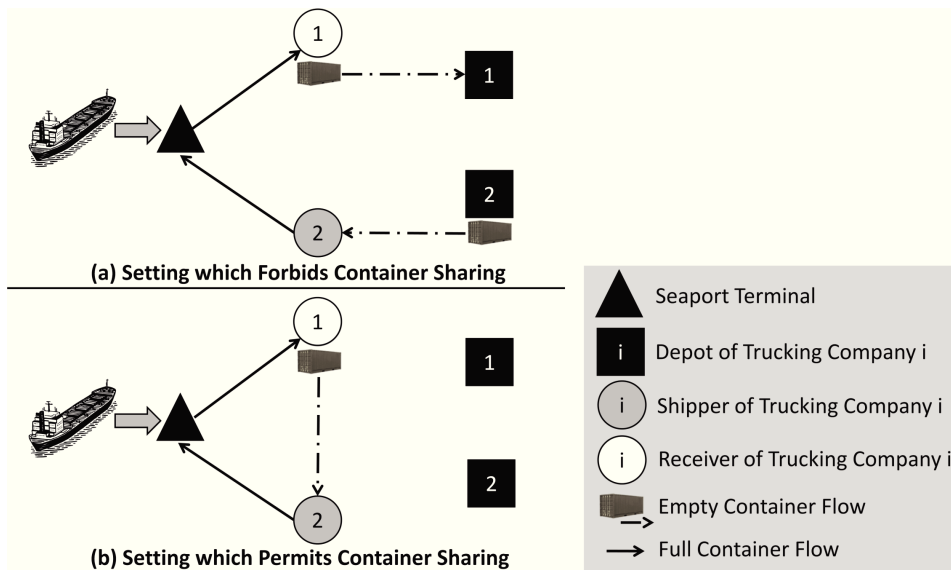


Figure 3.1: *Container Sharing Concept*

made available by the shipping companies. One idea to overcome this fragmentation of customers within one region is container sharing, where containers are not uniquely used by companies they are assigned to. Transport operators of a hinterland region cooperate with each other by sharing information regarding which locations empty containers are currently stacked at and, moreover, agree with the mutual exchange of these containers. As a consequence, all trucking companies can improve their routes and increase their profit by decreasing transportation costs in return.

The concept of container sharing can be well-illustrated well by using a simple example. Imagine a hinterland region in which two trucking companies operate their own container depots. Each company serves its own customer base by means of containers owned by two autonomous shipping companies. The customer base of trucking company 1 only consists of a receiver while the customer base of trucking company 2 includes only a shipper. Figure 3.1(a) then shows the usual setting in which both trucking companies operate independently from each other. In order to serve its receiver, company 1 moves the full container from the terminal to the customer. After the container is unloaded, the trucking company moves the empty container to its depot. Additionally, company 2 needs to move an empty container to the shipper so that it is able to fill freight into it. In this case, the depot is the origin of the empty container movement. After the container is loaded at the customer location, the full container can be moved to the terminal.

Figure 3.1(b) shows an example for the idea of container sharing where containers can be exchanged between cooperating companies. Besides the possibility of

using the depot as an origin or as a destination of an empty container, trucking company 1 can now integrate the obtained empty container at the receiver location of trucking company 2 in its route or serve its shipper customer. The two empty container flows in Figure 3.1(a) then become unnecessary and, thus, the required container flows of the illustrated setting are reduced.

3.2 Benefits of Container Sharing

Certainly, the idea of container sharing seeks to reduce the enormous transportation costs which are caused by empty container repositioning. Due to the interdependency of the transportation resource and the mean of transport, the emerging additional flexibility to allocate empty containers will consequently lead to a minimization of the trucks' transportation costs. Container sharing primarily tries to increase the number of street turns within one hinterland region. One can assume that the benefit of container sharing will grow tremendously through the rising flexibility to allocate empty containers if further customers and trucking companies are considered. In other words, the more empty containers are shared with other cooperating companies, the higher the probability to spare travelled distances required to serve transportation requests.

In general, the benefits of container sharing for the participating players, including the shipping companies, trucking companies, the depot/terminal operators, as well as the public, are as follows (Partridge (2007) and Hanh (2003)) :

- The shipping companies as the provider of containers mainly take advantage of the improving asset utilization. It can be assumed that the number of containers used in a container sharing coalition decreases since containers of cooperating companies can be used for the same number of transportation requests. At the same time, the remaining containers are used more frequently due to the fact that several trucking companies can access a certain box of the owning company. Certainly, the decrease of containers goes along with a reduction of leasing costs, as well as repair and storing costs. Hence, a greater operational efficiency can be achieved through the cost savings in equipment storage and handling of containers in yards.
- Focusing on trucking companies, it is most likely that transport operators can increase the number of street turns and, thus, decrease empty vehicle distances. Hence, the share of revenue-producing runs rises and the fuel is used more efficiently. Since container sharing can affect a reduction of

traffic volume at terminals, congestions can more likely be avoided so that truck drivers spend less time waiting in line at terminals. The decline of time spent on the roads goes along with the decrease of associated expenses, such as personnel costs, as well as wear and tear on assets. As a result, the costs per transportation request decrease as well.

- Finally, the decrease of congestions at terminals and traffic in the hinterland helps to improve the air pollution and traffic situation for the public nearby terminals.

3.3 Challenges of Putting Container Sharing Into Practice

The underlying thesis seeks to quantify the potential of container sharing in a perfect economic environment in which acting players cooperate willingly with each other. Companies act completely altruistically and seek to increase the welfare of the coalition. However, in reality there are several challenges which have to be faced to enable an ongoing container sharing coalition which encourages trucking companies to participate. These challenges are out of the scope of this thesis but are touched upon in the following in order to get a comprehensive overview of the factors to be figured out in a coalition to be put into practice.

Dealing with container movements in a seaport's hinterland always requires the coordination and cooperation between several actors in hinterland container transportation (Van der Horst and De Langen, 2008). The most important actors for realizing the container sharing idea are the container-owning players as well as the operating trucking companies. If containers shall be exchanged between trucking companies of a certain hinterland region, it is most notably required that shipping and leasing companies work together and overcome possible problems which are quite heterogeneous. As Veenstra (2005) mentions, shipping companies always try to stay in control of the containers. From the view of a shipping company, empty containers shall be best stacked in the port area rather than having them moved around in the hinterland region where they do not exactly know the container's location. Thus, if the equipment of a certain shipping company is used by "foreign" trucking companies which are not assigned by the container-owning shipping line, the situation in the underlying hinterland would be complicated. An aggravating factor is the fact that containers of a jointly used equipment pool can be exported to different regions. Hence, containers are completely out of the shipping company's sight in the worst case. However, it should be mentioned

that the possibility of a company to use external containers in a container sharing coalition does not change the number of ingoing and outgoing containers at the seaport terminal. In other words, the interface of the seaport terminal to the abroad sites and to the hinterland locations is only changed with respect to the identity of the containers, and not with respect to the size of the flows of containers.

During the last decades security initiatives on container transportation have been gaining in importance (Donath et al, 2005). Some of these programs, such as the “Authorized Economic Operator (AEO)¹” or the “Custom-Trade Partnership Against Terrorism (C-TPAT)²”, are on a voluntary basis. Trucking companies participating in those programs refuse to do business with companies which do not participate in order guarantee a steady safety level in the transportation chain (Mongelluzzo, 2006).

The risk of a participant using cooperating companies equipment which is not in a good condition and may not be suitable for a transportation request to be executed, increases the uncertainty of a trucking company. Moreover, containers which return to the actual owner can be in a bad condition and require repair (Pawlik, 1999). Thus, it has to be clarified how the owning party is to be compensated and how a homogeneity of shared equipment can be guaranteed. The suggestions to deal with this factor can be various. For instance, it can be agreed that the whole equipment which is shared needs to be repaired once in a given period. A further suggestion is to only repair the containers if necessary. Anyway, in each case it is to be clarified to whom the costs of repair are to be allocated. For instance, it is conceivable that only the originator of damage is forced to pay. Thereby, further complications arise through the questions of who caused the main damage. Furthermore, it is conceivable that the cooperating parties agree to proportionately deposit money for the containers’ repair costs. In this case, the question of which cost proportion is appropriate for a company who shares only a few versus a large number of containers has to be clarified.

One of the main challenges related to the container sharing idea concerns the allocation of potential profits between the companies. The basis of joining the

¹“An Authorized Economic Operator can be defined as an economic operator who is reliable throughout the [European] Community in the context of his customs related operations, and, therefore, is entitled to enjoy benefits throughout the Community.” (Fabio, 2010, pp. A 1 - A 2)

²“The C-TPAT is a voluntary United States Customs and Border Protection (CBP) business initiative designed to build cooperative relationships [between importers, carriers, brokers, warehouse operators and manufacturers] that strengthen overall supply chain and border security.” (Hinkelman, 2008, p. 6)

coalition lays in gaining an additional profit from the participation in a coalition. It needs to be ensured that the interests of each single partner are maintained. According to Van der Horst and De Langen (2008) “(...) coordination may not arise spontaneously (...) if one actor in the chain has to invest (...) while other actors obtain the benefits”. Consequently, it needs to be determined how companies who benefit at an above average level compensate the other players. Moreover, monetary incentives have to be provided so that not only unfavourable containers (e.g. containers located at the border of the considered region which can only be integrated into vehicles’ routes with much effort) are shared. Profit sharing models shall motivate participants to make rather more containers available for the coalition. The risk of free-rider behavior needs to be minimized. Therefore, a proper profit sharing model is of crucial importance (Krajewska and Kopfer, 2006).

A majority of shipping lines uses containers as a way of advertising the company’s name (Notteboom and Rodrigue, 2007). Using containers with foreign brand names deters shipping companies to participate in a coalition due to marketing reasons (Wolff et al, 2011). An approach to overcome this problem between shipping companies can be the introduction of neutral grey boxes (see Section 3.4). However, Lloyd’s List DCN Shipping (2010) states that the branding argument “tends to fall a little bit flat” since 40-50% of the shipping companies’ container pools are leased containers which also do not wear the brand name of the operating shipping company.

Another challenge lays in the reluctance of carriers to share market information on container positions and container quantities with competitors since it can reveal sensitive data concerning the demand and requirements of their customers (Notteboom and Rodrigue (2007) and Veenstra (2005)). Provided that companies are eager to share this data, an information exchange system is required which guarantees a neutral and safe transmission of information on, for example, a container’s type, location, condition, and the provided standstill time of the container at the underlying location (Pawlik, 1999). Certainly, on these platforms participants should mainly decide which and how many containers are shared with partners. As can be seen in Section 3.4, prior approaches related to container sharing handle the exchange of containers e.g. via internet-platforms.

Beside the mentioned challenges, it is of fundamental importance to quantify the benefits which can arise through a container sharing coalition. The reorganization of companies to participate in such coalitions causes costs (e.g. transaction costs). Since the container transportation market is highly competitive, these

costs constitute a risk for these companies. As a consequence, only if companies know the approximate benefit of joining such coalitions are they eager to take this step (Hanh, 2003).

3.4 Prior Approaches Related to Container Sharing

The concept of container sharing is not a completely new idea to avoid the amount of empty container moves in a seaport's hinterland. A few similar approaches have been investigated in the literature, as well as in practice, in the last decades. The container pooling approach describes a general coalition of transport operators in maritime transportation and had already been mentioned in the late 1960's. The participating players should share their containers in a pool which is jointly used by the cooperating players, which should initiate a better coordination and enable scale economy (Huch, 1973). The cooperation can vary in terms of the integration of the players. Hence, the cases vary from the exchange of containers in case of need to the complete fusion of the single container pools (Mencil and Krenkel, 1987). Although the idea of container pooling is relatively old, it almost has not been investigated in the literature. This is surprising since Damas (1995) states that the potential of savings are enormous.

A container pooling concept which has been put into practice is reported by Veenstra (2005) and Van der Houwen (2003). The so called "Boxsharing" concept was a database system of several small shipping companies at the Rotterdam port. It should improve the competitive advantages of the participating companies in the port's hinterland by sharing their empty container surpluses. In return, the members of the initiative can search for empty containers of foreign companies that they might want to use. Similar to the container sharing idea, companies can integrate them into their routes. Launched in November 2002, the system contained only 300 empty containers stationed all over Europe in 2005. As a consequence, the "Boxsharing" concept was stopped in 2009 (Portbase, 2012).

A further container pooling concept put into practice is the "Virtual Container Yard (VCY)" in the hinterland region of the ports of Los Angeles and Long Beach. This concept only includes trucking companies which move containers of the same shipping company. On an Internet-based program, the participating companies post available empty containers (Mongelluzzo, 2005). Thereby, confidential information such as position, type, and condition of the containers are recorded and allows a simple access for the participants. Through the introduction of a VCY, it is estimated that the number of street turns in this region can

be increased from two to ten percent (The Tioga Group, 2002). If the street turn rate is “only” increased to four percent, thousands of “unnecessary” truck trips can be eliminated each year (Mongelluzzo, 2006). Certainly, Mongelluzzo (2005) state that the savings can be even higher if the trucking companies of different shipping lines agree to cooperate with each other. Established in September 2003, there is to date no public information about the effects of the introduction of the VCY (Theofanis et al, 2007).

The “Grey Boxing” concept is based on the container pooling idea, but instead of sharing containers belonging to different shipping companies, the coalition uses neutral containers which are used apart from a company’s container pool. These neutral boxes are grey and, thus, not labelled with any advertisements of the operating companies. The equipment assets are transferred to a jointly owned off-shore holding corporation. Containers can be leased by the cooperating players for the mutual benefit of the shareholders. Although the grey boxing concept has been known for almost 30 years, it has not been discussed intensively (Vojdani et al (2010) and Transamerica Leasing (1995)). In the early 1990’s a consortium of several (primarily) Scandinavian shipping companies tried to make use of the grey box concept. In the project’s height, the container volume was at 100,000 containers. Nevertheless, the consortium was dissolved in 1994 (Canna, 1994). The reasons were the immense reduction of container volume due to a decline of participating members and the fact that the project was not successful in gaining shipping companies outside Scandinavia (Bonney, 1995b). In 1995, a large-scale experiment of eight participating shipping companies indicated that the grey box concept including 1,500 containers led to a cost savings of 1.5 million US dollars for the coalition within four months (Transamerica Leasing, 1995). These savings seem to be very high, however, a relation of this amount towards the primal total transportation costs is not given so that no concrete interpretation of this savings can be revealed. Moreover, the coalition focussed on sharing leasing containers mainly in sea transportation (Bonney, 1995a).

To the best of the author’s knowledge, only Vojdani and Lootz (2011) carry out computational experiments in order to analyze benefits of the container pooling approach. The authors indicate the reduction of the number of containers in seaports’ hinterlands, as well as in port-to-port business, if shipping companies and leasing companies cooperate with each other. The players have the choice of completely or partially sharing the containers so that three types of container types can be distinguished: containers belonging to the pool, to the shipping companies or to the leasing companies. A network flow model from the perspective of

a shipping company, which includes locations (terminals, depots, and customers) as well as the operations (storage, transport etc.) of the acting player is defined. The optimization of this network is achieved by implementing a MIP model in a commercial solver tool. Subsequently, Vojdani and Lootz (2011) analyze 30 test instances which are characterized by two shipping companies who completely provide their containers in a jointly used pool. Each instance is solved two times to compare scenarios with and without container pooling. The results show a huge reduction in the amount of containers. Thereby, repositioning mainly in port-to-port business can be reduced since up to 70% of the number of containers can be saved. However, these results should be accepted with caution since the characteristics of the instances are not illustrated clearly. Furthermore, the authors only concentrate on the containers as a transportation resource and excluded the consideration of transportation means. Thereby, the authors simplified the operations especially in the hinterland of seaports. A breakdown of the results which distinguish between hinterland and sea transportation is completely missing.

4 The Potential of Container Sharing Measured in Basic Scenarios

A first indication of the potential of container sharing in the hinterland of seaports is given in the following chapter. Through a precise definition of two basic scenarios which are based on a comprehensive truck container transportation problem known from the literature, it is investigated to what extent container sharing induces cost saving possibilities for trucking companies in seaport hinterlands. In the first basic scenario (distinct container problem (DCP)), empty containers are exclusively used by their owners for their actual transportation task. Therefore, empty containers will be sent to their originally predefined destinations. In this scenario the realization of street turns for the operating company is forbidden. In the second basic scenario (shared container problem (SCP)), empty containers are allowed to be interchanged among several owners and therefore can be assigned to transportation tasks which seem to be most appropriate for them. In the SCP, establishing street turns is allowed. Concrete saving possibilities for trucking companies regarding the fixed and variable costs are given by means of three different solution approaches. Based on several test instances, it is measured how container sharing affects a reduction in the number of operating vehicles and to what extent container sharing reduces the vehicles' total travel time.

The chapter is structured as follows: First, comprehensive descriptions for both scenarios are given. By comparing the distinct and the shared container problem, the advantages of container sharing are shown. Second, exact MIP formulations are defined for the basic scenarios. Especially the two solution approaches for the SCP are interesting from a theoretical point of view since two levels of transportation planning are considered: Empty container repositioning and vehicle routing and scheduling. On the one hand, these two levels are interlinked in a sequential way and on the other hand, a simultaneous MIP formulation considering both levels within one model is given. Finally, computational experiments are performed to investigate the efficiency and effectiveness of the sequential approach compared to the simultaneous approach. First results concerning the potential of container sharing are provided in the third section.

4.1 Definition of Basic Scenarios

The distinct and shared container problem are based on the one-depot container truck transportation problem with time windows (OD-CTTP). The OD-CTTP defines a comprehensive setting in the hinterland of a seaport with an inland depot, a terminal, and several customers who want to receive goods by inbound containers and several customers who want to ship goods by outbound containers. Thereby, full, as well as empty, containers have to be moved between the locations by a trucking company. The problem refers to the multi-depot container truck transportation problem with time windows (Zhang et al, 2009) which is abbreviated in the following with the acronym CTTP. The main difference between the CTTP and OD-CTTP lies in the consideration of multiple depots in the CTTP. Adopting all main characteristics of the OD-CTTP, the DCP and the SCP differ only in the repositioning of empty containers. By constraining the flexibility to allocate empty containers in the DCP and by permitting the exchange of empty containers between the underlying locations in the SCP, the advantages of container sharing for trucking companies can be illustrated very well. In the following, the OD-CTTP as the basic setting of the DCP and SCP is introduced. Afterwards, descriptions of the distinct and shared container problem are given. Finally, the advantages of the SCP compared to the DCP are illustrated by means of an example¹.

4.1.1 One-Depot Container Truck Transportation Problem with Time Windows (OD-CTTP)

In a local region, full and empty containers have to be moved between different locations by a trucking company. In detail, a hinterland of a terminal, a depot belonging to the operating trucking company, and a number of customers are considered. The considered terminal constitutes a seaport where the transportation mode of a container is changed. The depot is defined as a warehouse where an arbitrary number of vehicles can be parked. Moreover, the depot is defined as a repository for an arbitrarily large number of empty containers. A customer is considered a plant that receives or sends freight by containers (Zhang et al, 2009).

As can be seen in Figure 4.1, four transportation request types are distinguished: inbound full (IF), inbound empty (IE), outbound full (OF), and outbound empty

¹This section is based on Kopfer and Sterzik (2010).

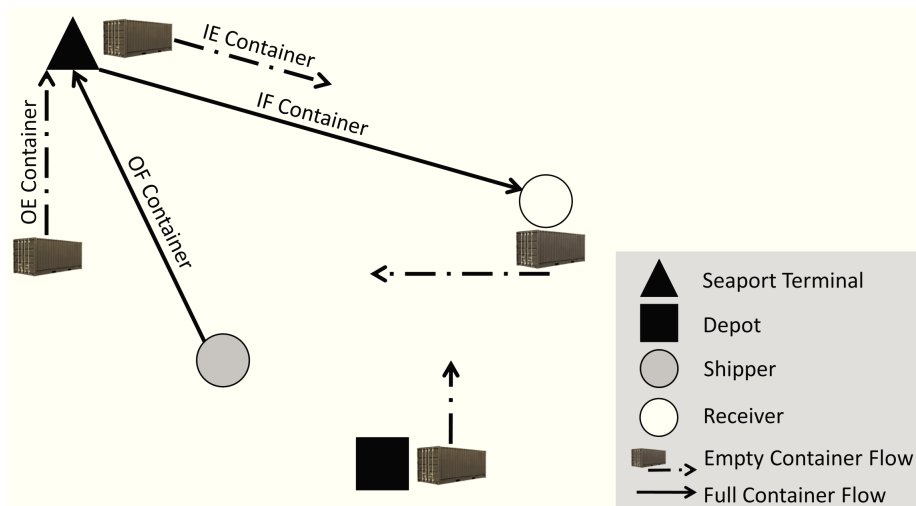


Figure 4.1: OD-CTTP

(OE). These requests can be separated into those requiring the transportation of *inbound* containers and those referring to *outbound* containers. Incoming containers located at a terminal that need to be moved to their destinations in the hinterland are called inbound containers. Conversely, containers located in the hinterland that need to be delivered to a terminal are called outbound containers. The defined container terms derive from the well-known research field of inbound and outbound logistics (see e.g. Lai and Cheng (2009)).

Two types of customers are considered. On the one hand, shippers offer freight which is to be transported to a foreign region via the terminal. The flow of a full container from a shipper to the terminal is defined as an OF request. As stated, this transportation request is defined as *outbound full* since a *full* container needs to be moved *from the hinterland to the terminal*. On the other hand, receivers require the transport of their goods from an outside region via the terminal. The *full* container which has to be transported *from the terminal to a receiver* is called an IF container. For both full transportation types, the pickup and delivery location are always given in advance. Obviously, these transportation tasks lead to an empty container positioning or repositioning problem. Firstly, before an OF task can be handled, a shipper requires an empty container to fill its freight into. The origin of this empty container must be determined during the solution process. Secondly, the receiver of an IF task obtains an empty container after the container is emptied. The determination of the container's destination also requires a decision for allocating empty containers.

Due to the imbalance between import- and export-dominated areas, one needs to take care of OE or IE containers which either have to be moved to a terminal

or derive from it. The origin of an OE container within the hinterland (i.e. which container to take for the OE process) and vice versa, the destination of an IE container is not given in advance and, thus, has to be determined during the solution process. Considering an import-dominated area, a surplus of empty containers is available in the hinterland related to this area. Therefore, these supplemental empty transportation resources must be moved to export-dominated regions as OE containers via the terminal. The possible origins of these containers are the locations at which empty containers accrue. Within the underlying setting these places are the depot and the receiver locations after an IF container is emptied. Additionally, in an export-dominated area, a lack of empty transportation resources arises and leads to necessary transportation of empty containers from different regions via the terminal to the hinterland. In other words, the trucking company needs to move empty containers from the terminal to locations at which empty containers are required. If there is no shipper node which needs an empty container, there is the possibility to store the containers temporarily at a depot. Due to the intransparency of local and global container flows in respectively between hinterland areas, it is possible that there are OE containers as well as IE containers at the same time and for the same hinterland area.

To complete the problem description, it should be noted that the operating trucking company considered in the OD-CTTP serves its requests using a homogeneous fleet of vehicles. Since the analysis is restricted to FEU, a vehicle can only move one container at a time. Each vehicle starts and ends its tour at the depot. While time windows at this node do not have to be considered, the time windows at the customer nodes and at the terminal vertices have to be kept. Containers are made available at customer locations for predefined time-intervals. During these time-intervals the containers can be loaded or unloaded by the customers. Since a truck need not to stay at the customer location during its container's predefined time interval, it can perform other transportation tasks before the container will be picked up. The flexibility of vehicle routing and scheduling is increased even further by the fact that it is not required that the delivery and the pickup of a certain container is performed by the same truck. The predefined time-interval for a container at a customer location is determined by two surrounding time windows at each customer location. During the first time window the full/empty container has to be delivered to the receiver/shipper location. After the container is unloaded/loaded, it can be picked up by a vehicle during the second time window. The assumption differs from the CTTP of Zhang et al (2009), who solely define one time window at a customer loca-

Table 4.1: Full Container Movements

	IF	OF
Origin	Terminal	Shipper
Destination	Receiver	Terminal

tion. In this case, an operating vehicle which moves a container to a customer location has to wait at the location until the container is dispatched. Changing this assumption by introducing a second time window allows vehicles to skip the container's time interval in between the customers' time windows. Skipping a container's service time in the hinterland is, for example, a typical proceeding for the port of Rotterdam. As Veenstra (2005) stated, the transportation tasks for a container's delivery and pickup are usually not done by the same vehicle since loading/unloading a container needs considerable time and "at locations where containers are delivered regularly, a truck driver could pick up empty containers delivered the day before."

By knowing all transportation tasks in advance, the OD-CTTP tends to achieve the overall business goal of minimizing the total costs of a company. Thereby, a dispatcher tries to minimize the total fulfillment costs for all customer orders. These fulfillment costs consist of fixed costs and variable costs. While fixed costs arise, for example, from the deployment of vehicles, variable costs may arise from the costs for fuel and for the driving personnel. Hence, the primary objective tends to achieve the minimization of the number of vehicles since the tied-up capital for the fleet is minimized. As a secondary objective, the total operating time, which can be seen as a main driver of transportation costs, is to be minimized (Daganzo, 2005). The goal to minimize the total fulfillment costs of a company is very common in the literature of vehicle routing (see e.g. Vahrenkamp (2007) and Toth and Vigo (2002)).

Based on the OD-CTTP, the DCP and the SCP are introduced. Both scenarios use the predefined pickup and delivery locations of the full container movements (see Table 4.1) and differ only in the repositioning of empty containers as stated in the following two sections.

4.1.2 Basic Scenarios

By including an inland-depot, a terminal, two types of customers, and time windows, the OD-CTTP is a comprehensive hinterland truck transportation problem

Table 4.2: *Predefined Empty Container Movements (DCP)*

	IE	OE	Empty Container	
			for a Shipper	from a Receiver
Origin	Terminal	Depot	Depot	Receiver
Destination	Depot	Terminal	Shipper	Depot

that is well-suited as an initial setting to measure the benefit of container sharing. The fact that only one trucking company is included in the OD-CTTP is well-considered. It is shown that the benefits for a particular trucking company of exchanging empty containers between cooperating trucking companies are due to the additional possibilities to allocate empty containers between the terminal and customer locations. By having the opportunity to integrate empty containers from additional locations into a company's tour, cost savings can be made accessible. Hence, the effects of container sharing for a particular trucking company can be measured by (not) restricting the possibilities to allocate empty containers between the terminal and the customer locations. In what follows, two scenarios which are based on this problem are presented. In the first scenario (DCP), container sharing is prohibited, i.e. containers must be used for their predefined transportation tasks. The options to allocate empty containers are, thereby, restricted. The second scenario (SCP) illustrates the idea of container sharing, i.e. containers can be arbitrarily interchanged between the underlying locations in order to achieve improved solutions and furthermore to exploit the potential of container sharing.

4.1.2.1 Distinct Container Problem (DCP)

The DCP illustrates the non-cooperative scenario where empty containers cannot be interchanged, perhaps, because they have different owners and have to be used for their specific purpose or perhaps, because they have to reach their specific destination. In the DCP, the usage of empty containers being available at some location is known in advance. As shown in Table 4.2, obtained or required empty containers always need to be moved to the depot or derive from it. For example, the empty container for an OF transportation request always has to be moved from the depot to the shipper. Permitting the receiver as a possible origin for an empty container movement is prohibited even if the receiver's second time window is consistent with the shipper's first time window. These problem characteristics illustrate the fact that the rate of empty container transport in the hinterland is

around 40% (Konings, 2005) and, thus, tours mainly comprise one full and one empty container move between the depot, the terminal, and the customers. That is why the origins and the destinations of all containers (empty containers, as well as full containers) are fixed by the given data of a problem instance in the DCP. Hence, the operating trucking company has precise specifications to reposition the containers. In this case, the optimization model related to the OD-CTTP comes to a pickup and delivery problem with time windows (PDPTW; see e.g. Parragh et al (2008)) with each container movement representing a full truckload request for the PDPTW. The only difference as compared to a usual PDPTW is that each customer has two time windows, one first time window for the delivery of a (full or empty) container in order to make the container available for the customer's loading or unloading operation, and another second time window for picking up the container after the container has completely been handled by the customer.

4.1.2.2 Shared Container Problem (SCP)

The SCP illustrates the cooperative scenario and explicitly permits the interchange of empty containers between the locations in the OD-CTTP. In this case, available empty containers can be used for any transportation task. Like in a container sharing cooperation, trucking companies have significantly more possibilities to allocate empty containers. For the SCP, the decision which empty container will be assigned to the usage of which freight transportation task constitutes an optimization problem of its own. There are three types of empty containers which are available for the assignment to upcoming transportation tasks. The first type of available empty containers originates from the company's depot. The second type consists of all inbound empty containers located at the terminal. Finally, the third type of available empty containers is constituted by all containers that have been emptied at a customer location and that are currently disposable for a new task. Available empty containers can be used for three types of tasks. They can either be used as an outbound empty container (to be delivered to the terminal) or as a container which will be used to fulfill a customer's request for an empty container in the local area (i.e. a street turn). Moreover, there is the opportunity for the trucking company to move the available empty containers to its depot. Every possible movement of an empty container is defined in Table 4.3. When empty containers can be interchanged, the origin of outbound empty containers and the destination of inbound empty containers are not defined by the problem data. The determination of these locations (i.e.

Table 4.3: *Repositioning Problem of Empty Containers in the SCP*

	Empty Container			
	IE	OE	for a Shipper	from a Receiver
Origin	Terminal	Receiver or Depot	Receiver, Terminal or Depot	Receiver
Destination	Shipper or Depot	Terminal	Shipper	Shipper, Terminal or Depot

a part of the input data of a PDPTW) is part of an optimization process itself. That is why the SCP cannot be modeled and solved as a usual PDPTW.

4.1.3 Advantages of Container Sharing According to the Proposed Concepts

By giving a short example of the distinct and shared container problem, the benefits of container sharing can be seen very well. The initial situation for both scenarios is as follows: a trucking company has to serve an IF and an OF transportation request. While customer 1 describes the shipper for the OF request, customer 2 illustrates the receiver for the IF request. The time window for the availability of a container at customer location i is given by $[b_i, e_i]$. Additionally, there is a terminal delivery time window for the outbound container and a terminal pickup time window for the inbound container. The shipper needs to pack the container provided to it during time window $[b_1, e_1]$. The container of the shipper has to reach the terminal respecting the terminal delivery time window for this container and will then leave the local area via the terminal. The time window for unloading the IF container at the receiver is defined by $[b_2, e_2]$.

The flow of goods induces a flow of containers. Figure 4.2 (a) shows the flow of containers for the case that containers used for the shipper and receiver cannot be interchanged (i.e. the situation of the DCP). Container C_1 respectively C_2 will be used for the realization of the flow of goods $C_1(F)$ respectively $C_2(F)$. The flow of empty container C_1 is denoted by $C_1(E)$ and afterwards when this container is loaded at customer site 1, its flow as a full container is denoted by $C_1(F)$. The flow of full container C_2 from the terminal to the receiver is shown as arc $C_2(F)$ and after this container is unloaded by the customer its flow continues as an empty container to the depot on the arc denoted as $C_2(E)$. As mentioned above, there is an availability time window for containers at each customer's site. It is assumed that the customer delivery time window for a container to be delivered

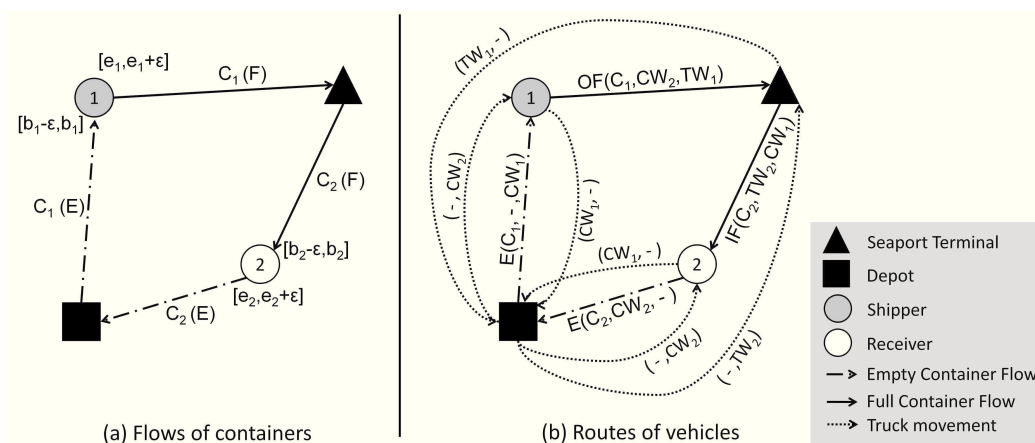


Figure 4.2: *Distinct Container Problem*

to a customer will be $[b_i - \epsilon, b_i]$ and the customer pickup time window will be $[e_i, e_i + \epsilon]$, respectively, with ϵ denoting the amount of time that a container may arrive earlier at a customer's site than necessary, or the amount of time that the container is allowed to remain at a customer's site after the availability time window is over.

The flow of containers requires corresponding truck operations. Figure 4.2 (b) shows the transportation processes needed to implement the intended container flows. The solid lines are marked by a denotation, for instance $OF(C_1, CW_2, TW_1)$. This denotation is used to describe the type of container, the identity of the container, and the relevant time windows. The first two characters denote the type of the container transported on that line: OF for outbound full, IF for inbound full, and E for an empty container. The first parameter within brackets identifies the container to be transported, e.g. C_1 for Container 1. The second parameter identifies the time window to be met when picking up the container. The values of that parameter might be CW_1 , respectively CW_2 , for the first, respectively the second, time window of the customer location where the container has to be picked up. Alternatively, the value of the second parameter might be TW_j for the time window which is relevant for container j at the terminal. Finally, the value of the second parameter might be “-” indicating that no time window is relevant for the pickup operation. The third parameter identifies the time window to be met for the delivery of the container at its destination. The possible values of the third parameter are the same as the ones for the second parameter. The dotted lines used for the illustration of empty container movements are marked by a denotation which describes the time windows for the locations at the origin and destination of that movement, for instance $(-, CW_2)$ for a truck movement from the

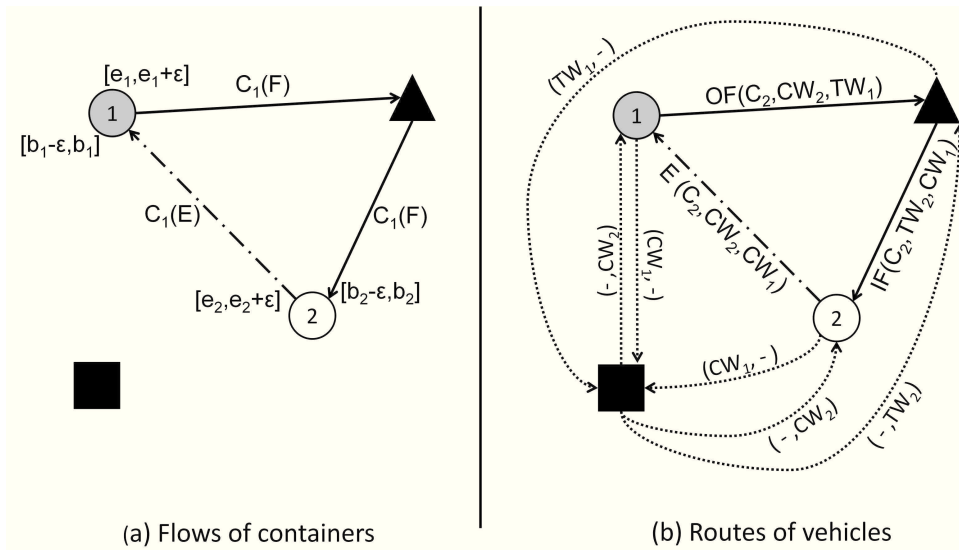


Figure 4.3: Shared Container Problem

depot to a customer who has to be reached at his second time window. The first parameter identifies the time window at the starting point of that empty truck movement and the second parameter identifies the time window at the endpoint of that movement. The values for the time windows of empty movements can be the same as for the time windows for container movements on the solid lines. Figure 4.2 (b) demonstrates the case that the time windows and the limitation of available trucks do not allow any bundling or concatenation of transport processes to common tours. For this case, Figure 4.2 (b) shows all transportation processes which are necessary in the local area to fulfill the container flows shown in Figure 4.2 (a). There are ten transportation processes needed for the transportation of the two containers. For each move of a container to or from the depot, there will be needed a pendulum tour (i.e. four truck movements for two containers). For each move of a container between a customer location and the terminal, there will be a tour with three transportation legs (i.e. six truck movements for two containers).

The optimization model for the DCP will minimize the transportation effort (in driving distances or operating times of the available trucks) for a given set of container movements. The two approaches for the SCP try to additionally minimize the container flows. Provided that the time windows $[e_i, e_i + \epsilon]$ and $[b_i - \epsilon, b_i]$ allow that the same container can be used for both customers, the container flows illustrated in Figure 4.2 (a) can be reduced to the container flows presented in Figure 4.3 (a). As a consequence, the set of needed transportation processes shown in Figure 4.3 (b) will also be reduced. The reduction of the

total covered travel time distances is obviously caused by the flexibility to move empty containers between the node sets. Since an empty container in the SCP can be moved directly from a receiver to a shipper, the urgent empty container movements within the DCP from or to a depot become avoidable. Hence, if the travel time from the depot 0 to customer 1 (i.e. the shipper) is defined as t_{01} and the travel time from the depot to customer 2 (i.e. the receiver) as t_{02} the reduction of the containers' and vehicles' travel times in the SCP compared to the DCP t_r results in the following formula:

$$t_r = t_{20} + t_{01} - t_{21} \quad (4.1)$$

Thus, given that the receivers' second time windows are consistent with the shippers' first time windows, it can be concluded that the SCP generates more benefits according to the total travel time if:

- the distance from the depot to the receivers or shippers gets bigger
- the receiver and shipper nodes are located close to each other.

4.2 Synchronization of Transportation Levels

The DCP is characterized by fixed origins and destinations of the full and empty container movements. Thus, the operating trucking company always knows in advance where to deliver an empty container and the location at which a container is supplied for a full transportation task. In this case, the optimization model related to the DCP comes up to a PDPTW. The PDPTW is a generalization of the famous vehicle routing problem with time windows (VRPTW; see e.g. Cordeau et al (2002a)). It addresses the construction of optimal routes to satisfy transportation requests, where each request requires a pickup at the origin and delivery at the destination under the consideration of time windows and precedence constraints. Certainly, each route satisfies pairing constraints since a transportation request must be served by the same vehicle (Dumas et al, 1991). The exact MIP model for the DCP is formulated in Chapter 4.3.2.

Modeling the scenario of the SCP is substantially more difficult compared to a solution approach for the DCP. While the full transportation tasks are also fixed in advance, the decision of which empty container will be assigned to the usage of which freight transportation task constitutes an optimization problem of its own. As shown in Table 4.3, the locations to which empty containers can be moved or

the vertices that can supply empty containers are various. For instance, an empty container for an OF transportation request can either derive from the depot, a receiver, or the terminal. Therefore, besides the consideration of the vehicles' routes, the models also need to include the allocation of empty containers to fix the container movements. A convenient side effect of the consideration of these two transportation levels is the possibility to show explicitly the effects of container sharing by illustrating the containers' flows. In the following, a literature review considering the application of container allocation and vehicle routing and scheduling within one solution approach is given. Subsequently, a sequential as well as a simultaneous solution approach for the SCP are proposed².

4.2.1 Literature Review

In the last decades, empty container repositioning and vehicle routing and scheduling has mainly been traded independently. Dejax and Crainic (1987) stress that authors either focus on "loaded vehicle freight transportation" or on empty flow management³. Since planning of empty flows is often inherently connected with the determination of loaded trips, Dejax and Crainic (1987) emphasize that the independent consideration of empty container repositioning and vehicle routing neglects possible positive emergences. The integration of both transportation levels allows a better representation of the transportation and logistics system since possible impacts of containers' flows and vehicles' routes on each other can be observed as a whole. However, Crainic et al (1993b) propose that a single mixed-integer model comprising the allocation of containers and vehicle routing would be computationally intractable. Therefore, the problem is often simplified by using a sequential approach for solving the operational planning of loaded and empty container movements (see e.g. Crainic et al (1993b) and Braekers et al (2011b)). Thereby, the problem is subdivided into a container allocation problem and a vehicle routing problem. Based on the demand and supply of a considered region, the containers are allocated between the locations on the first step. Subsequently, a vehicle routing model is used to guarantee the movement of the full and empty containers on the second step.

Due to the continuous improvement of Operations Research techniques and computer capabilities, the statement of Crainic et al (1993b) that solving an integrated model considering container allocation and vehicle routing at the same

²This section is based on Kopfer et al (2011).

³Literature reviews for both research fields can be found in Section 6.1.1 and Section 2.5.2.

time is not possible, has been disproved. Deidda et al (2008) define an optimization model which considers the allocation of empty containers between customers and the routing of vehicles in a post-optimization phase. The results indicate that this solution approach delivers promising results for shipping companies in dealing with street turns. However, the authors do not consider loaded container transport. Huth and Mattfeld (2009) propose an integrated approach for the Swap Container Problem. Their approach considers the allocation of empty containers (swap bodies) between hubs in accordance to the known demand in forthcoming periods and the routing of loaded swap bodies. A sequential and integrated decision-making solution approach for the allocation and the routing of the swap bodies in a hub-and-spoke network are proposed. While the allocation problem is represented as a multi-stage transportation problem, the routing problem is modeled as a generalized PDP. The approach of Braekers et al (2009) is based on a similar scenario by Huth and Mattfeld (2009). Instead of allocating and routing between hubs, the authors consider a hinterland region that includes depots, terminals, as well as shippers and receivers. Beside the two main differences (consideration of several depots and only one time window at each customer location), the problem is similar to the SCP. The authors define an integrated mathematical formulation and show that even for relatively small instances, the integration of both problem types results in smaller fleet sizes and lower transportation costs compared to sequential planning. Braekers et al (2011b) extend this work by formulating the problem as an asymmetric multiple traveling salesman problem with time windows (am-TSPTW). A single- and a two-phase deterministic annealing algorithm are presented and prove that the integrated approach outperforms the sequential one. Recently, a general comprehensive survey on routing problems with multiple synchronization constraints was given by Drexel (2012). It is stated that the synchronization of vehicles and load aspects constitute an emerging field in vehicle routing problem (VRP) research with considerably rising importance.

4.2.2 Solution Approaches for the SCP

Solving the SCP leads to two different solution approaches. While the first approach is based on a sequential process for solving the two sub-problems, the second approach pursues a simultaneous procedure for the solution of the SCP. By considering the containers as scarce transportation resources which have to be routed and scheduled in order to fulfill the given freight requests, it is possible to determine within the mathematical models:

- at which location empty containers should be picked up for OF and OE transportation requests,
- where IE containers and empty containers obtained at receiver locations should be delivered, and
- in which order, and by which truck, the loads should be carried out.

The first approach consists in the following two steps: In the first step, an optimal decision on the assignment of available empty containers to upcoming transportation tasks is aspired, i.e. it is tried to install optimal flows of empty containers in order to cope with the global objective. Certainly, the determination of the containers' flows fixes an origin and a destination for each empty container which has to be transported. Hence, at the end of the first step, the same type of problem as in the situation for the DCP has to be solved. As a consequence, the second step of the sequential approach for the SCP can also be represented as a PDPTW.

The two steps of the sequential solution approach (which is, therefore, also defined as 2-Step Method in the following) for the SCP can be seen very well in Figure 4.4. Two full transportation requests and one empty container request are given (see Figure 4.4 (a)). Firstly, the containers have to be allocated among the given locations so that the origins of the empty containers for the OE and OF transportation requests are determined. A possible solution to reposition the containers can be seen in Figure 4.4 (b). Based on this solution, the vehicles can then be routed by means of the PDPTW. The dotted and dashed lines in Figure 4.4 (c) illustrate two possible routes which are required to move the containers. Since the containers' allocation is completely disconnected from the global objective (i.e. minimizing the costs of operating vehicles) and, moreover, since every container has to be moved by a vehicle, attention should be paid to the first step of the sequential approach. Since different containers' flows cause different routes of vehicles in the second step, the objective for the empty container repositioning problem in the first step should be determined very well. The impact of different objectives on the vehicles' total costs can be clearly seen in Section 4.3.3.1.

Following the second approach, the two sub-problems of the sequential approach are solved in one single step, i.e. solving the assignment problem of empty containers simultaneously with the vehicle routing and scheduling problem induced by the originally given problem data and the compulsory assignment decisions. A big challenge in defining a problem simultaneously lays in interlinking the two considered transportation levels. In the underlying problem, it has to be assured

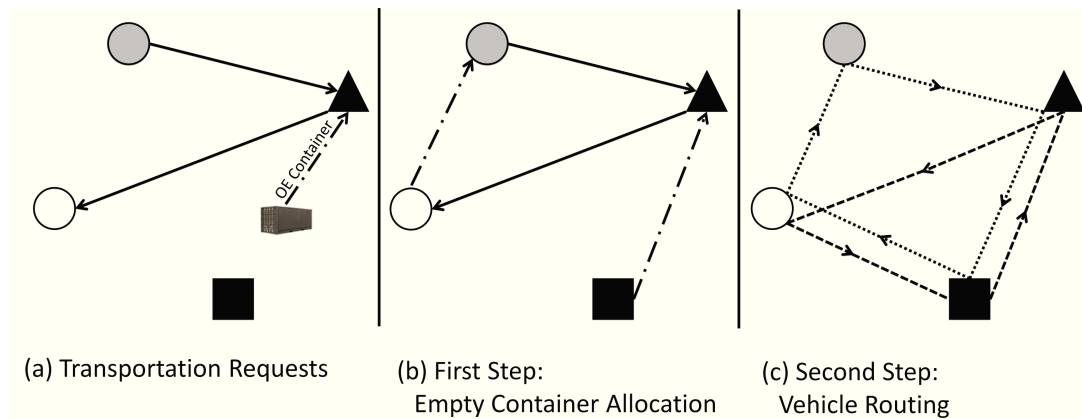


Figure 4.4: 2-Step Method for the SCP

that a container is always transported by a vehicle. The interlinking of these two levels, as well as a detailed description of the integrated solution approach (which is also defined as simultaneous solution approach in the following), is defined in Section 4.3.3.2.

The presented approaches for the distinct, as well as the shared, container problem tend to achieve the overall objective to minimize the fulfillment costs for all customer orders. Hence, in a first step, the number of used vehicles should be minimized, while in the second step, the optimization of the operating time symbolizing the transportation costs should be pursued. In the proposed models presented in the following sections, the first objective is formulated as a constraint and the minimization of the vehicles' total operating time is chosen as the objective function of the proposed models. In order to meet the first objective, the number of used vehicles within the employed models is raised iteratively until a feasible solution is found (Toth and Vigo, 2002).

4.3 Exact Mixed-Integer Programming (MIP) Formulation

In this section, formal representations of the basic scenarios are given. Firstly, the variables, parameters, and sets required for the MIP formulations are described. Afterwards, the distinct and shared container problem are defined. The SCP is presented by means of a 2-step method and an integrated routing approach.

4.3.1 Notation

The proposed models are based on the directed graph $G = \{V, A\}$ whereas V describes the node sets and $A = \{(i, j) \mid i, j \in V\}$ denotes the arc set. V consists of customer node set V_C , terminal node set V_T , as well as the start and end vertices $\{0\}$ and $\{v + 1\}$. V_C is defined by the shipper $V_S = V_{S^i} \cup V_{S^o}$ and receiver nodes $V_R = V_{R^i} \cup V_{R^o}$. V_{S^i} and V_{R^i} refer to the first time window of the shipper/receiver, in which an empty/full container has to be made available. After the container $c \in C$ has been completely filled or emptied, respectively, it can be picked up by a vehicle $k \in K$ during the second time window (V_{S^o} and V_{R^o}). Modeling two customer time windows requires doubling the customer nodes. Since n determines the total number of customers, e.g. node 1 and $(n + 1)$ define the first and second time window of shipper 1. Consequently, the nodes provide the same coordinates but different time window values. The terminal node set V_T refers to the transportation types, i.e. $V_T = V_{TIE} \cup V_{TIF} \cup V_{TOE} \cup V_{TOF}$. The number of all customer and terminal nodes is defined by v . Since for each IF and OF transportation request, the pickup and delivery node are explicitly given by the input data, every customer has its corresponding terminal node. In case of an OF transportation request, this means that, after a shipper $i \in V_{S^o}$ has been served by a vehicle, the full container has to be moved to terminal node $(i + n) \in V_{TOF}$. In case of an IF transportation request, a full container has to be moved from terminal node $i \in V_{TIF}$ to its corresponding receiver location $(i - 2n) \in V_{R^i}$. Since a vehicle starts and ends its tour at the depot, the depot vertex is subdivided into nodes 0 and $(v + 1)$. Furthermore, a large number of e_a empty containers can be stacked in the depots. To illustrate the different types of node sets, Figure 4.5 shows their interrelations within the distinct and the shared container problem. The additional possibilities of the SCP to allocate the containers between the node sets are illustrated through the dashed arrows.

During a route, node $i \in V_C \cup V_T$ has to be reached during its time window, determined by the interval $[b_i/e_i]$. Thus, a vehicle has to arrive at location i before time b_i . However, arrival before b_i is allowed and leads to waiting time for the vehicle. For each two distinct stop locations, t_{ij} represents the travel time from location i to location j . At node $i \in V_C \cup V_T$ a service time s_i for the picking up/dropping off operation of a container is considered. While the binary decision variables y_{ijc} and x_{ijk} define whether container c /vehicle k traverses the arc from location i to j , L_{ic} and T_{ik} specify the arrival time of a container/vehicle at a location.

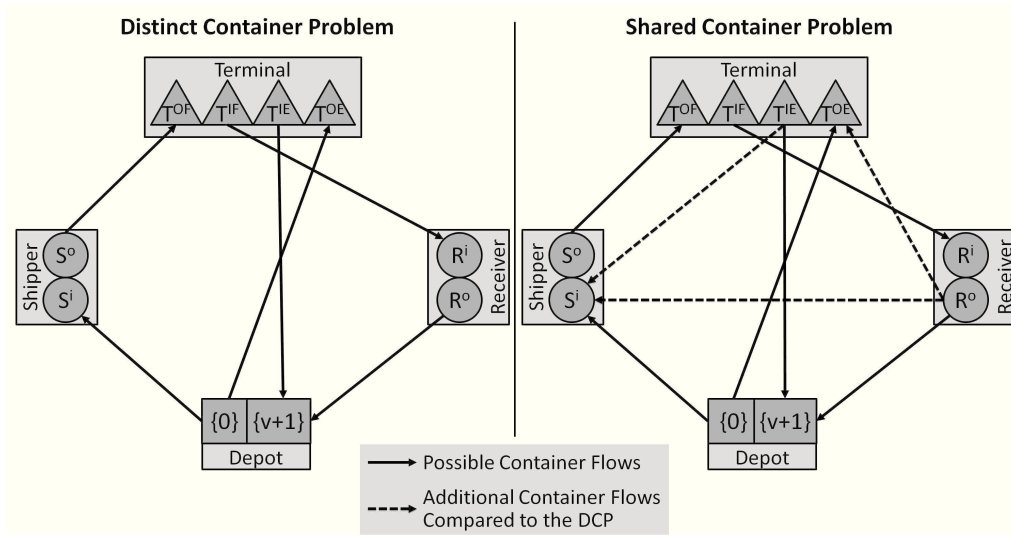


Figure 4.5: Possible Container Flows Between the Node Sets

To sum it up, for the model formulation the following sets are required:

$V = \{0\} \cup V_C \cup V_T \cup \{v+1\}$: Set of locations

$V_C = V_S \cup V_R$: Set of customer nodes

- $V_S = V_{S^i} \cup V_{S^o}$: Set of shippers
 - $V_{S^i} = \{1, \dots, s\}$: First time window
 - $V_{S^o} = \{n+1, \dots, 2s\}$: Second time window
- $V_R = V_{R^i} \cup V_{R^o}$: Set of receivers
 - $V_{R^i} = \{s+1, \dots, n\}$: First time window
 - $V_{R^o} = \{2s+1, \dots, 2n\}$: Second time window

$V_T = V_{TOF} \cup V_{TIF} \cup V_{TIE} \cup V_{TOE}$: Set of terminal nodes (corresponding to the number of customers and IE/OE containers)

- $V_{TOF} = \{2n+1, \dots, 2n+s\}$: OF terminal nodes
- $V_{TIF} = \{2n+s+1, \dots, 3n\}$: IF terminal nodes
- $V_{TIE} = \{3n+1, \dots, 3n+e_i\}$: IE terminal nodes
- $V_{TOE} = \{3n+e_i+1, \dots, v\}$: OE terminal nodes

$K = \{1, \dots, m\}$: Set of vehicles

$C = \{1, \dots, r+e_i+e_a\}$: Set of containers (corresponding to the number of IF/IE transportation requests and additional empty containers)

The following parameters have to be defined:

0 : Start node of a tour (Depot)

$(v + 1)$: End node of a tour (Depot)

$n = s + r$: Number of customers

- s : Number of shippers
- r : Number of receivers

e_i : Number of IE containers

e_o : Number of OE containers

e_a : Number of additional empty containers originating from the depot

$v = 3n + e_i + e_o$: Number of all customers and terminal nodes

m : Number of vehicles available at the depot

t_{ij} : Travel time from node i to j , where $i \neq j$

s_i : Service time required to pick up/drop off a container at node i

$[b_i/e_i]$: Time window of node i

M : Sufficiently big constant, e.g. $M = \sum_{i \in V} \sum_{j \in V} t_{ij}$

The following decision variables are used:

$$x_{ijk} = \begin{cases} 1 & \text{if vehicle } k \text{ drives from node } i \text{ to } j \\ 0 & \text{else} \end{cases}$$

$$y_{ijc} = \begin{cases} 1 & \text{if container } c \text{ is carried from node } i \text{ to } j \\ 0 & \text{else} \end{cases}$$

T_{ik} : Arrival time of vehicle k at node i

L_{ic} : Arrival time of container c at node i

4.3.2 DCP

The DCP has been published in Kopfer and Sterzik (2010) and consists of the equation (4.2) and the restrictions (4.3) to (4.14). As stated, the objective deals with the minimization of a company's total fulfillment costs. Within the proposed model, the minimization of fixed costs is achieved by raising the number of

operating vehicles m until a feasible solution is found. Subsequently, the model seeks to minimize the total operating time of the vehicles defined by the objective function (4.2).

$$\min z1 = \sum_{k \in K} (T_{(v+1)k} - T_{0k}) \quad (4.2)$$

The restrictions for the DCP can be separated into those which are well known for a standard VRP (see e.g. Bruce et al (2008)) and into those which have to be defined specifically for the DCP.

$$\sum_{i \in V} \sum_{k \in K} x_{ijk} = 1 \quad \forall j \in V_C \cup V_T \quad (4.3)$$

$$\sum_{j \in V} x_{0jk} = 1 \quad \forall k \in K \quad (4.4)$$

$$\sum_{i \in V} x_{i(v+1)k} = 1 \quad \forall k \in K \quad (4.5)$$

$$\sum_{j \in V} x_{jik} - \sum_{j \in V} x_{ijk} = 0 \quad \forall i \in V_C \cup V_T, k \in K \quad (4.6)$$

$$T_{jk} \geq T_{ik} + t_{ij} - M(1 - x_{ijk}) \quad \forall i, j \in V, k \in K \quad (4.7)$$

$$b_i \leq T_{ik} \leq e_i \quad \forall i, j \in V, k \in K \quad (4.8)$$

Restriction (4.3) requires that each customer and terminal node is visited exactly once. Each vehicle leaving a depot also has to return to this location if the route is finished, proposed by (4.4) and (4.5). The continuity of a route, meaning that a node has to be left if it is approached by a vehicle, is ensured by (4.6). While time continuity during a tour is defined by (4.7), (4.8) states that a truck reaches a location in its defined time window.

$$\sum_{k \in K} x_{i(i+n)k} = 1 \quad \forall i \in V_{S^o} \quad (4.9)$$

$$\sum_{k \in K} x_{i(i-2n)k} = 1 \quad \forall i \in V_{TIF} \quad (4.10)$$

$$\sum_{k \in K} x_{0jk} = 1 \quad \forall j \in V_{S^i} \cup V_T^{OE} \quad (4.11)$$

$$\sum_{k \in K} x_{i(v+1)k} = 1 \quad \forall i \in V_{R^o} \cup V_{TIE} \quad (4.12)$$

$$x_{ijk} \in 0, 1 \quad \forall i, j \in V, k \in K \quad (4.13)$$

$$T_{ik} : \text{real variables} \quad \forall i \in V, k \in K \quad (4.14)$$

Equations (4.9) to (4.12) define the full and empty container movements of the DCP. In detail, (4.9) ensures that a vehicle picking up an OF container from a shipper during the second time window drives to the terminal. Furthermore, a vehicle that serves an IF transportation request has to drive from the terminal to the corresponding receiver ((4.9)). Constraint (4.11) guarantees that a shipper and an OE transportation request is supplied by an empty container from the depot. Empty containers originating from a receiver or the terminal must be moved to the depot ((4.12)).

4.3.3 SCP

In this section, two different solution approaches for the SCP are formulated. Both are interesting from a theoretical point of view since two levels of transportation planning are considered so that active and passive transportation entities have to be synchronized. Containers constitute the set of passive entities which have to be routed within a local area in order to enable the containerized transport of cargo. The active transportation entities are represented by vehicles which are needed to move the containers. The active and the passive entities must be synchronized with each other since for each container movement there will arise a transportation task which must be performed by a vehicle carrying the container on one of the legs during its route. For the coordination of both entities, a sequential as well as a simultaneous solution approach for the SCP are described and defined in the following by means of MIP formulations.

4.3.3.1 2-Step Method

A 2-step method describes a solution approach that finds a solution by separating the problem into two subproblems. The solution of the first subproblem is thereby used as input for the second subproblem. Since these subproblems describe to a certain extent independent problems, one has to assure that the overall global objective is not lost from sight. Differently to the integrated routing approach that is described in Section 4.3.3.2, the sequential approach cannot guarantee to find the global optimum. At the expense of solution quality, sequential approaches are known to reduce the problem complexity. Hence, a big advantage of a 2-step

approach is the requirement of much less computation time in general. Bigger instances can be solved, whereas the solution quality of small instances decreases compared to the exact integrated approach.

Since the containers' allocation is completely disconnected from the global objective (i.e. minimizing the costs of operating vehicles) and, moreover, since every container has to be moved by a vehicle, it must be avoided that the containers' allocation generates results which require a gratuitous amount of operating vehicles. Therefore, it is important to detect an adequate objective for the first step. Two different objective functions are implemented and analyzed in terms of their impact on the solution space of the second step. The solution of the first step is then used as input for a modified version of the DCP. Thus, the determined container movements are used to find the best routes for the operating vehicles. Within the second step, the global objective is adopted for the modified DCP.

The optimization model for the containers' flows is based on Figure 4.5, which illustrates the possible movements of a full and empty container, respectively. The following 2-step method has been introduced by Sterzik and Kopfer (2012a)⁴.

$$\min z2 = \sum_{i \in V_{TIF} \cup V_{TIE} \cup \{0\}} \sum_{j \in V_{TOF} \cup V_{TOE} \cup \{v+1\}} \sum_{c \in C} (L_{jc} - L_{ic}) \quad (4.15)$$

$$\sum_{j \in V} \sum_{c \in C} y_{ijc} = 1 \quad \forall i \in V_C \cup V_{TIF} \cup V_{TIE} \quad (4.16)$$

$$\sum_{i \in V} \sum_{c \in C} y_{ijc} = 1 \quad \forall j \in V_{TOF} \cup V_{TOE} \quad (4.17)$$

$$\sum_{c \in C} y_{i(i-2n)c} = 1 \quad \forall i \in V_{TIF} \quad (4.18)$$

$$\sum_{j \in V_{Si} \cup \{v+1\}} \sum_{c \in C} y_{ijc} = 1 \quad \forall i \in V_{TIE} \quad (4.19)$$

$$\sum_{j \in V} \sum_{c \in C} y_{0jc} = e_a \quad (4.20)$$

$$\sum_{i \in V} \sum_{j \in V_{TIF} \cup V_{TIE} \cup \{0\}} \sum_{c \in C} y_{ijc} = 0 \quad (4.21)$$

$$\sum_{i \in V_{TOF} \cup V_{TOE} \cup \{v+1\}} \sum_{j \in V} \sum_{c \in C} y_{ijc} = 0 \quad (4.22)$$

⁴An extended abstract of this article can be found in Sterzik and Kopfer (2012d).

$$\sum_{i \in V} \sum_{j \in V_{TOF} \cup V_{TOE} \cup \{v+1\}} y_{ijc} = 1 \quad \forall c \in C \quad (4.23)$$

$$\sum_{i \in R^o \cup \{0\}} \sum_{c \in C} y_{ijc} = 1 \quad \forall j \in V_{TOE} \quad (4.24)$$

$$\sum_{c \in C} y_{i(n+i)c} = 1 \quad \forall i \in V_S \cup V_{R^i} \quad (4.25)$$

$$\sum_{j \in V} y_{jic} - \sum_{j \in V} y_{ijc} = 0 \quad \forall i \in V_C, c \in C \quad (4.26)$$

$$L_{jc} \geq L_{ic} + t_{ij} + s_i - M(1 - y_{ijc}) \quad \forall i, j \in V, c \in C \quad (4.27)$$

$$\sum_{j \in V} y_{ijc} * b_i \leq L_{ic} \leq \sum_{j \in V} y_{ijc} * e_i \quad \forall i \in V_C \cup V_{TOF} \cup V_{TOE} \cup \{v+1\}, c \in C \quad (4.28)$$

$$\sum_{j \in V} y_{ijc} * b_i \leq L_{ic} \leq \sum_{j \in V} y_{ijc} * e_i \quad \forall i \in V_{TIF} \cup V_{TIE} \cup \{v+1\}, c \in C \quad (4.29)$$

$$y_{ijc} \in \{0, 1\} \quad \forall i, j \in V, c \in C \quad (4.30)$$

$$L_{ic} : \text{real variables} \quad \forall i \in V, c \in C \quad (4.31)$$

As stated, the objective function of the first step has a big impact on the solution space of the second step. Therefore, two alternative objectives are implemented successively. Objective function z2 seeks to minimize the containers' total operating time. Conversely, objective function z3 solely seeks to minimize the travel time excluding the waiting and service times at the customer and terminal nodes:

$$\min z3 = \sum_{i,j \in V} \sum_{c \in C} y_{ijc} * t_{ij} \quad (4.32)$$

It is assumed that both objectives provide a promising basis for the vehicles' routes since z2 and z3 represent two variants for the minimization of the containers' flows. Due to the interdependency of the transportation resource and the means of transport, the minimization of the containers' flows will, therefore, consequently cause a minimization of the vehicles' total operating time.

Restrictions (4.16) and (4.17) ensure that every customer and terminal node is visited once by a container. The conditions for the start and end vertices of the different kinds of containers are considered by restrictions (4.18) to (4.24). Thereby, IF containers need to be moved from the terminal to the receivers. While IE containers begin their path at the terminal and are transported to a shipper or the depot, restriction (4.20) states that additional empty containers originate from the depot. These three types of containers are not allowed to start their path

from a different node stated by (4.21) and (4.22). Constraints (4.23) and (4.24) assure that a container ends its tour either at the depot or at the terminal nodes corresponding to OF and OE transportation requests. As stated by restriction (4.25), a container which is moved to a shipper/receiver node has to pass both time windows since in between these times the container's loading/unloading process is performed by the customer's service personnel. Moreover, the pickup and delivery locations of the OF transportation requests are defined by (4.25). The route and time continuity is stated by (4.26) and (4.27). Finally, restrictions (4.28) and (4.29) assure that a container reaches a location in its defined time window. Hereby, it has to be ensured that objective z_2 represents the exact containers' total operating time. Therefore, L_{ic} takes the value 0 if container c is not carried to node i .

The second step illustrating the vehicles' routes can be formulated through equation (4.33) and the restrictions (4.34) to (4.42)

$$\min z_1 = \sum_{k \in K} (T_{(v+1)k} - T_{0k}) \quad (4.33)$$

$$\sum_{j \in V} \sum_{k \in K} x_{ijk} = 1 \quad \forall i \in V_C \cup V_T \quad (4.34)$$

$$\sum_{j \in V} x_{0jk} = 1 \quad \forall k \in K \quad (4.35)$$

$$\sum_{i \in V} x_{i(v+1)k} = 1 \quad \forall k \in K \quad (4.36)$$

$$\sum_{k \in K} x_{P_i D_i k} = 1 \quad \forall i \in V_C \cup V_T \quad (4.37)$$

$$\sum_{j \in V} x_{jik} - \sum_{j \in V} x_{ijk} = 0 \quad \forall i \in V_C \cup V_T, k \in K \quad (4.38)$$

$$T_{jk} \geq T_{ik} + t_{ij} + s_i - M(1 - x_{ijk}) \quad \forall i, j \in V, k \in K \quad (4.39)$$

$$b_i \leq T_{ik} \leq e_i \quad \forall i \in V_C \cup V_T, k \in K \quad (4.40)$$

$$x_{ijk} \in \{0, 1\} \quad \forall i, j \in V, k \in K \quad (4.41)$$

$$T_{ik} : \text{real variables } \forall i \in V, k \in K \quad (4.42)$$

The objective function z_1 seeks to minimize the total operating time of the used vehicles. The most important restriction of the second step is given by equation (4.37) since it ensures that the determined origins and destinations of the

empty container flows of the first step are used as the input data for the vehicles' routes. Thereby, P_i defines the pickup locations and D_i the corresponding delivery locations of each customer or terminal node. The remaining model formulation is mainly adopted from the DCP. Restriction (4.34) ensures that every node is visited exactly once. A vehicle has to start and end its tour at the depot stated by (4.35) and (4.36). Constraints (4.38) and (4.39) assure the time and route continuity during a vehicle's route. Finally, a node's time window has to be held by an operating vehicle stated by (4.40).

4.3.3.2 Integrated Routing MIP Formulation

The simultaneous method solves the two sub-problems of the sequential approach in one single step. Thus, the assignment problem of empty containers is solved simultaneously with the vehicle routing and scheduling problem. A big challenge is thereby to guarantee that the vehicles and the containers are interlinked with each other so that each container movement is enabled by a vehicle. Based on the originally given problem data, all possible solutions are discovered and compared due to the global objective to minimize the vehicles' costs. Therefore, the integrated routing approach guarantees the determination of the global optimum. However, since a bigger solution space has to be handled, relatively small test instances can be solved to optimum by the approach as compared to the sequential approach.

The following integrated routing model formulation is based on Kopfer and Sterzik (2011).

$$\min z1 = \sum_{k \in K} (T_{(v+1)k} - T_{0k}) \quad (4.43)$$

$$(4.16)-(4.29)$$

$$(4.34)-(4.36) \text{ and } (4.38)-(4.39)$$

$$\sum_{k \in K} x_{ijk} \geq y_{ijc} \quad \forall i \in V_{S^o} \cup V_{R^o} \cup V_T, j \in V, c \in C \quad (4.44)$$

$$\sum_{k \in K} x_{ijk} \geq y_{ijc} \quad \forall i \in V_C \cup V_T, j \in V_{S^i} \cup V_{R^i} \cup V_T \cup \{v+1\}, c \in C \quad (4.45)$$

$$T_{ik} = L_{ic} \quad \forall i \in V_C \cup V_T, k \in K, c \in C \quad (4.46)$$

$$x_{ijk} \in \{0, 1\} \quad \forall i, j \in V, k \in K \quad (4.47)$$

$$T_{ik} : \text{real variables } \forall i \in V, k \in K \quad (4.48)$$

By considering the allocation of containers on the one hand ((4.16)-(4.29)) and vehicle routing and scheduling ((4.34)-(4.36) and (4.38)-(4.39)) on the other hand, the presented model pursues the minimization of the vehicles' total travel time ((4.43)). The minimization of fixed costs is achieved by raising the number of operating vehicles until a feasible solution is found. The main component of the integrated model is given through equations (4.44)-(4.46) which assure the interlinking of the transportation resource and the means of transport.

The description of the equations for the containers' flows and the routes of the vehicles can be found in Section 4.3.3.1. Considering the interlinking component of the model, one has to ensure that a container is always moved by a vehicle, i.e. that the vehicles cover the containers' flows. Through equations (4.44) and (4.45) the vehicles are interlinked with each other. Thereby, the flows of the containers are covered but the vehicles have the possibility to interrupt these flows and use different "untraveled" arcs. This is reasonable, in particular, to ensure that a vehicle can skip a container's loading/unloading service time. Obviously, if a vehicle moves a container, both have to leave a node at the same time provided by (4.46).

4.4 Computational Experiments

This section provides computational results concerning the performance of the 2-step method and the integrated routing approach, as well as first results of the potential of container sharing. The experiments are based on data sets that illustrate various hinterland regions. The distinct and shared container problem can be classified as an extension of the VRPTW. Since the VRPTW is known to be NP-hard, both basic settings can also be characterized as NP-hard. As a consequence, only relatively small instances of the underlying problems can be solved to optimality with the help of the proposed mathematical models. The stated solution approaches for the distinct and for the shared container problem are implemented in the commercial solver software CPLEX. All computational experiments are carried out on a computer with Intel® Core i7, 3.2 GHz and 12 GB system memory.

Firstly, the experimental settings for the computational experiments are defined. Afterwards, the solution approaches for the SCP are compared with each other. As stated, sequential approaches are known to reduce the problem complexity at

the expense of solution quality. Through a comparison of both approaches the performance of the 2-step method compared to the integrated routing approach can be measured precisely⁵. Finally, the benefit of container sharing is measured by comparing results of the DCP and the SCP for each experimental setting. For an objective comparison of the two described problem types, the integrated routing solution approach is used to solve the SCP. Like the solution approach for the DCP, the integrated routing solution approach for the SCP guarantees to find the global optimum for small test instances⁶.

4.4.1 Experimental Settings

The underlying test instances for the described problem types are based on Solomon's benchmark VRPTW data sets. In 1987, Solomon generated six sets of problems which highlight the characteristics of vehicle routing problems. These characteristics include the geographical data, the number of customers served by a vehicle, and time window characteristics, such as percentage of time-constrained customers, and tightness and positioning of the time windows. The nodes are situated within a $100 * 100$ coordinate plane and comprise a number of either 25, 50, or 100 customers. Due to the geographical data, the six sets of problems are defined as R1, R2, C1, C2, RC1, or RC2. While customers in R1 and R2 are randomly situated in a coordinate plane, the geographical data is clustered in problem sets C1 and C2. The nodes in RC1 and RC2 are situated due to random and clustered structures. Moreover, problem sets R1, C1, and RC1 can only be served during tight time windows so that only a few customers (approximately five to ten) can be visited per route. Additionally, sets R2, C2, and RC2 include wide time windows and, thus, many customers (> 30) can be served during a route (Solomon, 1987).

The settings for the comparison of the 2-step method and the integrated routing approach are based on Solomon's R1-data sets. Since CPLEX is used to solve the underlying problems, Solomon's instances are downsized to provide optimal solutions. Preferring randomly situated locations instead of clustered structures in a data set shall guarantee an objective comparison between the solution approaches. If the geographical data of the small instances is structured, the probability of finding a solution nearby the optimal solution by accident is higher than using randomly situated locations. The location's time windows must also be modified.

⁵The results are adopted from Sterzik and Kopfer (2012a).

⁶The results are adopted from Kopfer et al (2011).

This is due to the following reason: Solomon's data sets only provide one time window per location. Within the DCP and SCP it is required that at customer and terminal locations more than one time window is defined, respectively. Considering multiple time windows at locations leads to a duplication of nodes within the data sets, as can be seen by the given notation in Section 4.3.1. However, the tide time windows of Solomon's R1-data sets are taken as the containers' loading/unloading time. In detail, the time windows for the different locations are modified as follows:

- **Depot:** There is no time window at this location. Vehicles can start and end their tours at any point in time.
- **Shipper/Receiver:** Initially, a customer's first and second time window take the values of the given time window for the same location taken from the considered R1-data set. These tide time windows correspond to a containers' unloading/loading process. Subsequently, these time windows are adapted so that a customer's first and second time window are situated just before and immediately after the given service time window for a container (see also Figure 4.2 and 4.3). For both time windows the wideness is defined by factor ϵ , as can be seen in the following:

$$e_i = b_i \quad \forall i \in V_{S^i} \cup V_{R^i} \quad (4.49)$$

$$b_i = b_i - \epsilon \quad \forall i \in V_{S^i} \cup V_{R^i} \quad (4.50)$$

$$b_i = e_i \quad \forall i \in V_{S^o} \cup V_{R^o} \quad (4.51)$$

$$e_i = e_i + \epsilon \quad \forall i \in V_{S^o} \cup V_{R^o} \quad (4.52)$$

- **Terminal - IF/IE:** IE containers can be picked up at any point in time within the considered time horizon. The time windows for containers at nodes $i \in V_{TIF}$ are consistent with the first time windows of their corresponding receiver locations $(i - 2n) \in V_{R^i}$ and are defined as:

$$b_i = b_{(i-2n)} - t_{i(i-2n)} \quad \forall i \in V_{TIF} \quad (4.53)$$

$$e_i = e_{(i-2n)} - t_{i(i-2n)} \quad \forall i \in V_{TIF} \quad (4.54)$$

- **Terminal - OF/OE:** OE Containers can be delivered to the terminal at any point in time within the considered time horizon. The time windows

for containers at terminal nodes $i \in V_{TOF}$ are consistent with the second time windows of their corresponding shipper locations $(i - n) \in V_{S^o}$ and are defined as:

$$b_i = b_{(i-n)} + t_{(i-n)i} \quad \forall i \in V_{TOF} \quad (4.55)$$

$$e_i = e_{(i-n)} + t_{(i-n)i} \quad \forall i \in V_{TOF} \quad (4.56)$$

Based on these set characteristics, ten test instances are defined where each instance comprises ten transportation requests. In detail, four IF and four OF transportation requests as well as one IE and one OE transportation request are selected. The terminal and customer locations are duplicated for each transportation request. While the coordinates always stay the same, the time windows need to be adapted as defined above. Thereby, ϵ takes the value 25. The number of vertices that is included in an instance corresponds to the summation $3 * n + e_i + e_o + 2 = 3 * 8 + 1 + 1 + 2 = 28$, where 2 is defined through the start and end depot location.

Measuring the benefit of container sharing by means of small test instances is relatively difficult to accomplish since only a few transportation requests can be included. In this case, for example, it is hard to realize street turns due to the fact that the time windows of a receiver and shipper are most likely not consistent. To obtain reasonable results illustrating the potential of container sharing with small instances, data sets are, therefore, used which highlight the benefiting factors of the SCP (see Section 4.1.3). By means of customers that are located close to each other, one of the main beneficial factors of the SCP can be emphasized since container sharing is particularly profitable if shippers and receivers are nearby. Thus, and differently from the generated data sets for the comparison of the solution approaches for the SCP, the data sets used for measuring the potential of container sharing are based on Solomon's C1-data sets. Two coordinates of one cluster illustrating a receiver and a shipper are randomly chosen. Moreover, the time windows of these customers are adapted so that the shipper's first time window is consistent with the receiver's second time window. In detail, the time windows of the shipper $i \in V_{S^i}$ are defined in accordance with the appropriate receiver $(i + n + s) \in V_{R^o}$ in this cluster as follows:

$$b_i = b_{(i+n+s)} + t_{(i+n+s)i} \quad \forall i \in V_{S^i} \quad (4.57)$$

$$e_i = e_{(i+n+s)} + t_{(i+n+s)i} \quad \forall i \in V_{S^i} \quad (4.58)$$

Correspondingly, the time window of $i \in V_{S^o}$ is adapted. According to the R1-

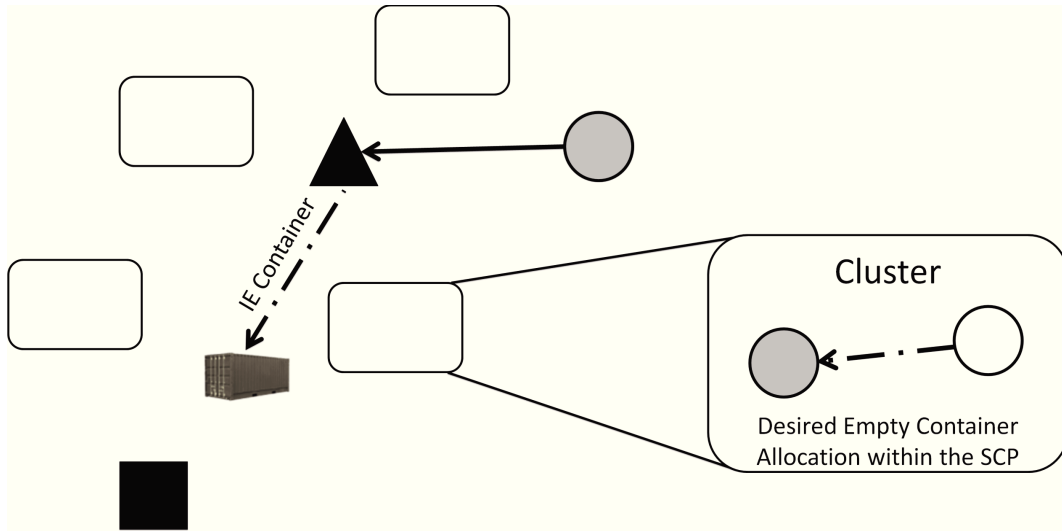


Figure 4.6: Framework of an Export-Dominated Hinterland Data Set

data sets, where the time window length is defined as 10 time units, the service time for the loading process requires $\delta = 10$ time units. The time window length is still defined as $\epsilon = 25$.

$$b_i = e_{(i-n)} + \delta \quad \forall i \in V_{S^o} \quad (4.59)$$

$$e_i = b_i + \epsilon \quad \forall i \in V_{S^o} \quad (4.60)$$

The time windows for the terminal and depot nodes are defined according to Equations (4.53)-(4.56). Based on these set properties, five test instances for export-dominated (data sets 1-5) and five test instances for import-dominated areas (data sets 6-10) are considered. According to an import-dominated area, four clusters, one single additional receiver node, and one OE container are selected for a data set. Additionally, an export-dominated area consists of four clusters, one single additional shipper node, and one IE container. A typical export-dominated hinterland setting that considers the stated transportation requests can be seen in Figure 4.6. Each data set includes 29 nodes.

4.4.2 Performance of the 2-Step Method and the Integrated Routing Approach

Since sequential approaches are known to reduce the problem complexity at the expense of solution quality, it is expected that much less computation time is needed and, hence, bigger instances can be solved, whereas the solution quality of small instances will decrease compared to the exact integrated approach. In

general, the amount of quality decrease obtained by switching to a sequential approach is not predictable. In this section, three goals concerning the performance of the 2-step method are examined. Firstly, it is analyzed which objective for the containers' allocation leads to the best results for the routing of the vehicles. Secondly, the solution quality of the sequential and the simultaneous approach are compared with each other. Moreover, it is examined whether it is advisable to implement the 2-step approach heuristically. Thirdly, the limitations of the 2-step approach, in terms of the maximum size of the barely-solvable instances, are determined.

The stated 2-step method may lead to container allocations which are disadvantageous for the routing of the vehicles because they may require a gratuitous number of vehicles to move the employed containers. Thus, it is analyzed whether objective z_2 or z_3 generates better solutions. As can be seen in Table 4.4, applying objective z_3 dominates the application of z_2 in terms of the number of operating vehicles. Thus, it can be concluded that applying z_2 leads to the assignment of additional containers so that, consequently, more vehicles are required to move them. Due to the fact that the employment of additional vehicles mostly induces a bigger solution space with more opportunities to solve the underlying problem instance, the first variant of the 2-step method leads to better objective values but also to worse results according to the computation time. Bearing in mind the global objective to minimize the total fulfillment costs of the operating company (i.e. the number of operating vehicles and the vehicles' total operating time), it is concluded that z_3 constitutes the dominating objective function for the first step of the sequential approach.

Subsequently, the results of the 2-step method are compared with those of the integrated routing approach. Obviously, applying the holistic simultaneous approach always leads to the global optimum of the SCP and the generated results, therefore, define benchmark values for the underlying problem type. Table 4.5 illustrates the results of both solution approaches. The assumption that the 2-step method generates a surplus of routes is only verified in instance 1 and 4, where one additional vehicle is required to serve all customers, respectively. Hence, for small test instances this hypothesis is scientifically not tenable if z_3 is applied. Comparing the objective values, it can be concluded that the solutions of the sequential approach deviate on average 7% from the best solution. Needless to say, that applying the 2-step approach has the big advantage of finding a solution much faster. The computational experiments show an extraordinary large advantage of 96% less computation time compared to the integrated routing

Table 4.4: Comparison of the Results - 2-Step Method

Inst.	2-Step Approach Applying z2			2-Step Approach Applying z3		
	Vh.	TT	CT (1 st +2 nd Step)	Vh.	TT	CT (1 st +2 nd Step)
1	6	600.07	10.52 (8.36+2.16)	5	621.27	4.01 (0.12+3.89)
2	6	825.96	8.17 (1.78+6.39)	4	915.12	1.55 (0.14+1.41)
3	6	671.46	19.89 (2.12+17.77)	4	717.20	12.15 (0.09+12.06)
4	5	767.45	5.10 (2.05+3.05)	5	862.50	3.62 (0.14+3.48)
5	8	996.90	3033.83 (2.03+3031.80)	5	1015.27	5.63 (0.19+5.44)
6	6	643.59	23.77 (1.77+22.00)	5	690.56	29.22 (0.14+29.08)
7	6	831.31	6.59 (1.95+4.64)	5	851.79	2.41 (0.14+2.27)
8	6	704.89	12.04 (2.09+9.95)	4	805.15	1.89 (0.09+1.80)
9	5	626.39	5.49 (3.63+1.86)	4	648.98	2.16 (0.11+2.05)
10	5	772.01	7.41 (2.30+5.11)	4	795.46	1.86 (0.14+1.72)

Inst. - Instance Number; *Vh.* - Operating Vehicles; *TT* - Total Travel Time; *CT* - Computation Time (in seconds)

approach.

Moreover, experiments are conducted to discover the limitations of the presented approaches in terms of the maximum problem sizes they can solve. The computation time needed to find a solution depends to a large extent on the characteristics of the instances. For the SCP, the number of transportation requests and the time windows' width are the most affecting factors since they have a great impact on the operating of containers and vehicles, which will influence the computation time. Due to the definitions that are given in Section 4.4.1, the width for each time window is already fixed. Thus, testing the limitations of the manageable problem sizes only refer to a variation of the number of transportation requests, which is raised iteratively. In each iteration, three instances are tested randomly. If there still exists a gap to the lower bound after six hours, CPLEX's solving process is stopped. Considering the simultaneous solution approach, the limitation is reached if ten transportation requests have to be served. Conversely, CPLEX is able to solve instances with 19 transportation requests applying the 2-step method. For future work, it is advisable to implement heuristic approaches for the 2-step method instead of simultaneous approaches. Thereby, efficient heuristics for the PDPTW known from the literature (e.g. Ropke and Pisinger (2006)) can be used for generating the vehicles' routes. Nevertheless, in doing so, further additional objective functions for the first step of the 2-step approach have to be developed and tested since even for small test instances, the results for the vehicles' total operating time reached by the 2-step method deviate

Table 4.5: Comparison of the 2-Step and the Integrated Routing Approach

Inst.	2-Step (z3)			Integrated Routing			Difference (in %)		
	Vh.	TT	CT	Vh.	TT	CT	Vh.	TT	CT
1	5	621.27	4.01	4	577.16	2964.73	20.00	7.10	-99.86
2	4	915.12	1.55	4	809.44	39.12	-	11.55	-96.04
3	4	717.20	12.15	4	676.55	126.12	-	5.67	-90.37
4	5	862.50	3.62	4	745.84	215.83	20.00	13.53	-98.32
5	5	1015.27	5.63	5	969.85	78.41	-	4.47	-92.82
6	5	690.56	29.22	5	690.56	541.74	-	-	-94.61
7	5	851.79	2.41	5	841.23	6601.01	-	1.24	-99.96
8	4	805.15	1.89	4	685.74	67.56	-	14.83	-97.20
9	4	648.98	2.16	4	572.18	100.34	-	11.83	-97.85
10	4	795.46	1.86	4	795.46	49.00	-	-	-96.20
Total	45	7923.30	64.50	43	7364.01	10783.91	4.00	7.02	-96.32

7% from the global optimum.

4.4.3 Potential of Container Sharing

To obtain first results of the potential of container sharing, the DCP and the SCP are compared with each other. The underlying approach for solving the SCP is given through the integrated routing model formulation. Through the implementation of this approach within CPLEX, it is guaranteed that for both problem types the best global solution is determined. Indicators for the benefits of container sharing are given through the underlying objective. Therefore, the number of operating vehicles, as well as the vehicles' total operating time, are considered. Although the number of used containers is not included within the global objective, this factor is also taken into account. It indicates further possible savings for trucking companies since reducing the stock of containers leads to a reduction of fixed costs. Due to the fact that the number of inbound containers cannot be reduced in any event, only the additional empty containers arising from the depot are counted. Regardless of an import- or export-dominated hinterland region, seven inbound containers have to be moved from the terminal to the hinterland in the following data sets since the number of inbound containers always refers to the summation $r + e_i$.

First, indications for the huge potential of container sharing can be seen in Figures 4.7 and Figure 4.8 which illustrate the solutions of the DCP and the SCP for the same data set. The constituted container flows for data set 7 are shown. As illustrated, the benefits of container sharing are caused by the flexibility to move

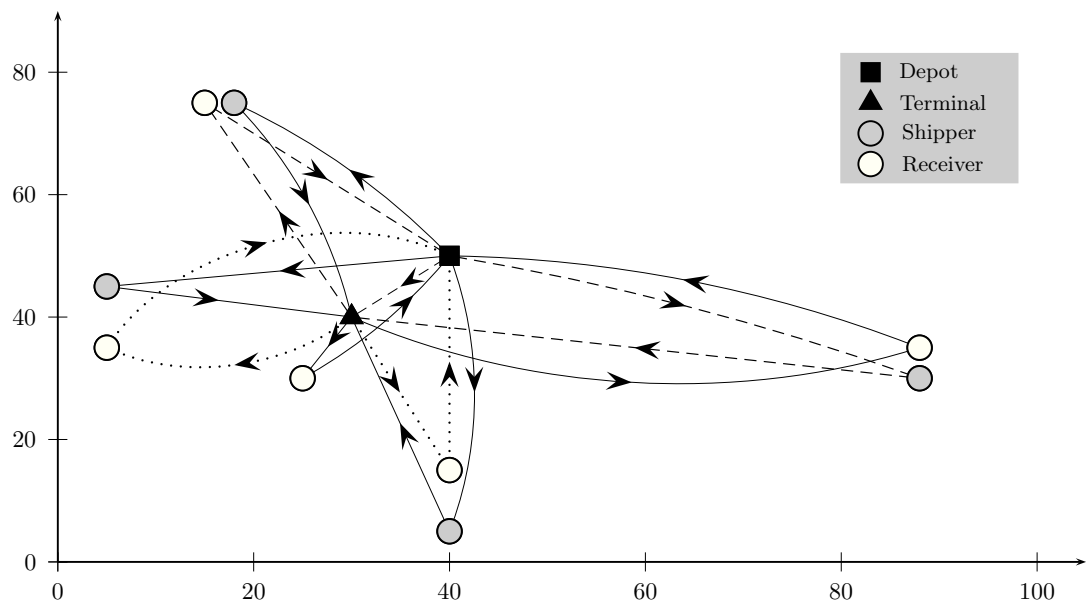


Figure 4.7: Containers' Flows for Data Set 7 (DCP)

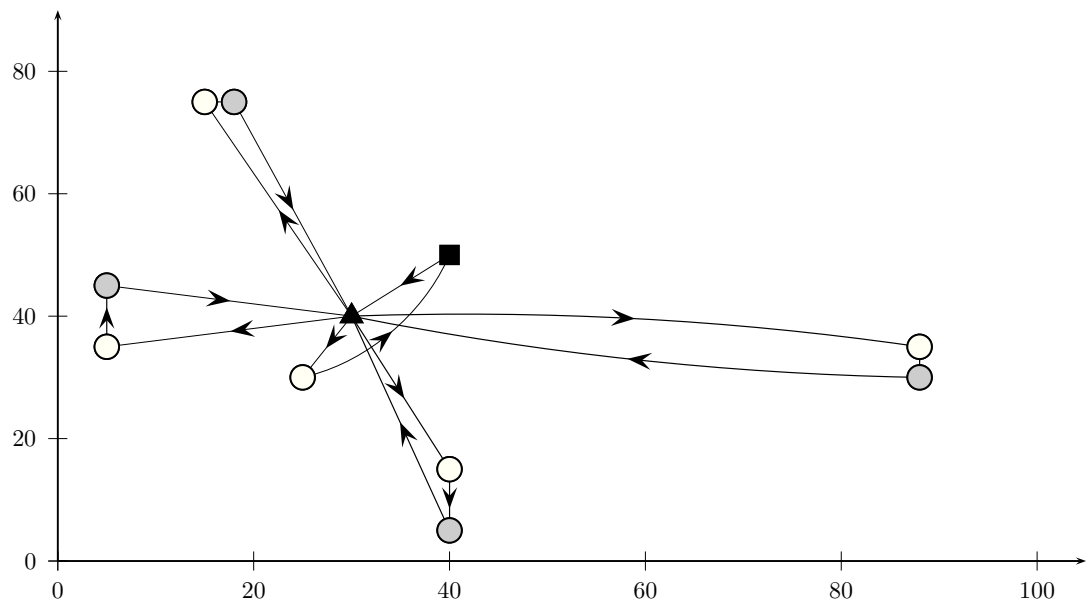


Figure 4.8: Containers' Flows for Data Set 7 (SCP)

containers between the locations. Especially the opportunity to use obtained empty containers from receivers for the goods of shippers can be considered as the main beneficial factor within the SCP. Applying the DCP for the same data set, the containers are only used for one transportation request. For instance, for an IF transportation request, the corresponding container is moved from the terminal to the predefined receiver and subsequently to the depot. In the SCP, the obtained empty container at the receiver after the trucking company has served an IF transportation request is used for an OF request. As desired through the modified test instances, the container is carried within a cluster from the receiver to the shipper (see Figure 4.6). Hence, one container is used for two transportation requests. An exception is the service of the OE transportation request. Thereby, the container flow starts at the depot and ends at the terminal so that only one transportation request is served with the same container. This container is, moreover, the only additional container originating from the depot which is used within the SCP for data set 7. All other container flows start and end their flows at the terminal as inbound and, afterwards, as outbound containers.

The flexibility to allocate containers obviously affects the number of used trucks and containers, as can be seen in Table 4.6. In all instances the SCP requires at most 1 container that originates from the depot. In instances 2 and 3, no additional container is required. Therefore, the SCP predominantly makes use of the inbound containers that in any event have to be moved within the hinterland. Consequently, the amount of used containers can be reduced by 84% on average. Due to the large reduction of containers, it is not surprising that the amount of vehicles responsible for the container movements can also be decreased. In comparison to the DCP, remarkably 45% less trucks are used in the SCP.

Besides the decrease of fixed costs, the variable costs are also reduced. The amplitude of the benefit goes from 12 to 25%. On average, the gain of container sharing of the SCP compared to the DCP is at 21%. The deployment of almost 100% more vehicles in the DCP compared to the SCP causes a much higher requirement of computational resources to solve this problem type: while the computation time to solve the underlying data sets amounts to 1.5 hours for the DCP, the computation time for the SCP requires only 2 minutes on average.

Obviously, these results indicate the huge potential of container sharing. Through the reduction of container movements by directly moving an empty container from a receiver to a shipper, a trucking company's costs can be reduced enormously. Nevertheless, it can be assumed that the stated results illustrate the upper limit

Table 4.6: *The Impact of Container Sharing (Basic Scenarios)*

Inst.	DCP			SCP			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	9	5	965.18	5	1	747.72	44.44	80.00	22.53
2	8	5	901.11	4	-	679.92	50.00	100.00	24.55
3	8	5	868.63	4	-	678.84	50.00	100.00	21.85
4	8	5	882.52	4	1	666.22	50.00	80.00	24.51
5	8	5	831.12	5	1	685.58	37.50	80.00	17.51
6	8	5	852.96	5	1	671.42	37.50	80.00	21.28
7	9	5	884.31	5	1	687.93	44.44	80.00	22.21
8	9	5	885.71	5	1	783.78	44.44	80.00	11.51
9	9	5	928.25	5	1	750.67	44.44	80.00	19.13
10	9	5	1043.83	5	1	795.44	44.44	80.00	23.80
Total	85	50	9043.62	47	8	7147.52	44.71	84.00	20.97

Cont. - Additional Containers (from the Depot)

of the possible cost savings for a trucking company due to the following factors. First, the flexibility to allocate empty containers in the non-cooperative scenario is very restricted since an obtained container from a receiver cannot be moved to a shipper in any event. To a certain degree, this situation illustrates the reality since most of the routes in seaport hinterlands are actually pendulum tours between a trucking company's depot, its customer,s and the terminal (Veenstra, 2005). However, there are certainly situations that allow these routes for a trucking company. In addition, the test instances highlight the advantages of the SCP. The solutions were predefined by the data input to a large extent by the geographical data and time conditions. However, even if a trucking company's benefit partly reaches these enormous cost savings, it has a strong positive impact on the financial situation of the trucking company since the profit margin in container trucking usually only amounts to a few percent.

5 The Potential of Container Sharing Measured in Comprehensive Scenarios

By means of the distinct and shared container problem it has been proven that the potential of container sharing can be enormous. However, within the basic scenarios of Chapter 4, the focus lays mainly on measuring the cost savings for a particular trucking company which benefits from the additional flexibility to allocate empty containers in a container sharing cooperation. The cooperation is only illustrated implicitly by means of the arcs which are allowed to pass by a vehicle. Consequently, a further step is to explicitly include more than one trucking company within the scenarios. The consideration of several trucking companies then enables the opportunity to analyze precisely how empty containers are exchanged between cooperating trucking companies in a container sharing coalition. Thereby, each company uses its own depot to serve its distinct client base.

The chapter is structured as follows¹: First, two comprehensive scenarios are introduced. While the first comprehensive scenario (multi-company container truck transportation problem (MC-CTTP)) forbids the exchange of empty containers between trucking companies, empty containers are allowed to be interchanged among several owners in the second comprehensive scenario (multi-company container truck transportation problem with container sharing (MC-CTTP-CS)). Second, the resulting advantages of the MC-CTTP-CS compared to the MC-CTTP are shown precisely by a simple example. Section 5.3 gives integrated routing MIP formulations for both comprehensive scenarios. The idea to interlink the containers and the vehicles is, thereby, adapted from the integrated routing solution approach for the SCP. In the final Section 5.4 computational experiments are performed on randomly generated data sets to give further results indicating not only the advantages for a particular trucking company, but also for a whole container sharing cooperation.

¹This chapter is based on Kopfer and Sterzik (2012). An extended abstract of this article can be found in Sterzik and Kopfer (2012c).

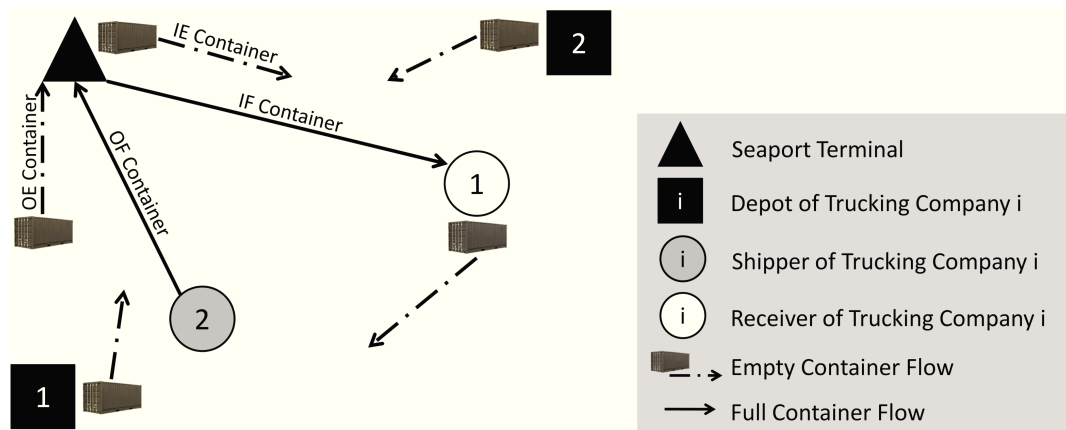


Figure 5.1: Basic Setting for the Comprehensive Scenarios

5.1 Definition of Comprehensive Scenarios

The two comprehensive scenarios analyzed in this chapter are defined as MC-CTTP and MC-CTTP-CS. Just like the basic scenarios, the comprehensive scenarios refer to the OD-CTTP (see 4.1.1) as their basic setting. The only exception marks the consideration of multiple depots for the seaport hinterland. Thereby, at least two trucking companies, each one with its own depot, are considered. Moreover, a company needs to serve its own client base by means of its own fleet of vehicles as can be seen in Figure 5.1. Apart from that, all problem characteristics and assumptions of the OD-CTTP are adopted and can be described comprehensively by the following criteria:

- At least two trucking companies are considered in the hinterland region. Exactly one depot belongs to each company.
- Each trucking company has to serve its own client base.
- Two types of customers (shipper and receiver) and four different transportation requests (IE, IF, OE, and OF) are distinguished.
- A single terminal is considered.
- Every transportation request is known by the corresponding trucking company in advance.
- The distances between any two locations are given before the beginning of the time horizon.
- One time window at the terminal and two time windows at each customer location are considered.

- A container has to be moved from/to a terminal or customer location during the given time windows.
- For the picking up/dropping off process of the container, as well as the loading/unloading process of the container at the customer/terminal location, a service time has to be considered.
- Transportation requests are served by a homogeneous fleet of vehicles.
- A vehicle starts and ends its tour at the depot of the corresponding company.
- The transportation resource is a FEU. Thus, only one container at a time can be moved by a vehicle.
- Transportation requests cannot be interrupted after a truck served the origin, but not the destination, location.
- A large number of empty containers can be stacked at the depot.
- The objective is to minimize the fulfillment costs consisting of fixed and variable costs.

Based on this setting, the MC-CTTP defines a scenario where empty containers are uniquely assigned to trucking companies, i.e. empty containers can only be switched between locations belonging to a specified trucking company. Different from the DCP, which only allows the depot as origin or destination of an empty container flow, empty containers in the MC-CTTP for a single company can also be allocated between the customer and terminal nodes if suitable. The MC-CTTP turns into a SCP if only one trucking company/depot is considered. For instance, an empty container obtained at a receiver location served by a certain trucking company can exclusively be used for transportation requests of this company. The possible origins and destinations of empty container flows for the locations of a single company can be seen in Table 4.2.

In the second scenario, the exchange of empty containers between cooperating partners is permitted. In other words, companies share their information about locations at which empty containers are currently stacked and they agree with the mutual exchange of these containers. That is why benefits arise through the emerging additional flexibility to allocate empty containers to a vehicle's tour. In detail, this scenario allows companies to use foreign empty containers which are obtained at a terminal or customer location. Companies have access to IE containers and can use obtained empty containers at receiver locations of cooperating companies. These containers can be integrated at each position in a tour of a foreign company. Thus, companies who use containers from a participating

company can use them for their transportation requests. Nevertheless, companies do not necessarily need to use these containers for their transportation requests and can also move foreign empty containers to their depots. This situation is realistic if trucking companies get a financial compensation from the coalition for this altruistic behavior. However, empty containers stacked at an external depot are excluded from use in a coalition. Furthermore, IF, OF, and OE transportation requests are still restricted to be served by the corresponding trucking company. This guarantees that the operating companies keep their autonomy in the cooperation. The permission of sharing empty containers between trucking companies leads to the MC-CTTP-CS.

It should be noted that the possibility of a company using external containers does not change the number of the ingoing and outgoing containers at the seaport terminal. In other words, the interface of the seaport terminal with the abroad sites and the hinterland locations is only changed with respect to the identity of the containers and not with respect to the size of the container flows.

To optimize the scenarios, the interests of a single company are disregarded. The companies' total benefits are measured from a central point of view. Hence, the benefit of a particular company is subordinated for the sake of the global optimum of the scenario. This is in accordance with the aim of the thesis to measure the potential of the container sharing idea, but suffers the drawback that companies can benefit above-average at the expense of cooperating companies. Bearing these criteria in mind, the objective of Chapter 4 is modified so that now the objective tends to achieve the overall business goal of minimizing the total costs of a coalition. As a first step, the number of vehicles of the operating companies is minimized. As a second step, the total operating time of all operating vehicles within a coalition is to be minimized.

5.2 Advantages of Container Sharing According to the Proposed Concepts

Figure 5.2 (a) gives an example of a common situation for trucking companies in the hinterland of seaports, where two trucking companies are in charge of four transportation requests. While trucking company 1 has to serve an OE and an OF transportation request, trucking company 2 is in charge of an IE and an IF request. Due to these transportation requests, the following empty container repositioning problems have to be solved. First, origin locations of the required

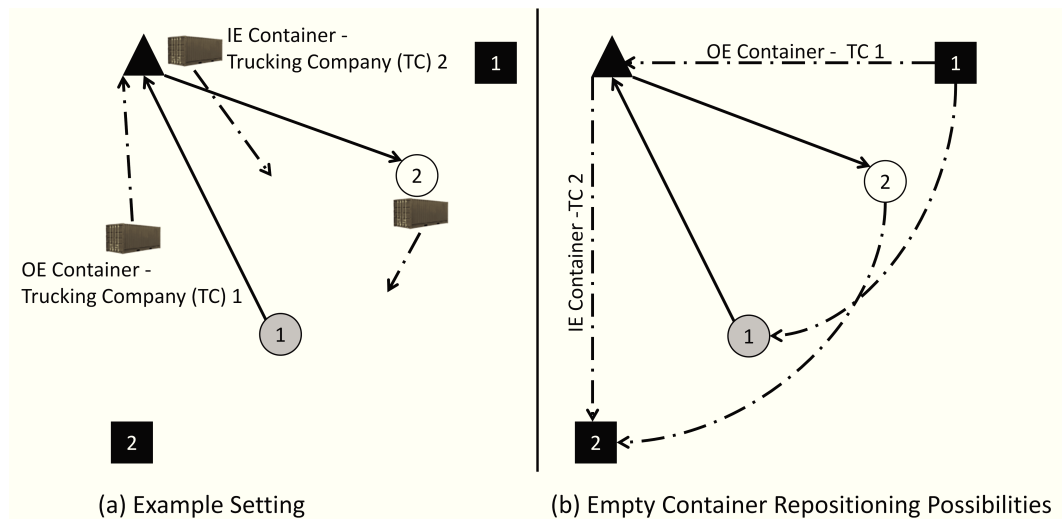


Figure 5.2: Example for the MC-CTTP

empty container flows for the OE and OF transportation request have to be determined. Moreover, the destinations for the IE container and for the obtained empty container at the receiver location are unknown.

Figure 5.2 (b) shows all possible empty container repositioning flows for the MC-CTTP within this example. As can be seen, the opportunities are very restrictive for the non-cooperating case since the required empty containers can only derive either from the depot (trucking company 1) or have to be moved to the depot (trucking company 2). Therefore, four different containers are needed to serve these requests.

If the exchange of empty containers between cooperating companies is permitted, trucking company 1 can integrate either the IE container or the obtained empty container at the receiver location of trucking company 2 in its route to serve its requests (see Figure 5.3 (a)). Additionally, it still has the opportunity to use an empty container from its depot for the transportation requests. Obviously, it has to be assumed that these time windows are consistent with the shipper's or the terminal's time window for the OE request. As can be seen in Figure 5.3 (b) the possibilities for company 2 to reposition empty containers did not change compared to the non-cooperative case. Nevertheless, company 2 will still profit by container sharing and, thus, reduce transportation costs if company 1 handles its IE request or the empty container at the receiver location. Overall, it is possible to reduce the number of containers to three compared to the MC-CTTP.

Due to the interdependency of the transportation resources and the means of transport, the emerging additional flexibility to allocate empty containers will

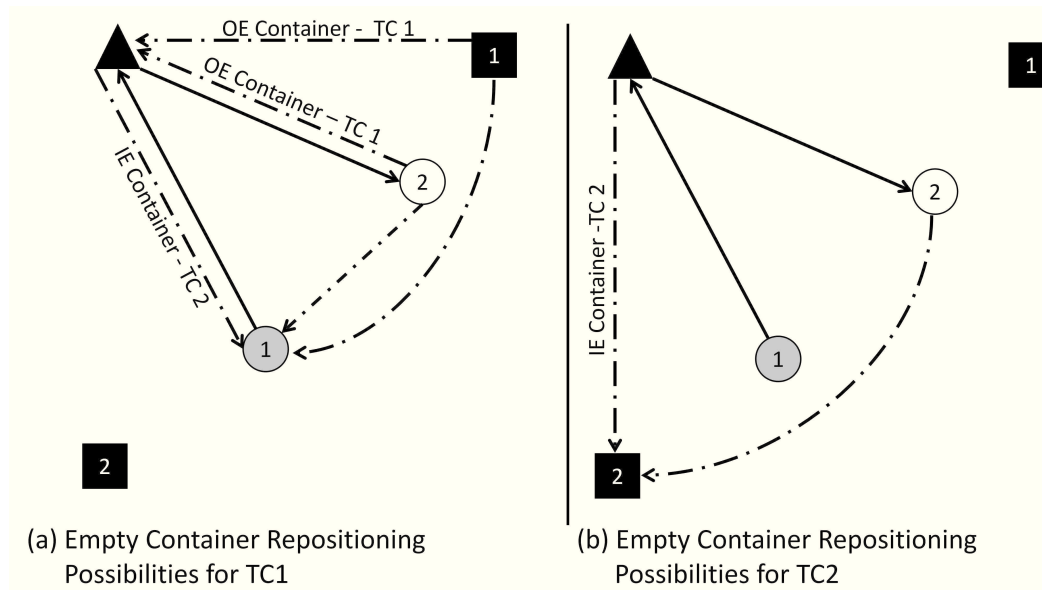


Figure 5.3: Benefits of Container Sharing According to the MC-CTTP-CS

consequently cause a minimization of the trucks' transportation costs. Especially trucking companies with a relatively small client base can benefit tremendously from the rising flexibility to allocate empty containers within a container sharing cooperation. In case of the MC-CTTP, the probability of serving numerous small routes, including only up to two transportation requests, is relatively high for these small companies compared to trucking companies who are in charge of a large client bases. This is due to the missing opportunities to integrate transportation requests in a vehicle's routes. This is due to the fact that time windows of different locations are not consistent or due to the fact that there is no origin or destination location for an empty container flow, besides the company's depot. Thus, the benefit of container sharing is assumed to grow tremendously for these companies through the rising flexibility to allocate empty containers, i.e. the more empty containers are shared with other cooperating companies, the higher the probability to save travelled distances that are induced by transportation requests.

5.3 Exact Integrated Routing MIP Formulation

For modeling the comprehensive scenarios, the simultaneous solution approach for the SCP is generalized to include more than one trucking company in a hinterland region. Hence, the synchronization of containers as passive entities and vehicles as active transportation entities is adapted from the integrated routing model

formulation in Section 4.3.3.2. The MIP formulations for the MC-CTTP and for the MC-CTTP-CS are defined in the following section.

5.3.1 Notation

Apart from the notation for the basic scenarios in Section 4.3.1, the MIP formulations for the MC-CTTP and MC-CTTP-CS require the introduction of parameters and sets that comply with the consideration of several trucking companies and their client bases. The number of depots that are included within the comprehensive scenarios refers to the parameter d . The arrangement of the depot nodes is changed so that node 0 is no longer defined as a start depot node. The depot nodes now refer to the depot set V_D consisting of start and end depot nodes $V_{D^s} = \{v + 1, \dots, v + d\}$ and $V_{D^e} = \{v + d + 1, \dots, v + 2d\}$. Each depot corresponds to one of the d trucking companies. The assignment of vehicles and customers to a trucking company is specified by d_k^{veh} and d_i^{cus} . For instance, if vehicle 3 belongs to trucking company 1, d_3^{veh} gets value 1. Similarly, if customer 14 should be served by trucking company 5, d_{14}^{cus} gets value 5. Since a company's depot constitutes the start and end location for a vehicle $k \in K$, all depot vertices are doubled so that nodes $(v + d_k^{veh}) \in V_{D^s}$ and $(v + d + d_k^{veh}) \in V_{D^e}$ describe the same depot. A truck always has to start and end its route at its company's depot regardless of which scenario is considered. Moreover, the arrangement and assignment of customer and terminal nodes to each other stay the same. For instance, a full container originating from IF terminal node $i \in V_{TIF}$ still has to be delivered to its corresponding receiver location $(i - 2n) \in V_{Ri}$. To sum up, the following sets and parameters, in addition to the stated notation in Section 4.3.1, have to be defined for the MIP formulations:

$V_D = V_{D^s} \cup V_{D^e}$: Set of depot nodes

- $V_{D^s} = \{v + 1, \dots, v + d\}$: Set of start depot nodes
- $V_{D^e} = \{v + d + 1, \dots, v + 2d\}$: Set of end depot nodes

d : Number of depots; each corresponding to a certain trucking company

d_k^{veh} : The corresponding depot/trucking company of vehicle k

d_i^{cus} : The corresponding depot/trucking company of customer i

5.3.2 Comprehensive Scenarios

Since the SCP is a special case of the MC-CTTP with only one trucking company, the MIP formulation for the MC-CTTP, as well as the MC-CTTP-CS, are based on the model for the SCP. As a consequence, the following three components of the SCP are also adapted for the comprehensive scenarios: container allocation, vehicle routing and scheduling, and the synchronization of these two transportation entities. In the following, the model for the MC-CTTP is introduced. The MIP formulation for the MC-CTTP-CS is based on the MC-CTTP and differs only in one equation. Compared to the simultaneous model formulation for the SCP, the equations for the container allocation, as well as for the routing of the vehicles, are only modified slightly in order to be able to include several depots. The models can be formulated through equation (5.1) and the restrictions (5.2) to (5.23).

$$\min z = \sum_{k \in K} (T_{(v+d+d_k^{veh})k} - T_{(v+d_k^{veh})k}) \quad (5.1)$$

Within the MC-CTTP, the minimization of fixed costs is achieved by raising the number of operating vehicles m of the container sharing cooperation until a feasible solution is found. Subsequently, the model tends to minimize the total operating time of all operating vehicles of the cooperating companies defined by the objective function (5.1).

$$\sum_{j \in V} \sum_{c \in C} y_{ijc} = 1 \quad \forall i \in V_C \cup V_{TIF} \cup V_{TIE} \quad (5.2)$$

$$\sum_{i \in V_{Ds}} \sum_{j \in V} \sum_{c \in C} y_{ijc} = e_a \quad (5.3)$$

$$\sum_{i \in V} \sum_{j \in V_{TOF} \cup V_{TOE} \cup V_{De}} y_{ijc} = 1 \quad \forall c \in C \quad (5.4)$$

$$\sum_{j \in V_{Si} \cup V_{De}} \sum_{c \in C} y_{ijc} = 1 \quad \forall i \in V_{TIE} \quad (5.5)$$

$$\sum_{i \in V_{Ro} \cup V_{Ds}} \sum_{c \in C} y_{ijc} = 1 \quad \forall j \in V_{TOE} \quad (5.6)$$

$$\sum_{c \in C} y_{i(i-2n)c} = 1 \quad \forall i \in V_{TIF} \quad (5.7)$$

$$\sum_{c \in C} y_{i(i+n)c} = 1 \quad \forall i \in V_S \cup V_{Ri} \quad (5.8)$$

$$\sum_{j \in V} y_{jic} - \sum_{j \in V} y_{ijc} = 0 \quad \forall i \in V_C, c \in C \quad (5.9)$$

$$L_{jc} \geq L_{ic} + t_{ij} + s_i - M(1 - y_{ijc}) \quad \forall i, j \in V, c \in C \quad (5.10)$$

Restrictions (5.2)-(5.3) require that every customer node is visited once and that a container flow begins either at the terminal as an inbound container or at the depot of a trucking company. A container's final destination is given by the terminal or the depot, stated by (5.4). While the possible origins/destinations of empty containers are defined by (5.5)-(5.6), restrictions (5.7)-(5.8) assure the defined locations of a full container transportation task. Additionally, (5.8) also states that a container has to pass the loading/unloading process at a shipper/receiver node. Equations (5.9) and (5.10) ensure the route and time continuity.

$$\sum_{j \in V} \sum_{k \in K} x_{ijk} = 1 \quad \forall i \in V_C \cup V_T \quad (5.11)$$

$$\sum_{j \in V} x_{(v+d_k^{veh})jk} = 1 \quad \forall k \in K \quad (5.12)$$

$$\sum_{i \in V} x_{i(v+d+d_k^{veh})k} = 1 \quad \forall k \in K \quad (5.13)$$

$$\sum_{j \in V} x_{jik} - \sum_{j \in V} x_{ijk} = 0 \quad \forall i \in V_C \cup V_T, k \in K \quad (5.14)$$

$$T_{jk} \geq T_{ik} + t_{ij} + s_i - M(1 - x_{ijk}) \quad \forall i, j \in V, k \in K \quad (5.15)$$

$$b_i \leq T_{ik} \leq e_i \quad \forall i \in V_C \cup V_T, k \in K \quad (5.16)$$

Equations (5.12)-(5.13) state that a vehicle starts and ends its tour at the depot of its trucking company. During a vehicle's tour, it also has to be assured that a customer and a terminal location is visited exactly once ((5.11)). The route continuity as well as the time restrictions are defined by (5.14)-(5.16).

$$x_{ijk} d_k^{veh} = x_{ijk} d_i^{cus} \quad \forall i \in V_C \cup V_T, j \in V, k \in K \quad (5.17)$$

$$\sum_{k \in K} x_{ijk} \geq y_{ijc} \quad \forall i \in V_{S^o} \cup V_{R^o} \cup V_T, j \in V, c \in C \quad (5.18)$$

$$\sum_{k \in K} x_{ijk} \geq y_{ijc} \quad \forall i \in V_C \cup V_T, j \in V_{S^i} \cup V_{R^i} \cup V_T \cup V_{D^e}, c \in C \quad (5.19)$$

$$T_{ik} = L_{ic} \quad \forall i \in V_C \cup V_T, k \in K, c \in C \quad (5.20)$$

$$x_{ijk}, y_{ijc} \in \{0, 1\} \quad \forall i, j \in V, k \in K, c \in C \quad (5.21)$$

$$T_{ik}, L_{ic} : \text{real variables} \quad \forall i \in V, k \in K, c \in C \quad (5.22)$$

The synchronization of the vehicles as active transportation entities and the containers as passive transportation entities is ensured by interlinking the containers' flows and the vehicles' routes with each other ((5.18)-(5.19)). Both entities need to leave a location at the same time if a vehicle moves a container stated by (5.20).

The equations that distinguish the MC-CTTP and MC-CTTP-CS are given by (5.17) and (5.23). In the non-cooperative scenario all terminal and customer nodes can only be served by the trucking company which is in charge of the corresponding transportation requests. Full as well as empty container movements are then only carried out between the locations of a particular company. In the MC-CTTP-CS these container movements are only restricted to locations which do not provide empty containers. In this case, empty containers can be used by all operating trucking companies:

$$x_{ijk}d_k^{veh} = x_{ijk}d_i^{cus} \quad \forall i \in V_S \cup V_{R^i} \cup V_{TOF} \cup V_{TOE}, j \in V, k \in K \quad (5.23)$$

5.4 Computational Experiments

During this Section the aim is to analyze the benefit of container sharing according to the comprehensive scenarios. The focus lays on measuring the benefit of a whole coalition. However, it is also analyzed how particular companies benefit. Hereby, a goal is to research if container sharing is more profitable for companies who are mainly in charge of inbound or outbound transportation requests, respectively. Companies who serve mainly inbound requests can supply the cooperating companies with empty containers. Besides, companies who serve mainly outbound requests generally demand empty containers during their routes in order to be able to serve additional customers.

The experiments are based on the same computational conditions as in Section 4.4. Hence, the stated mathematical models are implemented in CPLEX and carried out on a computer with Intel[®] Core i7, 3.2 GHz and 12 GB system memory. The underlying ten test instances are based on Solomon's C1-data sets and include two trucking companies. Each company is in charge of six transportation

requests. While the first company only serves outbound requests, the second company is in charge of inbound requests. In detail, the outbound requests comprise five OF requests and one OE request. The inbound requests include five IF requests and one IE request. Each data set includes 36 nodes.

The geographical data of the depot and the customer and terminal nodes, as well as the corresponding time windows of these nodes, are defined as stated in Section 4.4.1. Thus, the beneficial factors of container sharing are once more highlighted. According to the number of IF and OF transportation requests, five clusters are generated per data set. Each cluster includes a receiver and a shipper that belong to different companies. The coordinates are randomly taken from Solomon's C1-data sets. Moreover, the time windows of these customers are adapted so that the receiver's second time window is consistent with the shipper's first time window. Different from the non-cooperative scenario, the empty container from the receiver location can be used for the nearby shipper in the MC-CTTP-CS. Consequently, the framework of the instances is similar to the framework for the DCP and SCP, which is illustrated in Figure 4.6.

Table 5.1 shows the computational results for the MC-CTTP and the MC-CTTP-CS. The advantages of container sharing are presented by illustrating the advantages of a container sharing coalition and its participating companies. The computation time to solve the instances differs extremely depending on which problem has to be solved. While the solution process for the MC-CTTP requires 3 minutes on average, the process for the MC-CTTP-CS takes 20 minutes. These results are different from the results of Chapter 4 which show a higher computation effort to solve the non-cooperative DCP than the cooperative SCP. This can most certainly be ascribed to the small subproblems within the MC-CTTP which have to be solved. The consideration of two trucking companies and their two corresponding client bases in the data sets of the MC-CTTP lead to two independent problems. Since the special case of the MC-CTTP that only considers one trucking company turns into a SCP, the underlying instances can also be solved by dealing with two independent SCP's and 18 nodes per subproblem (instead of 36 nodes). The MC-CTTP solves these small subproblems simultaneously. However, the complexity is smaller compared to the MC-CTTP-CS. The larger computation expense for the cooperative case can be ascribed to the possibilities to allocate empty containers between the locations of both operating companies. Thus, many more arcs are included in the MC-CTTP-CS. This leads to a bigger solution space compared to the MC-CTTP.

Considering the advantages of a container sharing cooperation, the decrease of

Table 5.1: *The Impact of Container Sharing (Comprehensive Scenarios)*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	12	6	1333.24	8	1	1077.62	33.33	83.33	19.17
	6	6	687.22	4	1	597.84	33.33	66.67	13.01
	6	-	646.02	4	-	479.77	33.33	-	25.73
2	12	6	1393.90	7	1	1211.08	41.67	83.33	13.12
	6	6	592.65	4	1	606.05	33.33	83.33	-2.26
	6	-	801.25	3	-	605.03	50.00	-	24.49
3	12	6	1392.39	8	3	1341.41	33.33	50.00	3.66
	6	6	639.87	4	3	698.89	33.33	50.00	-9.22
	6	-	752.52	4	-	642.52	33.33	-	14.62
4	12	6	1305.83	8	1	1139.47	33.33	83.33	12.74
	6	6	617.81	4	1	597.62	33.33	83.33	3.27
	6	-	688.02	4	-	541.85	33.33	-	21.25
5	12	6	1376.14	9	-	1231.50	25.00	100.00	10.51
	6	6	640.38	5	-	662.40	16.67	100.00	-3.44
	6	-	735.76	4	-	569.10	33.33	-	22.65
6	12	6	1345.38	9	2	1173.69	25.00	66.67	12.76
	6	6	641.07	4	2	559.38	33.33	66.67	12.74
	6	-	600.19	5	-	614.31	16.67	-	-2.35
7	12	6	1260.36	9	2	1079.44	25.00	66.67	14.35
	6	6	627.00	5	2	591.47	16.67	66.67	5.67
	6	-	633.36	4	-	487.98	33.33	-	22.95
8	12	6	1326.44	7	-	1008.36	41.67	100.00	26.69
	6	6	591.77	4	-	503.06	33.33	100.00	14.99
	6	-	734.67	3	-	505.30	50.00	-	31.22
9	12	6	1233.38	7	2	991.15	41.67	83.33	19.64
	6	6	643.93	4	2	578.19	33.33	66.67	10.21
	6	-	589.45	3	-	412.96	50.00	-	29.94
10	12	6	1456.49	10	2	1305.78	16.67	66.67	10.35
	6	6	716.14	5	2	665.43	16.67	66.67	7.08
	6	-	740.35	5	-	640.35	16.67	-	13.51
Total	120	60	13423.55	82	14	11559.50	31.67	76.67	13.89

used vehicles is at 32% on average. Regardless of which data set is considered, at least 17% less vehicles are required to serve the customers. This magnitude is more than doubled in instances 2, 8 and 9. Instead of 12 vehicles in the non-cooperative scenario, only seven vehicles are required to allocate the containers between the locations in the cooperative scenario. One reason for this huge reduction is the decrease in containers which are needed to serve the transportation requests. The reduction of additional empty containers originating from the depots fluctuates at around 77%. In addition to the decrease of fixed costs, the variable costs range from 4% to 27% and have a mean value of 14%.

The possible cost savings of the two considered companies are influenced to a large extent by the transportation request types which have to be served. This becomes clear by having a look at a particular company of a cooperation. In Table 5.1, the first company listed below the results of a container sharing coalition is only in charge of outbound transportation requests. The second listed company has to serve only inbound transportation requests. Accordingly, trucking company 1 can integrate the containers from the receiver locations and the IE container at the terminal into its tours, while the second company misses the possibility to use the cooperating company's containers. Subsequently, the cooperation's whole container reduction is attributed to the first company. Although company 1 has much more flexibility to organize its routes through the cooperation, it surprisingly benefits less than the second company. In five of ten instances, company 2 requires less vehicles to serve its requests than company 1. In general, the reduction of vehicles is at 28% for company 1 and 35% for company 2. Considering the variable costs, this trend is even more significant. Given a mean reduction of the coalition's total operating time of 15%, the reduction of company 1 is only at 6% on average. This benefit is extremely below average, bearing in mind that the reduction of the second company is at 21% on average. In three of 10 instances (2, 3, and 5) trucking company 1 requires even more operating time to serve all customer requests compared to the non-cooperative case.

The reason for the above-average benefit for trucking companies who can supply empty containers to cooperating companies at their customer or terminal locations is evident when examining a certain solution for a data set. Tables 5.2 and 5.3 illustrate the optimal tours for data set 2 in the non-cooperative and in the cooperative scenario. As can be seen, a typical route of trucking company 1 and trucking company 2 in the MC-CTTP includes only one transportation request. For instance, a vehicle serving a usual tour of company 1 moves an

Table 5.2: Optimal Solution of Data Set 2 (MC-CTTP)

Trucking Company 1		
Tour 1	OE	
Tour 2	S(2)	OF(2)
Tour 3	S(3)	OF(3)
Tour 4	S(4)	OF(4)
Tour 5	S(5)	OF(5)
Tour 6	S(1)	OF(1)

Trucking Company 2		
Tour 1	IF(1)	R(1)
Tour 2	IF(2)	R(2)
Tour 3	IF(3)	R(3)
Tour 4	IF(5)	R(5)
Tour 5	IE	
Tour 6	IF(4)	R(4)

$S(r)$ - Shipper node (first time window) that corresponds to OF request r ; $R(r)$ - Receiver node (second time window) that corresponds to IF request r ; $OF(r)$ - Nodes that define OF request r . It consists of the shipper node (second time window) of OF request r and the related OF terminal node; $IF(r)$ - Nodes that define IF request r . It consists of the IF terminal node and the related receiver node (first time window) of IF request r ; OE/IE - OE/IE terminal node

Table 5.3: Optimal Solution of Data Set 2 (MC-CTTP-CS)

Trucking Company 1								
Tour 1	S(3)	OF(3)						
Tour 2	R(5)	OE	IE	S(5)	OF(5)	R(3)	S(2)	OF(2)
Tour 3	R(4)	S(4)	OF(4)					
Tour 4	R(1)	S(1)	OF(1)					

Trucking Company 2			
Tour 1	IF(1)		
Tour 2	IF(5)	IF(3)	R(3)
Tour 3	IF(4)	IF(2)	

empty container from the depot to a shipper and stays at this location during the container's loading time. Afterwards, the vehicle moves the full container to the terminal and ends its tour at the depot. Applying the MC-CTTP-CS to data set 2 changes a tour's structure for both companies noticeably. In this case, company 1 uses the opportunity to integrate empty containers of company 2 into its tour. Except for $R(3)$, all nodes of company 2 which supply empty containers are now integrated into company 1's tours. Subsequently, company 1 is able to serve many more nodes within a tour (see Tour 2) so that the number of required vehicles is reduced. As a consequence, the number of company 2's tours is also reduced since it only needs to serve $R(3)$ and the nodes that are forbidden to be served by company 1. Certainly, the unbalanced transport service of the number of nodes among the companies leads to an unequal arrangement of variable cost savings within the cooperation. While company 2 can reduce its costs by 24%, company 1 does not note a reduction. Its variable costs even rise by 2%. Nevertheless, this increase of variable costs have to be seen in relation to the reduction of fixed costs, which is at one-third.

6 Heuristic Solution Approaches

The stated results of Chapters 4 and 5 indicate the great potential of container sharing for certain trucking companies, as well as for a whole coalition. In both chapters CPLEX has been utilized for solving test instances for the proposed models. As a consequence, only small test instances have been analyzed. Furthermore, the underlying test instances were idealized to indicate the upper limit of possible cost savings for companies in a container sharing cooperation. In a further step, it needs to be analyzed how the container sharing idea influences possible cost savings for trucking companies if unmodified realistic-sized instances are considered. In order to handle large instances, a tabu search heuristic for the MC-CTTP and the MC-CTTP-CS is developed. Since heuristics and metaheuristics cannot guarantee the discovery of optimal solution and, thus, have to focus on finding high-quality solutions, the heuristic's performance needs to be assessed. Subsequently, realistic-sized data sets can be solved. On the basis of data sets with different characteristics, such as the number of trucking companies or time conditions, possible cost savings of container sharing coalitions in different hinterland settings can be indicated.

The chapter is structured as follows. In Section 6.1, a tabu search heuristic for the comprehensive scenarios is presented. The performance of the heuristic is tested in Section 6.2. Finally, the algorithm is applied to realistic-sized instances. The obtained results are discussed in Section 6.3.

6.1 Solution Procedure

The proposed scenarios are based on the CTTP (Zhang et al, 2009), which is classified as an extension of the NP-hard VRPTW. Solving these complex problems to optimality requires massive computational effort even for relatively small instances as shown in Chapter 4 and Chapter 5. Therefore, heuristics are mainly applied to solve container vehicle routing problems (Wen and Zhou, 2007).

Contrary to the integrated solution approaches in Chapter 5, the tabu search heuristic to be defined in the following sections tries to find high-quality solutions by considering vehicles as the only transportation entities of the problems.

In other words, that the simulation of containers' flows is not explicitly included in the solution procedure. However, the containers as passive entities are taken into account implicitly through the interdiction of certain arcs which are not allowed to be passed by a container. For instance, a vehicle which visits a receiver during the second time window is not allowed to pass the arc to an IE or OF terminal node since these container movements are forbidden by the containers' flows described in Chapter 5. The consideration of only one transportation level in heuristics is common practice for similar hinterland container transportation problems and has proven to perform well with respect to effectiveness and efficiency. In the literature, these problems are mainly defined as "full truckload problems" since this problem type concerns vehicle routing problems with full truckload restrictions. In the following, literature on full truckload routing is discussed. Afterwards, the algorithms for solving the MC-CTTP and MC-CTTP-CS, including some basic configurations that are required for the solution representation, are given¹.

6.1.1 Full Truckload Problems

Truck transportation problems have become a research field with growing attention in the last few years. Imai et al (2007) address a full truckload problem and define it as a vehicle routing problem with full containers (VRPFC). By using a subgradient heuristic based on a Lagrangian relaxation, they identify near optimum solutions. An integer programming model for a real-world case of an Italian container trucking company is given by Coslovich et al (2006). The authors simplify the solution process regarding time efficiency by decomposing the problem into three subproblems according to the different types of costs resulting in the defined problem. A full truckload pickup and delivery-problem with time windows (FTPDPTW) is defined by Caris and Janssens (2009) for the pre- and end-haulage of intermodal transport chains. As a solution approach, the authors use a simple local search heuristic to improve an initial solution. Based on this contribution, Caris and Janssens (2010) extend the solution approach by developing a deterministic annealing problem for the given problem. Jula et al (2005) propose an am-TSPTW to model the container movement by trucks in the hinterland of seaports. The authors implement a two-phase exact algorithm based on dynamic programming, as well as a modified genetic algorithm, to solve the problem. The CTTP introduced by Zhang et al (2009) serves as the basic setting for the basic and comprehensive scenarios. Characterized by multiple depots,

¹This section is based on Sterzik and Kopfer (2012b).

two types of customers, and one terminal, the authors model the problem as a m-TSPTW. A cluster method and a reactive tabu search (RTS) algorithm are developed to solve the problem. Zhang et al (2010) extended the setting of Zhang et al (2009) by considering more than one terminal. In the following, this problem is defined as the inland container transportation problem (ICT). Inspired by Wang and Regan (2002) the authors use a window-partition based method (WPB method) as a solution approach. The general idea of the WPB method is to find a feasible solution by using an over-constrained mathematical model. The quality of the obtained solutions is then tested by a second model which identifies a lower bound. Based on a number of randomly generated instances, the computational experiments show that the approach is able to generate high-quality solutions within reasonable computation times and that its total performance is better than the performance of the RTS algorithm by Zhang et al (2009). Due to the similarity of the comprehensive scenarios and the ICT, the WPB method of Zhang et al (2010) is compared with a modified version of the tabu search heuristic for the MC-CTTP and MC-CTTP-CS in Section 6.2.2.

6.1.2 Basic Configurations

The general outline of the solution methodology can be described as follows. For constructing an initial solution for the MC-CTTP, a modified Clark & Wright-savings algorithm (Clarke and Wright, 1964) is used. Subsequently, the tabu search heuristic is applied to generate a final solution. For the solution process, arcs $(i, j) : i, j \in V$ where $d_i^{cus} \neq d_j^{cus}$ are penalized, so that $t_{ij} = M$. Due to the fact that the solution space of the MC-CTTP-CS comprises all feasible solutions of the MC-CTTP for the same data set, the final solution of the MC-CTTP is used as the initial solution for the MC-CTTP-CS. Obviously, the distance matrix for the cooperative case has to be adapted in order to permit the exchange of empty containers among different trucking companies. The initial solution is improved by the proposed tabu search heuristic which is also applied for the MC-CTTP.

Due to a better comprehension of the heuristics, container movements, which comprise one or two locations as seen in Figure 6.1 are primarily mentioned. Two basic types are distinguished: while the first type describes the full container transportation requests which always comprise an origin *and* a destination location, the second basic transportation type describes container movements which require the allocation of empty containers and, thus, are only defined through one location (origin *or* destination location). This is an important difference

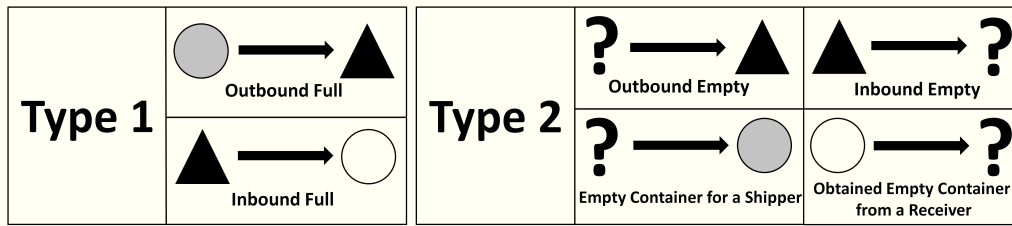


Figure 6.1: *Classified Container Movements*

since the local-search operators, as well as operators of the construction heuristic, deal with container movements being part of routes. For both scenarios the distance matrices are adapted so that container movements that cannot succeed each other are excluded. For example, an operating vehicle which just served an IF transportation request is not permitted to serve an OF or OE request since it does not carry an empty container. In consideration of the container movements, and according to the travel distances between requests, as well as the underlying time windows, a distance matrix for each container movement $r \in R$ is defined. Certainly, through the additional consideration of external containers for a particular company, these matrices are mainly bigger for the MC-CTTP-CS. By adapting the distance matrices, the solution space can be enormously reduced and, in consequence, so can the computational time.

In what follows, a modification of the Clark & Wright-savings algorithm used for constructing an initial solution is presented. Subsequently, a detailed description of the tabu search heuristic for the MC-CTTP and MC-CTTP-CS is given.

6.1.3 Modified Clark & Wright-Savings Algorithm

The savings algorithm of Clarke and Wright (1964) is perhaps the most widely known heuristic for the VRP. The technique for constructing VRP solutions is to merge existing routes using a savings criterion. Thereby, every node i is primarily served through a pendulum tour from the depot node 0. If merging two routes $(0, i, 0)$ and $(0, j, 0)$ can feasibly be done, a distance savings $sav_{ij} = c_{i0} + c_{0j} - c_{ij}$ is generated and noticed on a savings list. From the top of this list, it needs to be determined gradually whether there exist two routes: one containing arc $(0, j, \dots, 0)$ and the other route containing $(0, \dots, i, 0)$ which can feasibly be merged. If so, these routes have to be changed by deleting arcs $(0, j)$ as well as $(i, 0)$ and introducing arc (i, j) . Further information can be found in Toth and Vigo (2002).

To adapt this algorithm for the MC-CTTP, multiple depots and terminals,

different customer types, as well as time constraints, are additionally considered. In detail, each container movement is initially assigned to the corresponding depot of its corresponding trucking company d_r^{req} . Thereby, every container movement $r \in R$ is served by exactly one vehicle in a pendulum tour. Thus, considering container movement type 2, empty containers originate from the depot or have to be delivered to the depot. Subsequently, the construction of routes is handled as in the usual Clark & Wright-savings algorithm. The outline of the modified savings heuristic can be seen in Algorithm 1.

Algorithm 1 Savings Algorithm

- 1: Request $r \in R$ is assigned to the corresponding depot of the serving trucking company d_r^{req} ;
 - 2: Each request is served by exactly one truck;
 - 3: Savings for all container movements of the same depot are computed as follows: $sav_{ij} = t_{i(v+d+d_i^{cus})} + t_{(v+d_j^{cus})j} - t_{ij} \quad \forall i, j \in V_C \cup V_T$;
 - 4: Route pairs for each depot are sorted in descending order of the savings;
 - 5: From the top of the sorted list the given routes are merged into one if the established route is feasible and if this can be done without deleting a previously defined connection between two requests.
-

6.1.4 Tabu Search Heuristic

Tabu search is a local-search metaheuristic that is based on an iterative process for finding the best solution in the neighbourhood $N(s)$ of a given solution s . By using a memory structure, cycling, i.e. revisiting a solution again and again in a loop of the search trajectory, can be banned from the solution space for Θ iterations. New, inferior solutions are only chosen to avoid already investigated solutions. This ensures the exploration of new regions of a problem's solution space and, accordingly, being stuck at local minima is avoided. Solution or attributes can be set as "tabu" or forbidden. The tabu status can be abolished if a certain aspiration criteria is met, for instance, if a solution is determined that is superior to all solutions that have been found so far. Moreover, for many problems, it is profitable to use the memory structure of the algorithm to intensify or diversify the search process. On the one hand, intensification strategies concentrate the search process on regions which have been proven to include many high-quality solutions. On the other hand, diversification strategies tend to spread the exploration effort over different regions of feasible solutions. The main advantages of the tabu search heuristic lies in its simplicity. It can be flexibly adapted for several NP-hard problems and it is able to generate good solutions in a relatively

short time. The roots of the tabu search date from the 1970's (Aarts and Lenstra, 2003) and was first presented by Glover (1986). Further detailed information can be found in Glover et al (1989), Glover (1990), and Gendreau (2003).

6.1.4.1 Framework

The tabu search heuristic for the comprehensive scenarios comprises an initial phase and a main phase. In the initial phase, the algorithm seeks to reduce the number of required vehicles at depot $i \in V_{D^s}$ to the defined amount m_i . The aim is to diminish the solution space to a great extent. An adequate value for m_i that is not too large or too small highly depends on the investigated hinterland region and the considered time windows at the customer and terminal locations. The risk of excluding qualitatively good solutions if m_i is defined too small for a particular depot needs to be minimized by applying numerical experiments for a data set type. Every additional vehicle which exceeds the truck limit m_i is penalized with the additional costs $cost_{pen}$. Thereby, $p(s)$ determines the summation of all penalty costs which have to be added to the objective value $f(s)$. The initial phase ends if $p(s) = 0$. During the main phase enduring $iter_1^{max}$ iterations the excess of the defined truck limit is forbidden. While the first phase is mainly characterized by the *Operator Selection* component which rapidly seeks to find a solution that does not include penalty costs, the second phase specially emphasizes in the *Intensification Strategy*, as can be seen in the outline of Algorithm 2. Further general criteria that affect the search process of the tabu search heuristic are determined by the calculation of the objective function, the consideration of diversification elements, as well as the tabu tenure and aspiration criteria.

Algorithm 2 Framework of the Tabu Search Heuristic

- 1: $\Theta \leftarrow$ number of tabu iterations;
 - 2: Solution of *Savings-Algorithm* is used as s ;
 - 3: **while** $p(s) > 0$ **do**
 - 4: *Operator Selection* is applied;
 - 5: **end while**
 - 6: **while** $iter_1 < iter_1^{max}$ **do**
 - 7: *Operator Selection* is applied;
 - 8: *Intensification Strategy* is applied;
 - 9: $iter_1 = iter_1 + 1$;
 - 10: **end while**
-

6.1.4.2 Objective Function

The calculation of the values of the objective function during the solution procedure is a problem of its own. As mentioned before, the objective function seeks to minimize the trucks' total operating time. The degree of freedom for determining the vehicles' arrival times for a given route is relatively large since it depends on the number and character of container movement types in a vehicle's route, the travel times between these locations, and mainly on the time windows' amplitude at the corresponding customer and terminal vertices. A heuristic approach is proposed to reduce waiting times and thus to estimate the best start and end times of vehicle $k \in K$. First of all, it is checked if a route is feasible. Thereby, a surplus of waiting time is allowed since T_{ik} should always be defined as the minimal arrival time, i.e. a vehicle that traverses arc (i, j) arrives at node j at time b_j where applicable. Otherwise T_{jk} is defined by $T_{ik} + s_i + t_{ij}$ if $b_j < T_{ik} + s_i + t_{ij} \leq e_j$. Assuming that the route of vehicle k is feasible, unnecessary waiting times should be reduced. The determined arrival time at the last customer on the route of vehicle k is used to recursively improve the arrival times of the prior customers. Since multiple deployments of trucks are not permitted, vehicle $k \in K$ is used as a synonym for the route of k in the following. If k_l determines the node that marks the last position of k , $T_{k_{l-1}k}$ is then defined as $T_{k_lk} - s_{k_{l-1}} - t_{k_{l-1}k_l}$ or as $e_{k_{l-1}}$ if $T_{k_lk} - s_{k_{l-1}} - t_{k_{l-1}k_l} \geq e_{k_{l-1}}$. The heuristic then uses the determined arrival time successively to calculate the remaining arrival times until $T_{(v+d_k^{veh})k}$ is defined. The number of required routes is also minimized by introducing a further penalty parameter $cost_{rout}$ that is added to the travel time of every required route during the search process. Necessarily, these costs are deducted from the best solution s^{best} that is determined when the algorithm terminates.

6.1.4.3 Container Movement Selection

The container movements which seem to be assigned to an inappropriate position within a route, or to an unsuitable route of the solution, should be identified and be replaced through other movements or inserted into other routes, respectively. Therefore, a remove saving $saving_r = f(s) - f_{-r}(s)$ for each movement $r \in R$ located in the current solution $s \in S$ is defined. Besides the usual cost function $f(s)$, the term $f_{-r}(s)$ defines the costs of s without movement r . To obtain better objective values, the container movements with the highest savings should be selected for the local search operators. The emerging risk of cycle situations where the same movements are always chosen, for instance, due to the fact that

movements are located at the border of the observed hinterland, should be avoided by including a certain degree of randomization. Thereby, the requests with higher savings are not always chosen, but get a higher probability value for the selection process. The container movement selection's execution sequence can be seen in the pseudocode of Algorithm 3.

Algorithm 3 Container Movement Selection

```

1:  $saving_r = f(s) - f_{-r}(s)$ ;
2: Container movements are sorted in list  $L$  in descending order of the savings;
3:  $saving_{sum} \leftarrow 0$ ;
4:  $saving_{total} \leftarrow \sum_{r \in R} saving_r$ ;
5:  $\Xi \leftarrow$  random number in the interval  $[0, 1]$ ;
6: for  $x \in L$  do
7:   if  $\Xi < saving_{sum} + saving_x / saving_{total}$  then
8:      $r^* \leftarrow x$ ;
9:     Container Movement  $x$  is removed from  $s$ ;
10:    Algorithm terminates;
11:   end if
12:    $saving_{sum} \leftarrow saving_{sum} + saving_x / saving_{total}$ 
13: end for

```

6.1.4.4 Operator Selection

The neighborhood of a current solution s is composed of all solutions that can be reached by applying one of the local-search operators. Three types of moves are used in the given tabu search approach:

- The *insertion operator* removes a randomly selected container movement r^* from its route and inserts it in another route or at another place in its current route. The operator is illustrated by Figure 6.2, where one circle illustrates a container movement.
- The *cross operator* swaps a randomly selected container movement r^* from its route and exchanges it with container movement $r \in R \setminus \{r^*\}$ (see Figure 6.3).
- The *route reduction operator* tries to reduce the number of routes by inserting the elements of each short route into another route. Thereby, a short route is defined as a route which comprises less than y container movements with 2 and 3 as reasonable values for y (see Figure 6.4). Obviously, the operator is very similar to the first operator since for each element of a short route the *insertion operator* is applied.



Figure 6.2: *Insertion Operator*



Figure 6.3: *Cross Operator*

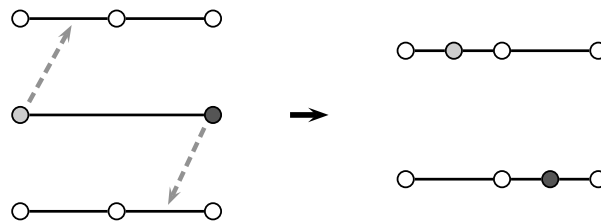


Figure 6.4: *Route Reduction Operator (with $y = 3$)*

Algorithm 4 Operator Selection

- 1: $\Xi \leftarrow$ random number in the interval $[0, 1]$;
 - 2: $\alpha \leftarrow$ probability value;
 - 3: **if** $\Xi < \alpha$ **then**
 - 4: *Route Reduction Operator* is applied;
 - 5: $s \leftarrow s^*$;
 - 6: Tabu list T is updated;
 - 7: **end if**
 - 8: *Container Movement Selection* is applied;
 - 9: r^* is used for *Cross Operator*;
 - 10: *Cross Operator* is applied;
 - 11: $s \leftarrow s^*$;
 - 12: T is updated;
 - 13: *Container Movement Selection* is applied;
 - 14: r^* is used for *Cross Operator*;
 - 15: *Insertion Operator* is applied;
 - 16: $s \leftarrow s^*$;
 - 17: T, Ξ are updated.
-

As can be seen in the pseudocode of Algorithm 4, the *insertion* and *cross operator* are applied in each iteration while the usage of a *route reduction operator* depends on the probability value α . Due to the fact that applying this operator takes a lot of computational time, one has to find an adequate value for y and α which do not impair the algorithm's efficiency. After applying an operator, the best non-tabu solution $s^* \in N(s)$ becomes the new current solution s . The tabu list T has to be updated.

6.1.4.5 Intensification and Diversification Strategies

The *usual* search process can be interrupted for an *intensification strategy* that is defined in Algorithm 5. The frequency of interruption depends on the probability value β and the quality of s , which is related to $(1 + \gamma) * f(s^{best})$ whereas s^{best} determines the best known solution so far, and γ is a constant parameter in the interval $[0, 1]$. Thereby, s is modified $|R|$ times where $|R|$ defines the cardinality of R . By using each $r \in R$ once for the *cross and insertion operator*, respectively, both solutions are compared and the best solution according to the objective value is chosen. Based on this modified solution, the *operator selection* algorithm is applied for $iter_2^{max}$ iterations. For an efficient tabu search algorithm, this iteration limit value should be defined well since the execution of the *operator selection* algorithm is applied for $|R| * iter_2^{max}$ iterations. The *intensification strategy* is an important component of the tabu search heuristic and is, therefore, defined as an autonomous algorithm within this framework. Hence, the tabu list is restarted each time the *intensification strategy* is applied. Furthermore, Θ can be adapted according to the modified framework within this component.

To diversify the search, a mechanism is implemented which penalizes any neighborhood solution $s^N \in N(s)$ by a factor that is proportional to the additional frequency of its attributes and a scaling factor. In detail, q_{rk} describes the number of times container movement r has been added to route k during the search process. The intensity of the diversification process can be adjusted by parameter λ . Thus, unless $f(s^N) < f(s^{best})$, penalty term $\lambda * q_{rk}$ is added to the total solution costs $f(s^N)$. The illustrated diversification strategy is a modification of the mechanism used in Taillard (1993).

6.1.4.6 Tabu Tenure and Aspiration Criteria

The tabu list T is constituted as a deterministic list which records each container movement r that is removed from its routes k . After the removal r is not allowed

Algorithm 5 Intensification Strategy

```

1:  $\beta \leftarrow$  probability value;
2:  $\gamma \leftarrow$  number in the interval  $[0, 1]$ ;
3: if  $(\Xi < \beta) \wedge (f(s) < (1 + \gamma) * f(s^{best}))$  then
4:    $T = \{\}$ ;
5:    $\Theta$  is updated;
6:   for  $r \in R$  do
7:      $r$  is used for Cross Operator and leads to solution  $s_{CO}^*$ ;
8:      $r$  is used for Insertion Operator and leads to solution  $s_{IO}^*$ ;
9:     if  $f(s_{CO}^*) < f(s_{IO}^*)$  then
10:       $s \leftarrow s_{CO}^*$ ;
11:     else
12:       $s \leftarrow s_{IO}^*$ ;
13:     end if
14:     while  $iter_2 < iter_2^{max}$  do
15:       Operator Selection is applied;
16:        $iter_2 = iter_2 + 1$ ;
17:     end while
18:   end for
19:    $\Theta$  is updated;
20: end if

```

to be served by vehicle k for Θ iterations. An exception of applying the tabu status can be marked for the *route reduction operator*. Hereby, any chance to always get the best neighborhood solution should be grabbed even if r is tabu for k . The risk of getting caught in a cycle is not given since the *route reduction operator* is not applied in every iteration and, moreover, the other two operators would be applied before returning to this move type. However, in general a tabu status is overruled if the algorithm finds a solution which is better than any solution known so far.

6.2 Performance of the Tabu Search Heuristic

The evaluation of any heuristic or metaheuristic method ² involves the comparison of a number of criteria that are related to various aspects of the algorithm's performance. As Cordeau et al (2002b) state, most heuristics are usually measured against two criteria: *accuracy* and *speed*. While accuracy measures the relative gap between a heuristic's solution value and the best known solution value, the speed refers to the computation time until an adequate solution is determined.

²In the following, metaheuristics are attributed to the research field of heuristic methods.

By means of these two criteria, the tabu search heuristic is compared to the optimal solutions that were determined in Chapter 5. Subsequently, it is tested how the tabu search heuristic performs if it is applied on large-sized instances. Therefore, the heuristic is modified in order to be able to generate solutions for the ICT of Zhang et al (2010), which is similar to the comprehensive scenarios³.

6.2.1 Small-Sized Test Instances

Measuring the relative distance of a solution to the known optimal solution is a standard measure of quality (Braysy and Gendreau, 2005). By means of the integrated routing models defined in Section 5.3.2, the optimal solutions for small-sized test instances can be generated. Therefore, the proposed tabu search heuristic is compared to the computational results of Section 5.4.

The algorithms have been applied in Java 6 on the same PC as in Chapter 5⁴. After several experiments with the tabu search heuristic to characterize the tradeoff between computation time and solution quality, the following parameters were used: $(iter_1^{max}, iter_2^{max}, y, \alpha, \beta, \gamma, \lambda, \Theta) = (1000, 10, 2, 0.1, 0.12, 0.008, 1.5, 6)$.

The generated results that are achieved by applying the algorithms to the MC-CTTP and the MC-CTTP-CS are more than satisfying. While the heuristic yields the optimal solution in every trial for the MC-CTTP, the optimal solutions for the MC-CTTP-CS were achieved after 6 runs at the most.⁵ However, Braysy and Gendreau (2005) state that an algorithm which is non-deterministic and, thus, includes random components, should be able to produce good solutions in every trial for a given instance. Using only the best achieved results for a comparison can create a false picture of a heuristic's real performance. The numerous experiments for the instances of the MC-CTTP-CS show that the generated results deviate 2.4% at most from the optimal solutions. Hence, it can be concluded that the tabu search heuristic delivers very good results for the comprehensive scenarios according to the criteria of *accuracy*.

Testing the criteria of *speed* leads to the following procedure. For each test instance the tabu search heuristic is applied five times. In every run the heuristic is stopped if the optimal solution value s^{opt} is found (MC-CTTP) or if the best determined solution value s^{best} during a single run is nearby the optimal

³This section is based on Sterzik and Kopfer (2012b).

⁴Intel® Core i7, 3.2 GHz PC with 12GB system memory.

⁵Extending the maximum number of iterations $iter_1^{max}$ of the tabu search heuristic does not significantly improve the best determined solution values.

Table 6.1: Computation Time (in seconds) - Comprehensive Scenarios

Inst.	MC-CTTP		MC-CTTP-CS	
	CPLEX ¹	TSH ¹	CPLEX ¹	TSH ²
1	241.45	0.33	3116.88	0.93
2	263.83	0.31	1494.37	0.55
3	285.28	0.42	93.36	0.81
4	492.28	0.42	2310.03	0.50
5	61.59	0.28	289.23	0.30
6	30.03	0.26	365.86	1.52
7	123.12	0.37	1203.06	0.20
8	149.56	0.41	440.92	1.39
9	371.53	0.39	335.53	1.44
10	40.27	0.24	2502.28	0.17
MV	205.89	0.34	1215.15	0.78

TSH - Tabu Search Heuristic; MV - Mean Value

¹ - CPLEX/ The tabu search heuristic is stopped if the optimal solution s^{opt} is determined. The computation time of the TSH represents the mean value of five trials.

² - The TSH is stopped if the solution value is nearby s^{opt} ($s^{best} \leq 1.025 * s^{opt}$). The computation time represents the mean value of five trials.

solution value (MC-CTTP-CS). “Nearby” is defined by the following formula: $s^{best} \leq 1.025 * s^{opt}$. Table 6.1 illustrates the mean values of these trials. Unsurprisingly, the heuristic requires much less time to solve the instances than the exact approach. As can be seen, the CPU times of the tabu search heuristic are stable and require around one second to identify a high quality solution, regardless of which scenario is considered. In sum, the algorithm performs very well with respect to effectiveness and efficiency if small test instances have to be solved.

6.2.2 Realistic-Sized Test Instances

The analysis of the comprehensive scenarios discussed in this thesis is new to the literature. Thus, there exist no large-sized benchmark problems for these problem types. Instead, the performance of the tabu search heuristic needs to be compared with algorithms for similar problem types.

As stated, the CTTTP by Zhang et al (2009) serves as the basic setting for the MC-CTTP and the MC-CTTP-CS. The authors model the problem as a m-TSPTW and develop a RTS algorithm to solve the problem. Zhang et al (2010) extend the CTTTP slightly and define the emerging problem as ICT (see Section

6.1.1). For large-sized instances they show that their WPB solution approach performs better than the RTS algorithm.

Due to the similarity of the comprehensive scenarios and the ICT, the WPB method of Zhang et al (2010) is compared with a modified version of the tabu search heuristic for the MC-CTTP and MC-CTTP-CS. The characteristics of the ICT and, especially, the factors which distinguish the ICT from the comprehensive scenarios are illustrated in the following section. In Section 6.2.2.2 the heuristic solution approach is modified slightly in order to be able to solve the ICT. Finally, the algorithm's performance for realistic-sized instances is tested in Section 6.2.2.3.

6.2.2.1 Inland Container Transportation Problem (ICT)

The ICT refers to the same hinterland region as the MC-CTTP. In other words, in a local region a trucking company has to move full and empty containers between different locations. Thereby, the containers' flows arise due to IF, OF, IE and OE transportation requests. The main differences that distinguishes the ICT from the MC-CTTP are given through the following factors: *multiple terminals, number of operating trucking companies, restricted number of operating vehicles, one customer time window, different transfer and service times*, as well as the *objective function*.

The hinterland region in the ICT is characterized by several depots, several customers, and, different from the MC-CTTP, a number of terminals. All depots belong to only one operating trucking company and at each depot a specified number of vehicles is parked. A vehicle has to start its route at its corresponding initial depot and ends the route at the depot that is chosen by minimizing a vehicle's total operating time. A further difference is given by the customer time windows. Contrary to the consideration of two time windows at a customer location, the ICT only includes one time window at each customer location. In this case, an operating vehicle which moves a container to a customer location has to wait at the location until the container is dispatched. Skipping the loading/unloading time of the container is not permitted. Consequently, the service time is not only comprised of the container's picking up/dropping off operation as in the MC-CTTP. Now, the service time s_i depends on the container type and on the pickup/delivery location. As shown in Table 6.2, the service consists of several activities. These activities are the picking up/dropping off of a container and the loading/unloading process performed by a shipper or receiver. For instance,

Table 6.2: Definition of Service Time

Container Type	Pickup Node	Delivery Node
Outbound Full (OF)	$l + p_i + l$	l
Outbound Empty (OE)	l	l
Inbound Full (IF)	l	$l + p_i + l$
Inbound Empty (IE)	l	l

l =time for the picking up/dropping off operation of a container

p_i =time for the loading/unloading process of a container at node i

a truck has to pick up an IE container at the terminal and drop the container off at the delivery location. Both activities take l minutes. Regarding an OF or IF transportation request, p_i minutes have to be considered for the loading or unloading process at the shipper or receiver location i .

A trivial problem occurs if nodes i and j of a traversed arc (i, j) mark the same customer location and if, additionally, node i determines the delivery location of an IF transportation request and node j declares the pickup location of an OF request. In this case, the IF container is dropped off at its delivery location and it needs to wait until the unloading process is finished. Since the obtained empty container can immediately be used for the filling process of the OF transportation request at this location, the picking up and dropping off of an empty container is redundant and is thus omitted.

A further difference between the MC-CTTP and the ICT lays in the calculation of transfer time. Usually for each two distinct locations t_{ij} represents the driving time from location i to location j . However, in some cases an arc $(i, j) \in A$ also includes a detour to the depot and the time for picking up or dropping off of an empty container. These cases can be obtained if a vehicle has to serve two inbound or two outbound transportation requests in succession, as can be seen in Table 6.3. In other words, a vehicle which is disposed for an IF/IE request after it just served an IF/IE request, needs to drive to the nearest depot to drop off the transported empty container first. Afterwards it can serve the assigned first location of the second transportation request. Additionally, a vehicle which shall handle two outbound (OE/OF) requests in sequence needs to pick up an empty container at the depot with the minimum total driving distance before it can attend to the second transportation request. This behaviour is forbidden in the MC-CTTP and needs the deployment of two different routes. Thus, if a vehicle is pleased to serve two IF/IE transportation requests in succession, it has to finish its route at the depot and a further vehicle needs to serve the second

Table 6.3: Special Cases for Transfer Time t_{ij}

$j \in V_{TIF} \cup V_{TIE}$	
$i \in V_R \cup V_{TIE}$	$\min_{d \in V_D} (t(i, d) + t(d, j)) + l$
$j \in V_S \cup V_{TOE}$	
$i \in V_{TOF} \cup V_{TOE}$	$\min_{d \in V_D} (t(i, d) + t(d, j)) + l$

transportation request. Consequently, while successively serving two inbound or two outbound transportation requests requires only one vehicle in the ICT, two vehicles are required in the MC-CTTP.

As in the comprehensive scenarios, a large number of containers can be stacked at the depots. Moreover, FEU are assumed so that a vehicle can only move one container at a time. The objective in the ICT is to minimize the vehicles' total operating time and, thus, excludes the minimization of the number of operating vehicles as in the comprehensive scenarios.

6.2.2.2 Adaptation of the Tabu Search Heuristic

Due to the differences of the ICT compared with the comprehensive scenarios, the tabu search heuristic needs to be adapted to cope with the already stated factors: *multiple terminals, one time window at each customer location, different transfer and service times, number of operating trucking companies, restricted number of operating vehicles*, as well as the *objective function*.

The consideration of several terminals in the ICT can be handled easily by the tabu search heuristic since the terminal nodes are always duplicated according to the number of transportation requests. Therefore, they can be attributed with any coordinates. Reducing the time windows at the customer locations goes along with the reduction of customer nodes for a data set. Hence, instead of two nodes representing the same customer location, only one customer node needs to be considered now. Accordingly, instead of considering the loading/unloading time of a container at the customer location in between the two time windows as in the comprehensive scenarios, this time needs to be added to the service time as already shown in Table 6.2. The allowance of a detour to the depot within a vehicle's route needs a modification of the distance matrix according to Table 6.3.

So far, all stated changes are extraneous for the construction algorithm and the tabu search heuristic since they only affect the framework of the algorithms. The only factors that influence the algorithms are due to the *number of operating trucking companies* and the *restricted number of operating vehicles*. Since a container movement can be served from any depot of the operating trucking company in the ICT, a mechanism for the construction heuristic has to be defined to allocate the container movements initially to a certain depot. Afterwards, the proposed savings-algorithm can then proceed as already proposed. The utilized mechanism for the ICT refers to Tillman (1969) who introduced a simple savings algorithm for the multi depot vehicle routing problem (MDVRP), where a customer is allocated to its nearest depot. Accordingly, for the ICT a container movement $r \in R$ is disposed to its nearest depot before the routes for each depot are constructed. For the construction heuristic it is not allowed that a vehicle's start depot is different from its end depot in order to maintain the simplicity of the construction heuristic.

During the execution of the tabu search heuristic, the container movements are allowed to be disposed to every depot. Certainly, a vehicle now ends its route at the depot which minimizes the total operating time. Since the savings algorithm can lead to an initial solution that comprises more than the available vehicles situated at a depot, every route which exceeds the vehicle limit m_i of depot i is penalized during the search process of the tabu search heuristic. Similar to the proposed algorithm for the comprehensive scenarios where m_i is defined as "an adequate value that is not too large or too small" in order to diminish the solution space (see Section 6.1.4.1), parameter m_i now gets a certain value according to the available vehicles at each depot. Subsequently, a route that exceeds the vehicle limit at a depot is penalized with the additional costs $cost_{pen}$. Parameter $p(s)$ then determines the summation of all penalty costs which have to be added to the objective value $f(s)$ in order to reach a feasible solution. If the algorithm firstly detects a solution where $p(s) = 0$, the excess of the defined vehicle limits are, thereafter, forbidden. For the remaining iterations, only feasible solutions are allowed. Finally, the objective of the tabu search heuristic for the ICT is to minimize the vehicles' total operating time. As opposed to the comprehensive scenarios, the minimization of the number of operating vehicles is not considered in this problem type. Hence, penalty parameter $cost_{rout}$ that is added to the travel time of every required route gets value 0.

6.2.2.3 Computational Experiments

After implementing the proposed modifications, the ICT can be solved by the algorithms. In the following, the performance of the modified tabu search heuristic is tested by means of the data sets of Zhang et al (2010). The authors defined 20 data sets for the ICT which include five depots, three terminals, and 75 transportation requests. Usually, ten trucks per depot are considered which have to serve the customers within a time horizon of one day. The proposed algorithms have been implemented in Java 6.

The same parameters as in Section 6.2.1 are used for the main component of the tabu search heuristic. Therefore, parameter y defining the routes that have to be examined by the *route reduction operator* takes value 2. Thus, if the operator is applied, each route comprising one transportation request should be integrated into different routes. According to the heuristic's efficiency, this value should not be raised since most of the generated routes comprise two requests (see Figure 6.6). Defining, for instance, $y = 3$ causes the consideration of the majority of routes for this operator. The computational experiments indicate that the solution quality cannot be increased by defining $y > 2$. However, the computation time increases remarkably if the value for α stays the same.

Taking a closer look at the resulting routes of test instance 13, Figure 6.5 and Figure 6.6 show four typical truck paths for the illustrated eight requests. Focusing on Route 1, one can see that a truck mostly serves an inbound request after an outbound request. In detail, the truck starts its path from the depot in the south to the shipper in the northeast to handle the OF container. In order to save time, it is likely to serve a disposable IE transportation request from the same terminal if the succeeding time windows are consistent. In this case, the IE container can be used to handle the succeeding OF request at the shipper location in the northwest. Finally, the truck ends its route at the nearest depot which is, in this case, also the truck's starting depot. Additionally, Routes 2-4 show another typical characteristic of the ICT concerning size. While Route 3 solely includes Request 6, Routes 2 and 4 comprise at the most two transportation requests. However, one has always to bear in mind that an IF or OF transportation request is defined through two locations.

Since some random factors influence the heuristic's search procedure, the fluctuation of the generated solutions is assessed by applying the algorithm at least ten times per test instance. The deviation of the obtained solutions lay in a range of $< 3\%$ compared to the best found solution of the underlying test instance and,

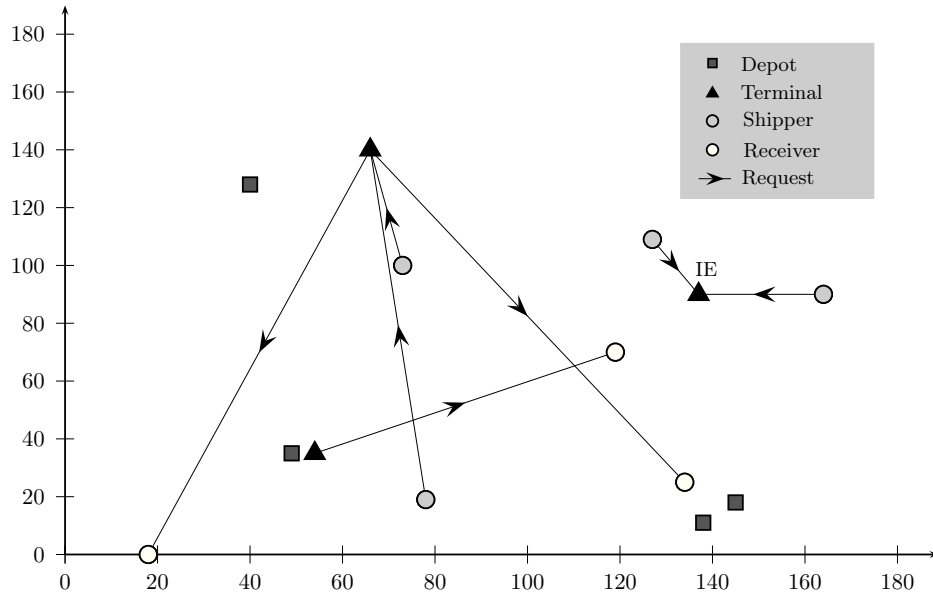


Figure 6.5: Given Locations and Transportation Requests (Test Instance 13)

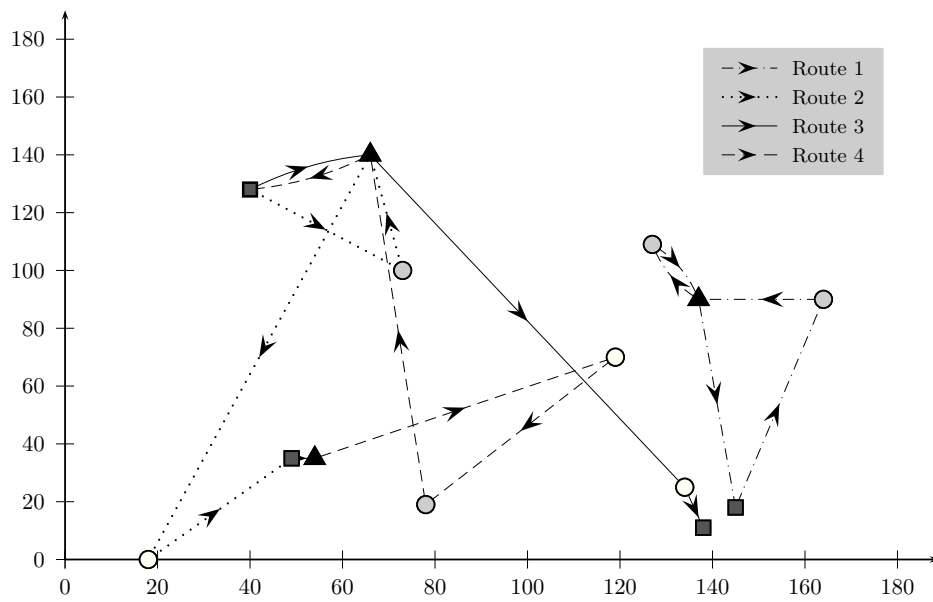


Figure 6.6: Generated Routes (Test Instance 13)

Table 6.4: Performance of the Tabu Search Heuristic - ICT

Inst.	TSH		Zhang et al (2010)		Difference	
	Vh.	TT	Vh.	TT	Vh.	TT
4	46	14995	46	15042	0	-47
5	46	15790	47	15803	-1	-13
6	53	14788	53	14829	0	-41
7	50	15772	51	15857	-1	-87
8	40	12791	41	12863	-1	-72
9	47	17752	49	17946	-2	-194
10	45	14686	45	14688	0	-2
11	49	15898	50	16082	-1	-184
12	42	12766	43	12892	-1	-126
13	52	17671	54	17829	-2	-158
14	40	14313	43	14495	-3	-182
15	42	15458	45	15870	-3	-412
16	42	14584	44	14905	-2	-321
17	44	15976	44	15960	0	16
18	40	13836	40	13887	0	-51
19	37	15260	39	15334	-2	-74
20	34	13464	34	13476	0	-12
21	37	14337	39	14485	-2	-148
22	40	16003	41	16110	-1	-107
23	35	12024	35	12032	0	-8
Total	861	298164	883	300385	-22	-2223

thus, revealed the algorithm’s stability. The generated results are compared with the best known solutions generated by the WPB method of Zhang et al (2010). Table 6.4 lists the best known solutions due to these works. As can be seen, the tabu search heuristic works very well for the ICT. Except for instance 17, it outperforms the WPB method at all times. Even for this exceptional case, it finds a solution value which is quite near to the best-known solution ($\sim 0.1\%$). Although the objective concerns the minimization of the total operating time, the number of used trucks are also considered. For some instances, a high potential for reducing fixed costs is observed (see e.g. instance number 14 and 15).

A comparison of the computational time needed by the addressed solution methods is difficult to realize objectively since different computers and programming languages have been used. Nevertheless, Figure 6.7 indicates that the proposed tabu search heuristic also outperforms the WPB method of Zhang et al (2010) in terms of efficiency. The relatively long computational times of instances 6 and 13 derive from a solution space which is characterized by many “good” solutions situated close to the best found solution. In these cases, the *intensification strat-*

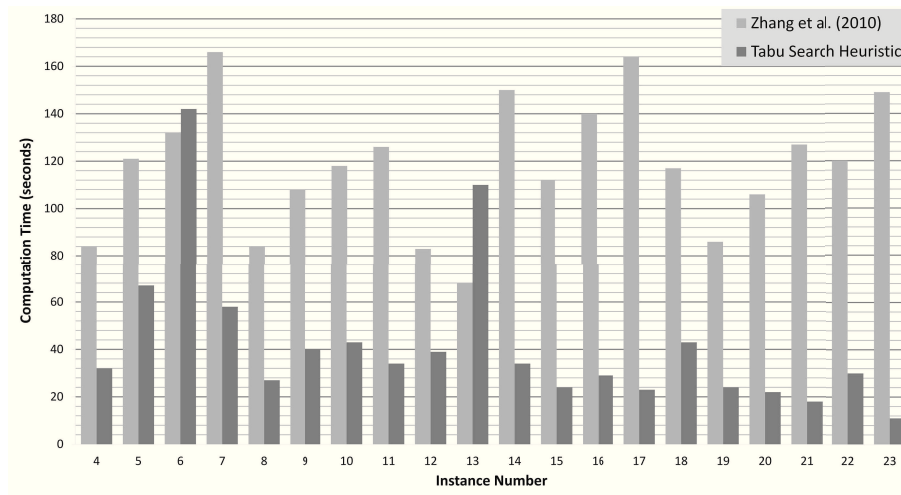


Figure 6.7: *Computation Time*

egy is applied very often and leads to increasing computation times. However, regarding the other instances, it has been demonstrated that the tabu search heuristic performs very well.

6.3 Benefit of Container Sharing Measured in Realistic-Sized Test Instances

The previous section demonstrated that the tabu search heuristic is able to determine high-quality solutions for small and realistic-sized instances. In order to measure the benefit of container sharing for large-sized instances, the proposed algorithms are applied once again for the MC-CTTP and MC-CTTP-CS. In the following Section 6.3.1, the characteristics of the underlying instances which are based on the ICT test instances, are illustrated. Subsequently, first computational results are given. Since modifying certain characteristics of test instances can dramatically influence computational results of vehicle routing problems, it is revealed in Section 6.3.2 how the service time, the length of time windows, and the number of operating trucking companies change the benefits of a container sharing coalition⁶.

6.3.1 Adaption of ICT Test Instances

Based on the described data sets of Zhang et al (2010) for the ICT, ten test instances are generated for the comprehensive scenarios. Thereby, the data is

⁶This section is based on Sterzik et al (2012).

modified slightly in order to cope with the characteristics of the MC-CTTP and the MC-CTTP-CS. The consideration of two time windows at a customer location is realized by duplicating the customer nodes. As opposed to Chapters 4 and 5, the time windows of the shipper and receiver customers are not idealized. Thus, the computational results give a realistic indication to what extent trucking companies can profit by exchanging their empty containers with cooperating trucking companies.

Initially, a customer's first and second time window take the values of the given time window for the same location taken from the ICT data sets. Afterwards, time windows of nodes $i \in V_{S^i}$ and $j \in V_{R^o}$ are adapted from the corresponding nodes $(i+d) \in V_{S^o}$ and $(j-d) \in V_{R^i}$. Thereby, the interval between, for example, $e_i \forall i \in V_{S^i}$ and $b_{(i+d)} \forall i \in V_{S^i}$ depends on a container's loading time p_i . The length of time window $[b_i/e_i] \forall i \in V_{S^i}$ is defined according to the time window length of the corresponding customer node $j \in V_{S^o}$; i.e. $b_i = e_i - (e_{(i+d)} - b_{(i+d)}) \forall i \in V_{S^i}$. The same procedure is adapted for customer nodes $i \in V_{R^i} \cup V_{R^o}$. In sum, the time windows are defined as follows:

$$e_i = b_{(i+d)} - p_i \quad \forall i \in V_{S^i} \quad (6.1)$$

$$b_i = e_i - (e_{(i+d)} - b_{(i+d)}) \quad \forall i \in V_{S^i} \quad (6.2)$$

$$b_i = e_{(i-d)} + p_{(i-d)} \quad \forall i \in V_{R^o} \quad (6.3)$$

$$e_i = b_i + (e_{(i-d)} - b_{(i-d)}) \quad \forall i \in V_{R^o} \quad (6.4)$$

Since the ICT solely considers one trucking company serving its requests from several depots, the number of operating trucking companies in the comprehensive scenarios is characterized by the number of depots. The transportation requests are then assigned equally to these companies. According to the underlying ICT-data sets, five trucking companies need to serve 15 requests. Since a usual ICT-data set is comprised of 30 OF transportation requests, 40 IF transportation requests, and five IE transportation requests, in the comprehensive scenarios each trucking company serves six OF transportation requests, eight IF transportation requests, and one IE transportation request.

The first ten test instances of Zhang et al (2010) are chosen to be adapted for the comprehensive scenarios. Since the data sets shall stay the same as far as possible, the consideration of multiple terminals is preserved. As stated, this

Table 6.5: *The Impact of Container Sharing*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	58	25	24676	54	23	23193	6.90	8.00	6.01
2	61	26	21239	57	25	20281	6.56	3.85	4.51
3	61	28	20882	58	26	19943	4.92	7.14	4.50
4	60	29	22112	54	26	20871	10.00	10.34	5.61
5	58	28	19796	51	25	18395	12.07	10.71	7.08
6	59	27	26270	54	26	24173	8.47	3.70	7.98
7	57	29	22970	51	27	20709	10.53	6.90	9.84
8	58	28	22952	54	27	21505	6.90	3.57	6.30
9	51	28	20023	45	26	18729	7.14	7.14	6.46
10	65	28	27311	58	26	25263	10.77	7.14	7.50
Total	588	276	228231	536	257	213062	8.84	6.88	6.46

can be handled easily by the provided tabu search heuristic since the terminal nodes are always duplicated according to the number of transportation requests. Therefore, they can be attributed with any coordinates.

Table 6.5 illustrates the benefit of container sharing for realistic-sized instances. Regarding the fixed costs, the computational experiments show that the decrease of used vehicles is at 9% on average. At least 5% less vehicles are required to serve the customers regardless of which data set is considered. This magnitude is doubled (test instance 4), or even more than doubled, in instances 5, 7, and 10. For example, in test instance 5, instead of 58 vehicles in the non-cooperative scenario, only 51 vehicles are required to allocate the containers between the locations in the cooperative case. This reduction is favored by the reduction of containers which is at 7% on average. In addition to the decrease of fixed costs, the variable costs range from 5% to 10% and have a mean value of 6%.

By having a look at the results of a certain data set, it can be seen that some companies benefit above-average from container sharing. For instance, in Table 6.6, which illustrates the detailed computational results of test instance 9, trucking company 1 realizes savings which are 43% above the average values of the variable costs. Regarding the fixed costs, the savings are even 155% greater than the mean value. Obviously, this can only be accomplished at the expense of other trucking companies like company 4, which almost does not benefit by the cooperation. As can be seen, it requires more total operating time to serve its clients. However, company 4 can still benefit since it is able to reduce its fixed costs.

Table 6.6: Results for Each Company of Test Instance 9

TC	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	11	6	4062	9	5	3688	18.18	16.67	9.21
2	9	5	3902	9	5	3606	0	0	7.86
3	10	6	5004	9	5	4553	10.00	16.67	9.01
4	9	5	3542	8	5	3587	10.00	0	-1.27
5	12	6	3513	10	6	3295	16.67	0	6.21
Total	51	28	20023	45	26	18729	7.14	7.14	6.46

TC - Trucking Company

6.3.2 Impact of Certain Data Set Characteristics on a Container Sharing Coalition

The stated results give a realistic indication of the benefits that a container sharing coalition can generate. Nevertheless, these results should be taken conditionally since the modification of certain data set characteristics can have a strong impact on the benefit of a container sharing coalition. Therefore, three factors which are assumed to have a big impact on the computational results are analyzed in this section. The modification of these factors leads to different problem settings which, however, are realistic and can be found in hinterland regions. In the following, Sections 6.3.2.2-6.3.2.3 examine the influence of varying the time window length, the service time, and the number of trucking companies on the benefit of container sharing. The generated computational results are analyzed by comparing them with the solutions in the foregoing Section 6.3.1

6.3.2.1 Time Window Length

The time windows considered in the modified ICT data sets of the foregoing Section 6.3.1 are defined very tightly, i.e. vehicles need to serve nodes within a relatively short time span. The first and second customer time windows are situated just before and immediately after the given service time windows for the containers. As a consequence, containers at customer nodes need to be delivered/taken punctually. Contrary to tight time windows, wide time windows provide the opportunity for trucking companies to leave empty containers at customer places for a defined period after a container's unloading is completed. Thereby, IF containers that are emptied at receiver locations and IE containers at terminals are available after the service has finished and should be picked up

Table 6.7: *The Impact of Container Sharing (Wide Time Windows)*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	54	27	23937	53	25	22787	1.85	7.41	4.80
2	52	26	19729	52	26	19239	0	0	2.48
3	54	29	20315	54	29	19149	0	0	5.74
4	54	30	21345	51	28	20108	5.56	6.67	5.80
5	49	27	19112	49	25	18282	0	7.41	4.34
6	50	28	25072	49	27	23842	2.00	3.57	4.91
7	51	29	22142	50	30	20502	1.96	-3.45	7.41
8	50	30	22279	50	28	21028	0	6.67	5.62
9	46	28	20406	45	27	18814	2.17	3.57	7.80
10	58	29	26642	57	28	25255	1.72	3.45	5.21
Total	518	283	220979	510	273	209006	1.54	3.53	5.42

before the end of the underlying time period. The consideration of wide time windows is common practice in many hinterland regions, especially in Europe (e.g. Braekers et al (2011a) and Veenstra (2005)).

In the following, the effects of wide time windows at customer locations are measured and compared with the results of the foregoing Section 6.3.1. The data sets to be used are based on the modified ICT data sets but use a different formula for defining the time window length of the nodes $i \in V_{R^o} \cup V_{S^i} \cup V_{TIE}$. Since depots are accessible during the whole time period, the depot $(v+1) \in V_{D^s}$ is used as a measure. In detail, the formula is as followed:

$$e_i = e_{v+d+1} \quad \forall i \in V_{R^o} \cup V_{TIE} \quad (6.5)$$

The computational results reveal that the consideration of tight or wide time windows has a great impact on the advantages of a container sharing coalition. In 40% of the test instances in Table 6.7, no reduction of fixed costs can be achieved. The peak of decrease which can be seen in data set 4 is only at 6%. Compared to the results of the instances including tight time windows, the relative difference of the number of operating vehicles declines from 9% to 2% on average. These results go along with the lower reduction of containers which decline from 7% to 4% on average. Surprisingly, container sharing does not consequently cause a reduction of containers. In test instance 7, the savings of operating vehicles in the cooperative case leads in some cases to an increase of used containers. The vehicles' total travel time for the data sets with wide time windows can be

reduced by 5% on average and is, therefore, 1% below the comparable value in Section 6.3.1.

The reduced decline in the container sharing benefit can be explained through the rising alternatives to integrate containers from different locations into a vehicle's route in the non-cooperative case if wide time windows are considered. This becomes obvious by means of a simple example: Imagine a certain vehicle 4 which is located at terminal node 8 at time $T_{84} = 65$. This vehicle should next serve a shipper node. Obviously, the truck driver needs an empty container before he or she can drive to the customer location. Besides the possibility of getting the empty container from the company's depot, there is only a receiver location nearby the terminal that provides an empty container in time window $[40/50]$ if tight time windows are considered. In this case, the vehicle ends its tour at the depot and a further vehicle starting from the depot drives to the shipper. Thus, the number of vehicles is increased. In the case of wide time windows, however, the empty container at the receiver location is available until the end of the time period which is defined by value 200. Since the distance to this location is only at 30 units, the truck driver can use the container for the next transportation request at the shipper location. No additional vehicle is required. This example shows that a single trucking company that operates on its own has much more planning flexibility to organize its routes if wide time windows are considered, so that the benefit of container sharing is not as large as for data sets which include tight time windows. Nevertheless, the benefit a container sharing coalition, even for data sets with wide time windows, is still remarkable.

6.3.2.2 Service Time

If a vehicle waits at a customer location until the container is loaded/unloaded, the total operating time is raised by $p_i \forall i \in V_C$ time units in any event. Generally, a vehicle only skips this "nonproductive" waiting time if it is profitable to serve other nodes or transportation requests during this service time. The term "profitable" is certainly defined by the objective function. Providing that a vehicle skips the waiting time, it has to be assured that the same vehicle or a vehicle from a different tour can move the container during the customer's second time window. Otherwise, an additional vehicle from the depot has to take over the container after it is unloaded/loaded, which is forbidden by the objective. It can be assumed that the probability to skip the waiting time is most likely raised if the vehicles have more alternatives of serving nodes during a tour *and* if the load-

ing/unloading time of a container is increased. Certainly, in a container sharing coalition, a trucking company has more possibilities of visiting nodes compared to the non-cooperative scenario, so that increasing the service time can possibly superiorly favor a container sharing coalition.

In reality, the increase of service time is very applicable for trucking companies in order to avoid uncertainty due to unforeseeable waiting times. These delays can occur if there happen to be irregularities in the application flow at customer locations. For instance, the service of unloading a container at a receiver location can be late since the unloading of the foregoing container is still in progress. By increasing the designated service time by means of a safety buffer, trucking companies can reduce these delays and decrease the uncertainty at the same time.

In the following, the effects of adding a safety buffer to a container's loading/unloading time is analyzed. Bearing in mind that the underlying test instances are characterized by a loading/unloading time $p_i \forall i \in V_C$, which varies between values five to 50, the safety buffer successively takes the following values for the computational experiments: 5, 10 and 15. Hence, three different data sets based on the illustrated formulas of Section 6.3.1 are defined and solved. Due to the mentioned safety buffers, the containers' loading/unloading times are, thereby, defined as follows: $p_{i+} = 5, p_{i+} = 10, p_{i+} = 15$. The computational results can be seen in Table 6.8, Table 6.9, and Table 6.10.

For a better overview, a comparison of the final mean values of the different data sets with increasing service time is given in Table 6.11. Thereby, it can be seen that the hypothesis that a longer loading or unloading time of the container leads to a rising benefit of container sharing is not scientifically tenable. Regarding the number of vehicles, the fluctuation of the benefit is relatively low since it deviates between 8-9%. Surprisingly, the results for data sets with $p_{i+} = 0$ are even slightly better compared to the data sets with $p_{i+} = 15$. In accordance with that, the number of containers fluctuates between 6-7%. Concerning the variable costs, a steady improvement of the relative benefit of the cooperative scenario can be determined. However, these improvements are minor since they lay in a range of 0.59%.

Table 6.8: *The Impact of Service Time ($p_{i+} = 5 \forall i \in V_C$)*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	57	24	24521	55	23	23427	3.51	4.17	4.46
2	61	25	21177	56	24	20150	8.20	4.00	4.85
3	61	28	21104	57	26	20061	6.56	7.14	4.94
4	61	29	22366	53	26	20697	13.11	10.34	7.46
5	58	27	19868	51	24	18295	12.07	11.11	7.92
6	58	27	26059	52	26	24375	10.34	3.70	6.46
7	56	29	22578	51	27	20758	8.93	6.90	8.06
8	59	29	23063	54	27	21428	8.47	6.90	7.09
9	50	27	20357	46	26	18757	8.00	3.70	7.86
10	64	27	27299	58	26	25162	9.38	3.70	7.83
Total	585	272	228392	533	255	213110	8.89	6.25	6.69

Table 6.9: *The Impact of Service Time ($p_{i+} = 10 \forall i \in V_C$)*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	57	24	24760	53	22	23170	7.02	8.33	6.42
2	61	25	21358	55	24	19831	9.84	4.00	7.15
3	62	28	21030	55	25	19436	11.29	10.71	7.58
4	60	29	22253	55	26	20945	8.33	10.34	5.88
5	58	27	19968	51	24	18350	12.07	11.11	8.10
6	58	27	25972	55	26	24497	5.17	3.70	5.68
7	54	28	22343	52	27	20832	3.70	3.57	6.76
8	58	28	23073	53	26	21541	8.62	7.14	6.64
9	51	27	20472	47	26	18657	7.84	3.70	8.87
10	64	27	27309	58	26	25321	9.38	3.70	7.28
Total	583	270	228538	534	252	212580	8.40	6.67	6.98

Table 6.10: *The Impact of Service Time ($p_{i+} = 15 \forall i \in V_C$)*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	58	24	24902	55	23	23660	5.17	4.17	4.99
2	61	26	21379	54	25	19884	11.48	3.85	6.99
3	61	28	20962	55	25	19429	9.84	10.71	7.31
4	59	28	22169	56	26	20806	5.08	7.14	6.15
5	58	27	19943	50	24	18338	13.79	11.11	8.05
6	59	27	26341	52	26	24200	11.86	3.70	8.13
7	54	28	22401	52	27	20955	3.70	3.57	6.46
8	58	28	23297	53	26	21648	8.62	7.14	7.08
9	50	27	20066	47	26	18498	6.00	3.70	7.81
10	65	28	27543	59	26	25443	9.23	7.14	7.62
Total	583	271	229003	533	254	212861	8.58	6.27	7.05

Table 6.11: *Comparison of Results - Service Time*

	Benefit of Container Sharing (in %)		
	Vh.	Con.	TT
$p_{i+} = 0^1$	8.84	6.88	6.46
$p_{i+} = 5^1$	8.89	6.25	6.69
$p_{i+} = 10^1$	8.40	6.67	6.98
$p_{i+} = 15^1$	8.58	6.27	7.05

$$^1\forall i \in V_C$$

6.3.2.3 Number of Trucking Companies

The number of operating trucking companies can have a great impact on the benefit of a container sharing coalition, since with every additional participating company, the number of transportation requests usually increases. In the following, the computational results of container sharing coalitions with two, five and ten trucking companies are compared. Due to the fact that a coalition with five participants has already been analyzed, only two variants of data sets have to be generated. According to a coalition of two companies, the modified data sets of Section 6.3.1 are modified so that only the first two of the five trucking

companies and their transportation requests are considered. The remaining three companies are discarded. The consideration of ten trucking companies within a test instance is more complicated due to the fact that the ICT data sets only consider five depots and 75 transportation requests. For an objective comparison of the computational results in this section, it is evident that the data sets are comparable. Each of the ten trucking companies to be considered should still serve 15 transportation requests from its own depot. As a consequence, an extension of the data sets is inevitable. Fortunately, Zhang et al (2010) generated 20 data sets for the ICT. So far, only the first data sets have been used for the computational experiments based on the comprehensive scenarios, so that the last ten data sets can be used as an extension of the first ones. For instance, data set 1 is extended by implementing a modified ICT data set 11.⁷ By doing this, data sets can be generated as intended since they are now characterized by ten depots and 150 transportation requests.

Table 6.12: *Two Trucking Companies*

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	21	9	7951	19	8	7989	9.52	11.11	-0.48
2	24	9	7419	23	9	7208	4.17	0	2.84
3	26	12	8764	26	12	8649	0	0	1.31
4	23	12	8209	23	12	8002	0	0	2.52
5	26	11	8761	22	11	8261	15.38	0	5.71
6	25	11	11557	24	11	11390	4.00	0	1.45
7	22	12	10164	20	11	9624	9.09	8.33	5.31
8	22	10	8713	21	9	8495	4.55	10.00	2.50
9	21	11	7960	19	11	7467	9.52	0	6.19
10	25	12	11418	25	12	11038	0	0	3.33
Total	235	109	90916	222	106	88123	5.53	2.75	3.07

⁷As can be seen in Section 6.2.2.3, the first defined ICT data set of Zhang et al (2010) yields number 4 so that the eleventh data set is technically defined by number 14.

Table 6.13: Ten Trucking Companies

Inst.	MC-CTTP			MC-CTTP-CS			Difference (in %)		
	Vh.	Cont.	TT	Vh.	Cont.	TT	Vh.	Con.	TT
1	110	52	45303	103	48	41864	6.36	7.69	7.59
2	113	54	43587	107	52	40694	5.31	3.70	6.64
3	113	57	43419	106	54	40409	6.19	5.26	6.93
4	117	56	46367	105	50	42357	10.26	10.71	8.65
5	112	55	40335	100	49	36398	10.71	10.91	9.76
6	107	55	47933	95	52	43628	11.21	5.45	8.98
7	105	56	41880	99	55	39422	5.71	1.79	5.87
8	106	54	43666	98	50	41021	7.55	7.41	6.06
9	102	55	43761	93	53	40042	8.82	3.64	8.50
10	112	58	48379	101	55	43602	9.82	5.17	9.87
Total	1097	552	444630	1007	518	409437	8.20	6.16	7.92

At this point it should be noted that the tabu search heuristic, like any other heuristic, has some inaccuracies in generating solutions, especially if the data sets include ever increasing transportation requests. Moreover, since the problem complexity of the MC-CTTP-CS is higher than the problem complexity of the MC-CTTP, the inaccuracy can be higher for the cooperative case, i.e. the gap to the global optimum for large-sized instances is most certainly greater if the cooperative scenario is regarded. Due to these facts, the relative benefits of the MC-CTTP-CS, particularly in the case of ten participating trucking companies, can be higher with a greater probability if the global optima for both problem types could be determined. Nevertheless, the heuristic has shown to deliver high-quality solutions for small-sized and large-sized instances. Thus, it can be assumed that the inaccuracy is relatively low.

The results of the computational experiments can be seen in Table 6.12 and Table 6.13. As in the foregoing section, the final mean values of each table are illustrated in order to give a better overview (see Table 6.14). Remarkably, the improvements of generating tours is relatively high even if only two companies cooperate with each other. While the total operating time reduction is at 3%, the number of vehicles decreases by 6%. The decline in the number of containers is at 3%. As assumed, these savings increase notably if more trucking companies participate in a coalition. Regarding the results of five participating companies, the fixed cost savings illustrated by the number of vehicles increase by three

Table 6.14: Comparison of Results - Number of Trucking Companies

	Benefit of Container Sharing (in %)		
	Vh.	Con.	TT
$d = 2$	5.53	2.75	3.07
$d = 5$	8.84	6.88	6.46
$d = 10$	8.20	6.16	7.92

percentage points compared to a coalition with two companies. At the same time, the savings regarding the number of containers rise even by four percentage points. A similar huge increase in cost savings can be seen if the total operating time is regarded. By examining the results of a coalition with ten companies, these huge increase in savings seem to stagnate at the level of five trucking companies. While the savings according to the vehicles' total operating time still increases from 6% to 8%, a minor decrease of the relative benefit according to the number of vehicles and containers can be determined. Although the decrease is not huge, these results are surprising. They indicate that the limits of a container sharing coalition for the underlying data sets are near the generated results of a coalition with five and ten participants.

7 Analysis of the Obtained Findings

In the previous three chapters, several computational experiments concerning the quantitative benefits of the container sharing idea have been performed. Without a doubt, the generated results show that exchanging empty containers between trucking companies helps significantly reduce transportation costs for the participating companies. In this chapter, the reasons for the reduction of transportation costs in a container sharing coalition are analyzed. Furthermore, the obtained findings of this thesis are discussed in order to expose possible challenges of putting the container sharing idea into practice.

The transportation costs required to serve a company's client base depend strongly on the distances to move containers. Consequently, a decline in fulfillment costs is inherently connected with the decline in total container movements, which are defined by the distances of full and empty container flows. Obviously, the distances of full container flows for a certain data set do not change regardless of which problem is applied (MC-CTTP or MC-CTTP-CS). This is due to the fact that the number of IF and OF transportation requests stays the same for both problem types. Consequently, minimizing total container movements means minimizing empty container repositioning distances. According to the comprehensive scenarios, the decline of empty container movements induced by container sharing is illustrated in Table 7.1. Thereby, the results of the proposed ten data sets for each problem setting are aggregated. The proportion of empty container movements (explicitly) and full container movements (implicitly) for a certain problem setting are given. Furthermore, the reduction of empty container movements from the non-cooperative scenario to the cooperative scenario is shown.

Understanding the information of a single row can best be explained by means of an example. For the ten data sets in Chapter 5, 8,857 distance units are required to move containers in the MC-CTTP. 58.16% of these units are needed to transport empty containers. Consequently, 41.84% constitutes the proportion of distance units to move full containers. In case of the MC-CTTP-CS, only 31.43% of 5,405 distance units are required for moving empty containers. As mentioned, the full container movements stay the same whether the MC-CTTP or the MC-CTTP-CS is applied. Thus, bearing in mind that the results are rounded, the

Table 7.1: Reduction of Empty Container Movements

Problem Setting	MC-CTTP		MC-CTTP-CS		R-ECM
	TCM	S-ECM	TCM	S-ECM	
Chapter 5					
Potential	8857	58.16	5405	31.43	67.03
Chapter 6					
Basic Results	132180	51.24	123190	47.68	13.27
Wide Time Windows	132954	51.52	122928	47.57	14.64
$p_i+ = 5 \forall i \in V_C$	131664	51.05	122337	47.31	13.88
$p_i+ = 10 \forall i \in V_C$	131366	50.94	121201	46.82	15.19
$p_i+ = 15 \forall i \in V_C$	131476	50.98	121680	47.03	14.62
$d = 2$	54283	52.75	52465	51.11	6.35
$d = 10$	261806	50.85	240374	46.47	16.10

TCM - Total Container Movements; S-ECM - Share of Empty Container Movements (in %); R-ECM - Reduction of Empty Container Movements (in %)

following formula defines the distance units for the movement of full containers: $0.4184 * 8857 \approx 0.6857 * 5405 \approx 3706$. The relative reduction of empty container flows in case of container sharing then depends on the empty container flow distances in the cooperative scenario, as well as in the non-cooperative scenario, and are calculated as follows: $\frac{0.5816 * 8857 - 0.3143 * 5405}{0.5816 * 8857} = 0.67$.

Focusing on the proportions of empty container movements, it can be concluded that around 51% to 52% of the container movements are caused by empty container flows in the MC-CTTP. These shares are reduced to 46-48% in the MC-CTTP-CS, which is quite remarkable since the proportions generally decline by 4%. An exception marks the problem setting with two trucking companies. In this case, the shares of empty container movements in both scenarios are relatively large and decline only by 2%. Bearing in mind that in Europe, over 50% of the container movements are empty, the MC-CTTP and MC-CTTP-CS seem to represent the situation in practice very well (Branch, 2006). The results of Chapter 5 indicate that these shares can eventually be reduced to almost 30% if the situation for realizing street turns is near the optimum (for two participating trucking companies). In this case, the distances required to move empty container decline remarkably by 67%. Moreover, the results of Chapter 6 indicate that the reduction of empty container flow is around 14% regardless of which variation of the basic setting is applied. However, two exceptions can be found for the situation if two and ten trucking companies cooperate with each other. While the reduction of empty container movements for a coalition with two trucking

companies is only at 6%, the reduction is at 16% for a coalition with ten participating companies. These exceptions prove the findings in the previous chapter that the benefit of container sharing rises if more and more trucking companies participate in a coalition. Since the possibilities of exchanging containers are relatively low in a small coalition, empty container movements cannot be reduced that much and, therefore, the reduction of transportation costs is relatively low as well. Considering a coalition of ten trucking companies, there are many more alternatives for integrating empty containers in a tour. As a consequence, the reduction of empty container movements rises. However, the relative increase in this reduction from coalitions with $d = 5$ to coalitions with $d = 10$ is slight compared to the relative increase of empty container flow reduction from coalitions with $d = 2$ to coalitions with $d = 5$. This finding goes along with the knowledge of the last chapter that a coalition's fulfillment cost savings rises much less after a certain coalition size.

The reduction of empty container movements in container sharing coalitions are mainly caused by the following two reasons. Firstly, container sharing enables a higher probability of realizing street turns. Secondly, the chance to use IE containers for a shipper customer rises in case of container sharing. Both factors generally increase the number of possible solutions and, consequently, cause a generation of tours which lead to less required vehicles and less operating time to serve underlying transportation requests. In the following, these two factors are analyzed further.

According to the first container movement pattern, Table 7.2 illustrates the realization of street turns in the comprehensive scenarios. It is measured how many street turns are realized in case of the cooperative scenario and in case of the non-cooperative scenario. Afterwards, the number of established street turns are put in relation to the possible number of street turns that could hypothetically be realized. For instance, the ten data sets of the basic setting in Chapter 6 include 300 shippers and 400 receiver customers. Hence, 300 street turns could be realized if every shipper's time windows were consistent with at least one receiver time window. Since 17 street turns are realized in the cooperative scenario, the share of street turns is at $17/300 = 5.67\%$. The results for the comprehensive scenarios can be seen in Table 7.2.

In Chapter 5, the share of street turns deviates strongly. While there are 34 street turns in the cooperative scenario, zero of 50 street turns are realized in the non-cooperative scenario. These results were expected bearing in mind that the benefiting factors of a container sharing coalition are idealized. Examining

Table 7.2: *Share of Street Turns*

Problem Setting	P-ST	MC-CTTP		MC-CTTP-CS	
		E-ST	S-ST	E-ST	S-ST
Chapter 5 Potential	50	0	0	34	68.00
Chapter 6 Basic Results	300	7	2.33	17	5.67
Wide Time Windows	300	7	2.33	13	4.33
$p_i+ = 5 \forall i \in V_C$	300	7	2.33	17	5.67
$p_i+ = 10 \forall i \in V_C$	300	7	2.33	20	6.67
$p_i+ = 15 \forall i \in V_C$	300	6	2.00	18	6.00
$d = 2$	120	4	3.33	7	5.83
$d = 10$	600	12	2.00	33	5.50

P-ST - Possible Number of Street Turns; *E-ST* - Established Number of Street Turns;
S-ST - Share of Street Turns (in %)

the particular data sets of the MC-CTTP-CS in more detail, only in one of 10 data sets can a share of 100% be identified. This is quite remarkable since clusters were generated in which a receiver and a shipper with consistent time windows are included. Hence, in each cluster, a street turn is possible to realize. In Chapter 6, the results of the MC-CTTP stabilize on an average level of 2% realized street turns. In the MC-CTTP-CS, this rate is at around 6%.

Although the number of street turns increases significantly by means of container sharing, the share still seems to be relatively low in both scenarios and shows that realizing street turns is cumbersome. This is corroborated by The Tioga Group's report. The authors refer to the hinterland of the Southern California region, where 1.1 million IF containers and 500,000 OF containers were handled in 2002. It is stated that an estimated 25,000 empty containers, which is a rate of 5%, were "street turned"¹. The authors assume that the potential of street turns in Southern California may roughly be expanded to 8% with the help of container pooling methods. Please note that these shares of street turns cannot be compared to the results of Table 7.2 offhand. The case study of The Tioga Group (2002) with 1.1 million receivers and 500,000 shippers benefits to a certain degree from the realization of street turns since the number of empty con-

¹The presented street turn rate (5%) differs from the calculated rate of The Tioga Group (2002) (2%) who put the number of street turns in relation to the number of IF containers. In this case, a rate of 100% cannot be realized in any event, since $500,000/1,100,000=45.5\%$. Due to this fact, the introduced street turn rate is put in relation to the possible number of street turns that could hypothetically be realized.

Table 7.3: Use of IE Containers for Shipper Customers

Problem Setting	P-IE	MC-CTTP		MC-CTTP-CS	
		E-IE	S-IE	E-IE	S-IE
Chapter 5					
Potential	10	0	0	7	70.00
Chapter 6					
Basic Results	50	19	38.00	28	56.00
Wide Time Windows	50	10	20.00	14	28.00
$p_i+ = 5 \forall i \in V_C$	50	22	44.00	30	60.00
$p_i+ = 10 \forall i \in V_C$	50	23	46.00	29	58.00
$p_i+ = 15 \forall i \in V_C$	50	25	50.00	30	60.00
$d = 2$	20	7	35.00	8	40.00
$d = 10$	100	37	37.00	50	50.00

P-IE - Possible Number of IE Containers that Can Be Used for Shipper Customers; *E-IE* - Established Number of IE Containers Used for Shipper Customers; *S-IE* - Share of IE Containers Used for Shipper Customers (in %)

tainers at receiver locations far exceeds the maximum number of possible street turns which can be realized. The probability of realizing street turns, obviously, decreases if the difference in the number of receivers and shipper tends towards zero. In this case, all empty containers from the receiver locations need to be used for the shipper customers to achieve a street turn rate of 100%. Consequently, the probability of finding consistent time windows of shippers and receivers is smaller than in the underlying data sets² and even more so in the stated case study³.

A further reason for the benefit of a container sharing coalition is the utilization of IE containers for OF transportation requests, which is more likely to occur. Similar to Table 7.2, Table 7.3 illustrates the use of IE containers for a shipper customer. At first glance, the relatively high rates of used IE containers for shippers, compared to the share of street turns, are conspicuous. These high proportions result from the numerous appearances of vehicles at terminals due to the underlying OF transportation requests. If IE containers simultaneously arrive at these locations, vehicles can easily integrate these boxes in their tours and use them for e.g. OF requests.

According to Chapter 5, no container is employed for a shipper in the MC-CTTP since the two considered companies either only serve inbound or outbound

²Surplus of one-third IF transportation requests.

³Surplus of 55% IF transportation requests.

requests. Moreover, the share of IE containers used for shippers is at 70% in the MC-CTTP-CS. Focusing on the results of Chapter 6, the calculated values vary relatively strong. While the proportions deviate between 35% and 50% in the non-cooperative scenario, the values are constituted between 40% and 60% in the cooperative scenario. In the MC-CTTP-CS, these shares are constantly bigger compared to the corresponding data sets of the MC-CTTP, regardless which problem setting is considered. An exception is the problem setting with wide time windows. This share is only at 20% in the MC-CTTP and increases to 28% in case of the MC-CTTP-CS. Instead of moving IE containers to shippers, IE terminal nodes are predominantly served at a tour's end and then moved to the depot. At first glance, this is surprising since wide time windows rise the probability of consistent shipper time windows. By having a closer look on the general appearance of receiver nodes that follow IE terminal nodes along a tour, these shares are put into perspective. Regardless of which problem setting is considered, the utilization of IE containers, used for shippers in the middle of tours, is scarce. Although approaching an IE terminal node at the tour's first position is dispensable, due to the fact that a large number of containers is available at every depot, these combinations occur mainly at a tour's beginning. If wide time windows are considered, it is more profitable for companies to integrate IE containers at the end of tours instead of needlessly serving the corresponding terminal nodes at the beginning of a tour. In comparison to the other problem settings, IE containers can then more likely be integrated into a tour after serving an OF request at the same terminal node. In this situation, two transportation requests can be served without the consideration of additional travel time in any case and without the consideration of waiting time at best.

Besides the two proposed container movement patterns, a further and last reason for the advantage of container sharing lays in the possibility of a trucking company to integrate an external empty container at each position in a tour. In other words, companies who employ containers from a participating company do not necessarily need to use these containers for their transportation requests and can also move them directly to their depots. In this case, the container is integrated at the last position of the tour. This criteria shows its advantages if more and more trucking companies are considered. In this case, the probability that a location which provides an empty container is nearby a depot of a trucking company is larger. Subsequently, empty containers from these locations are integrated into a vehicle's tour, although the operating company has no real use for it. But in doing so, this benefits the reduction of a coalition's fulfillment costs.

Obviously, the last criteria implicates a main challenge of the container sharing idea which has to be faced. Companies will not integrate containers in their tours if they do it for altruistic reasons. According to The Tioga Group (2002), the strategy of empty container handling must yield concrete financial and operational benefits in order to achieve a coalition's optimum. As a consequence, companies of a coalition need a financial compensation from the coalition in order to encourage altruistic behavior to a certain degree for the common good of a coalition.

An adequate compensation concept is even more important when looking at the results generated during this thesis. Due to the applied objective to minimize the fulfillment costs of a coalition, the participating trucking companies profit highly unequally. On the one hand, there are companies who benefit disproportionately due to above-average savings in fixed and variable costs. On the other hand, there are companies who even need to deploy an additional vehicle or need to invest further operating time to serve its requests. This is a big challenge that needs to be faced in order to encourage companies to participate in container sharing coalitions. Therefore, concepts like profit sharing methods need to be addressed in the future. Only if this challenge is faced will container sharing coalitions as introduced in this thesis have a chance to be put into practice and, moreover, achieve the cost savings that were measured in the foregoing chapters.

8 Conclusions and Further Research

During this thesis the quantitative benefit of the proposed container sharing idea has been explored. In doing so, comprehensive hinterland container transportation settings have been defined and analyzed by solving several small and large-sized test instances. At this point, it is time to reflect on the main results obtained through this study. In addition, limitations of this thesis, as well as aspects which were out of the scope of this work, are revealed.

8.1 Concluding Remarks

Without a doubt, the defragmentation of a hinterland's container fleet is a powerful solution approach for trucking companies to reduce costs in hinterland container transportation. During this thesis, the remarkable effects of the container sharing idea have clearly been shown. The proposed computational experiments help to estimate the quantitative benefit of this specific container pooling idea for trucking companies in seaport hinterlands. Bearing in mind that similar approaches to the container sharing idea have not yet been analyzed to this degree of comprehensiveness, this thesis gives a first realistic indication of how trucking companies can profit by exchanging their empty containers with cooperating companies. Therefore, it can constitute an important step to overcome the reluctance of shipping and trucking companies to take the step of joining a coalition.

Focusing on the potential of the container sharing idea, the computational experiments in Chapter 4 and Chapter 5 indicated to what extent possible trucking companies can benefit by participating in a container sharing coalition. Thereby, it was explicitly documented that the realization of street turns is of eminent importance in order to reduce the huge amount of empty container movements. In particular, the computational experiments of Chapter 6 were interesting from a practical point of view since they indicated concrete cost saving possibilities for trucking companies if they would participate in container sharing coalitions. The observed results are very promising. In light of the situation that the profit margin in container trucking usually only amounts to a few percent, the computational experiments demonstrate that the exchange of empty containers among

companies has a strong positive impact on the financial situation of the container sharing coalition.

It is important to note that these significant benefits do not only hold for a specific hinterland setting. The computational results of several hinterland settings with varying data set characteristics revealed the robustness of these advantages since the relative benefits of container sharing in different hinterland settings differ only slightly from each other. Nevertheless, the following tendencies have become clear: certainly, the benefit reached by container sharing grows if more trucking companies participate in a coalition. However, it is notable, that even for small coalitions the benefit is relatively large. At the same time, the relative benefit seems to increase only slightly, and almost stagnates at a certain level of participating trucking companies. While the increase of service time has almost no impact on the computational results, the impact of wide and tight time windows is strong. Especially if tight time windows are considered companies can benefit within the cooperation by reducing fixed and variable costs.

From a methodological point of view, this thesis analyzed several different approaches to solve hinterland container transportation problems in terms of accuracy and speed. Thereby, the 2-step method and the integrated routing approach provide two interesting and comprehensive solution approaches since they both consider the containers and vehicles as passive and active transportation entities. The analysis of the 2-step method and the integrated routing approach revealed that the sequential solution approach generated adequate results which, however, partially deviate too strong from the optimal solution. Nevertheless, if data sets with increasing complexity are considered, it can be advisable to implement heuristic approaches for the 2-step method since the sequential solution approach is much more efficient in finding a solution. The provided tabu search heuristic pursues a further solution approach since it considers the allocation of containers on the transportation level of the vehicles. The computational experiments proved that it performs very well for realistic-sized test instances in terms of effectiveness and efficiency.

8.2 Outline of Further Research Directions

During this thesis it has been verified that the idea of container sharing constitutes a very promising solution approach to reduce empty container movements in a seaport's hinterland region. However, the observed quantitative benefits should

be considered with caution since they illustrate the advantages of container sharing for the modified ICT data sets. Although several different hinterland settings have been analyzed, the framework of these data sets always stayed the same. In other words, the share of shipper and receiver customers remained unchanged throughout the computational experiments. Therefore, the investigation of hinterland settings with varying shares of customer types would be very interesting. Moreover, since this thesis only investigated coalitions with trucking companies of the same size, it can be analyzed how the total benefit is portioned if trucking companies that serve different numbers of transportation requests participate. A further interesting approach could be the restriction of the container amount at each depot. Due to the fact that the relative flexibility of integrating empty containers decreases above average in the case of non-cooperating scenarios, if the amount of containers is restrained, it can be assumed that the benefit of container sharing increases.

Since the proposed tabu search heuristic focuses mainly on the routing of vehicles, a very interesting approach would be the heuristic implementation of the proposed integrated routing method. In contrast to the 2-step method, it does not inherently exclude solutions, but still has the advantage to represent the problem more comprehensively by illustrating the containers' flows as well as the vehicles' routes. However, this approach is very challenging to implement since the containers' flows, and the vehicles' routes have to be generated simultaneously. Thus, local operators for both transportation entities have to be determined. At the same time, it has to be guaranteed that both transportation entities are interlinked with each other so that each container movement is enabled by a vehicle.

The computational experiments considered a perfect economic environment in which acting players cooperated willingly with each other. Companies act completely altruistic and seek to increase the welfare of the coalition. However, in reality, there are several challenges which have to be addressed in order to enable an ongoing container sharing coalition which encourages trucking companies to participate. Putting a successful long-term container sharing cooperation into practice requires tackling three main hurdles. Firstly, companies providing their empty containers fear that they might help competitors benefit in the cooperation above-average without being compensated. Secondly, companies are unwilling to share all their empty containers for strategic reasons (e.g. revealing their client base). Thirdly, shipping or leasing companies who mainly own the containers in intermodal door-to-door services fear to lose control of their property which can get damaged or lost. As a consequence, future research has to focus on meth-

ods and mechanisms to motivate companies to participate and stay in a container sharing cooperation in order to overcome these challenges. Subsequently, it would be of great interest to combine the determined mechanisms with the proposed solution approaches in this thesis in order to be able to analyze to what extent the benefit would result in a much richer and more realistic economic environment.

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