MODELLING CORRIDOR NETWORKS IN INTERMODAL BARGE TRANSPORT

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ABSTRACT

In this paper the design of the service network in intermodal barge transport is studied. The network of inland barge terminals is modeled to demonstrate potential cooperations in a corridor network. Cooperation between inland terminals leads to bundling of freight flows in the hinterland of major ports. A service network design methodology for intermodal barge transport is developed and applied to the hinterland network of the port of Antwerp in Belgium. Selected cooperation schemes are simulated by means of a discrete event simulation model for intermodal barge transport and compared with simulation results of bundling in the port area. Cooperation between inland terminals offers an opportunity to attain economies of scale, but may not be perceived as a sole solution for reducing waiting times of inland barges at sea terminals. A combination of bundling measures in the port area and in the hinterland may be necessary to improve the intermodal transport chain.

Keywords: inland navigation, corridor network, hinterland, service network design, simulation.

1 INTRODUCTION

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

In the intermodal context in Belgium, the importance of inland navigation is increasing. Inland navigation plays an important role in the hinterland access of the port of Antwerp (Notteboom, 2007). Hinterland access of ports constitutes a key element in their competitiveness (Notteboom and Rodrigue, 2005). Ports have become a part of intermodal networks and competition takes place amongst transport chains instead of between ports. However, waiting times of inland barges for container handling in the port of Antwerp have been increasing. The hinterland of the port of Antwerp in Belgium is characterized by many small container terminals, each organizing their own shuttle services to the port area. Inland barges visit multiple sea terminals with relatively small call sizes in the port of Antwerp. Calling at several terminals may be a time-consuming process. The queue of barges waiting to be handled may be substantial at peak periods. This is partly due to a limited capacity of labour forces, quaysides or cranes at sea terminals. Capacity of quaysides and cranes has significantly expanded through the construction of the Deurganck-dok. Secondly, the layout of sea terminals is aimed at handling seagoing vessels. Inland barges are handled with the same infrastructure and equipment. Sea terminals give priority to handling seagoing vessels, since the cost of a delay for sea-going vessels is much higher than for inland vessels. However, this may further increase waiting time of inland vessels. Moreover, a delay at one terminal may result in missing the agreed time window for handling at a next terminal. Thirdly, sea terminals only have a contractual commitment with sea shipping companies. There is no legal tie between barge operators and sea terminal operators. This places barge operators in a very weak negotiation position concerning service levels, modes of operation and handling charges. In light of the expected ongoing increase in container throughput in the port of Antwerp, the problem of congestion and waiting times for barges may become worse. Container barge services need to be reorganized in order to stay competitive as transport mode. Bundling of load offers opportunities to realize a more efficient handling of inland barges in the port area.

Cooperation of inland terminals along the same waterway may be classified as a corridor network in the generic framework of transport network design by Woxenius (2007). An alternative term in literature for this type of bundling is 'line bundling'. Woxenius (2007) defines a corridor network as a design based on using a high-density flow along an artery and short capillary services to nodes off the corridor. Freight transport along inland waterways are a typical application of the corridor design due to geographical reasons. Notteboom (2007) describes the development of corridor networks along the Rhine. As stated in the framework of Konings (2003), network design determines vessel size and circulation time in barge transport. A corridor network design requires stops at intermediate terminals to be relatively short in order to keep a reasonable circulation time for all terminals along the corridor. When determining vessel size, slack capacity needs to be reserved for terminals along the corridor. In a corridor network no additional transhipment is required, contrary to a trunk collection/distribution network with an inland terminal serving as a hub in the hinterland.

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

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

In section 2 service network design is discussed and a generic model is presented. This model is adapted to incorporate characteristics of intermodal barge networks in section 3. Next, the service network design methodology for intermodal barge transport is applied to identify opportunities for cooperation between Belgian inland barge terminals in the hinterland network of the port of Antwerp (section 4). Cooperation schemes selected in section 4, are simulated by means of a discrete event Simulation model for InterModal BArge transport (SIMBA) in section 5 and compared with the results of bundling in the port area described by Caris et al. (2010). The description of the simulation model can be found in Caris et al. (2009). The simulation model evaluates the impact on turnaround times and on performance measures in the port area. Finally, conclusions are drawn in section 6.

2 SERVICE NETWORK DESIGN

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

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

Empty balancing and crew and motive power scheduling may also be included in the design of the service network.

2.1 Generic model

The path-based multicommodity capacitated network design formulation (PMCND) of Crainic (2000) is presented next, as this general formulation will be adapted in section 3 to model a service network in intermodal barge transport. The problem is defined on a graph $G = (N, A)$ with N the set of nodes and A the set of arcs in the network. P is the set of products to be transported. In intermodal barge transport each origin-destination pair may represent a flow of a product. A path-based formulation permits to define a set of possible paths for each origin-destination pair in advance. The decision variables in the model are:
y_{ij} = 1 if link(i, j) is open
h_l^p = flow of commodity p on path l
The following notation is used:
P = set of products (origin-destination pairs)
L = set of all paths in the network
L^p = set of paths for product p
f_{ij} = fixed cost of opening link (i, j)
w^p = total demand of product p
k_l^p= transportation cost of product p on path l
c_{ij}^p = transportation cost per unit of product p on link (i, j)
δ_{ij}^{lp} = 1 if arc (i, j) belongs to path $l \in L^p$ for product p
u_{ij} = capacity of link (i, j)

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

subject to

$$\sum_{l\in L^p} h_l^p = w^p \qquad \forall p \in P \tag{1}$$

$$\sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ij}^{lp} \le u_{ij}y_{ij} \qquad \forall (i, j) \in A \tag{2}$$

$$y_{ij} \in Y = \{0, 1\} \qquad \forall (i, j) \in A \tag{3}$$

$$h_l^p \ge 0 \qquad \forall p \in P, \forall l \in L^p. \tag{4}$$

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

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

Constraints (1) ensure that the demand for all products is met. The second group of constraints represents capacity restrictions on links in the network. The total flow on a link cannot exceed its capacity and must be zero when the link is not chosen in the network (y_{ij} = 0). Constraints (3) and (4) define the formulation as a mixed-integer programming problem.

2.2 Applications in intermodal transport

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

3 MODEL FORMULATION FOR INTERMODAL BARGE TRANSPORT

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

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

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

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

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

All other notation is maintained as in the previous section, leading to the non-linear integer programming formulation:

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

subject to

$$\sum_{l \in L^p} h_l^p = w^p \qquad \forall p \in P \tag{5}$$

$$\sum_{p \in P} \sum_{l \in L^p} h_l^p \delta_{ij}^{lp} \leq u_{ij} \sum_{k \in K} a_{ij}^k g^k \qquad \forall (i,j) \in A^B \tag{6}$$

$$\sum_{k \in K} a_{ij}^k g^k \leq 1 \qquad \forall (i,j) \in A^B \tag{7}$$

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

$$\forall i, m \in N, j \in N^P, i \neq j, j \neq m \tag{8}$$

$$g^k \in \{0,1\} \qquad \forall k \in K \tag{9}$$

$$e_{ij}^k \text{ positive integer} \qquad \forall (i,j) \in A^B \cup A^P, k \in K \tag{10}$$

$$h_l^p \text{ positive integer} \qquad \forall p \in P, \forall l \in L^p \tag{11}$$

The first component of the objective function represents the base cost of operating selected roundtrips k. The base cost includes the cost of hiring a vessel to perform the roundtrip, a waiting cost in the port area along arcs connecting two port nodes and a cooperation cost along arcs connecting two inland nodes. The cooperation cost represents the overhead of setting up a corridor network. The waiting cost is incurred when barges have to pass through a lock system in the port area. In the second component a concave variable cost function is used on the links in set A^B to model economies of scale achieved by bundling freight flows in the hinterland network. This concave cost function thus represents the benefit of cooperation. Constraints (5) and (6) are similar to the generic model. The set of constraints (7) assure that links between inland nodes and port nodes may only belong to a single selected roundtrip k. Decision variables e_{ij}^k in the fourth group of constraints measure the imbalance between inbound and outbound freight flows. This imbalance needs to be taken into account in the concave variable cost function of the links between inland nodes and port nodes. The cycle design variables g^k are restricted to binary values. Since the aim is to model the transportation of containers, flow variables h_l^p and e_{ij}^k are defined to take on a positive integer number.

4 SCENARIO ANALYSIS IN HINTERLAND OF ANTWERP

In this section the service network design methodology for intermodal barge transport is applied to identify opportunities for cooperation between Belgian inland barge terminals in the hinterland network of the port of Antwerp. Shuttle services transport containers from inland terminals to sea terminals in the port area and carry containers from sea terminals to inland destinations in a round trip. A structural overview of the current network figuration, as assumed in the further analysis, is presented in figure 1. Three regions of origin can be identified in the Belgian hinterland network of the port of Antwerp (figure 2). The first group of container terminals is situated along the Albert Canal towards the eastern part of Belgium. A second region of origin is located in the central part of the country, connected to the port of Antwerp by the Brussels - Scheldt Sea Canal. The third group of intermodal container flows originates in the basin of the Upper Scheldt and the river Leie. In the port area clusters are identified as all sea terminals at the same side of three lock systems. A first cluster of sea terminals is situated on the right river bank behind the locks. This cluster will be referred to as 'right river bank'. The second cluster consists of sea terminals on the left river bank at the Deurganckdok and the sea terminals on the right river bank in front of the locks at the river Scheldt. These sea terminals are directly accessible from the sea side through the river Scheldt and are jointly referred to as 'left river bank' in the subsequent analysis. Barges have to pass one of the three available lock systems to sail between the two clusters. Barges may also sail through the Scheldt-Rhine connection to Rotterdam and Amsterdam or through the Scheldt estuary to the port of Zeebrugge.

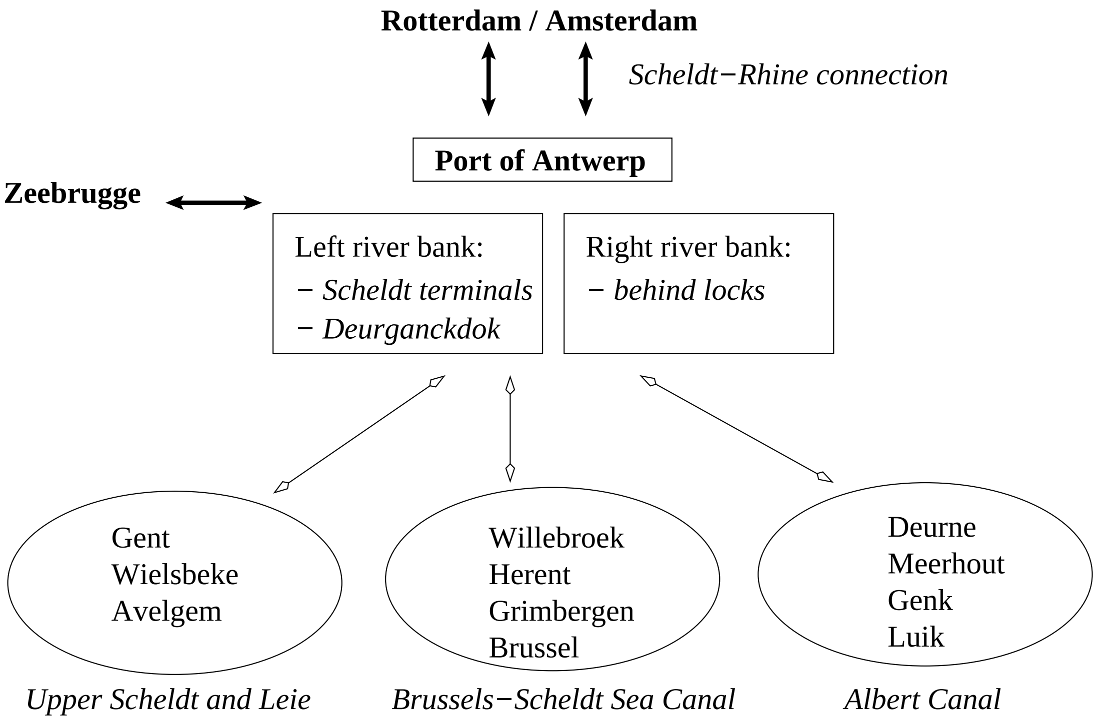

Figure 1: Current network configuration

The problem size of line bundling in intermodal barge transport is restricted by the number of terminals involved. Therefore, the number of possible scenarios is limited and may thus be enumerated. Possible cooperation scenarios are identified based on practical knowledge and rationale. The result of this section is an insight in promising cooperation scenarios between inland barge terminals along each of the three main waterway axes. These cooperation schemes are introduced in the SIMBA model in the next section and compared with the results of bundling in the port area, as presented by Caris et al. (2010). In order to analyze potentials for cooperation, the assumption is made that each terminal maintains the same service level towards its customers as in the current situation. This implies that the same number of departures needs to be offered. Therefore, cooperation scenarios are analyzed per departure day. The analysis of bundling in the hinterland is based on the same data collection as described in Caris et al. (2010).

Figure 2: Belgian hinterland network of Antwerp (www.containerafvaarten.be)

4.1 Albert Canal

Four inland terminals are situated along the Albert Canal, each offering departures to sea terminals on the right and left river bank in the port of Antwerp. Figure 3 depicts the hinterland network along the Albert Canal. Cooperation scenarios are discussed in detail for departures on Tuesday, which is the first weekday all terminals offer a departure to the port of Antwerp. Results for other departure days are based on similar scenario analyses. Products are defined by an origin node, destination node and daily demand w^p, expressed in Twenty feet Equivalent Units (TEU). Average volumes demanded on Tuesday are summarized in table 1. On this day of the week the terminal of Meerhout bundles its own freight to the left river bank.

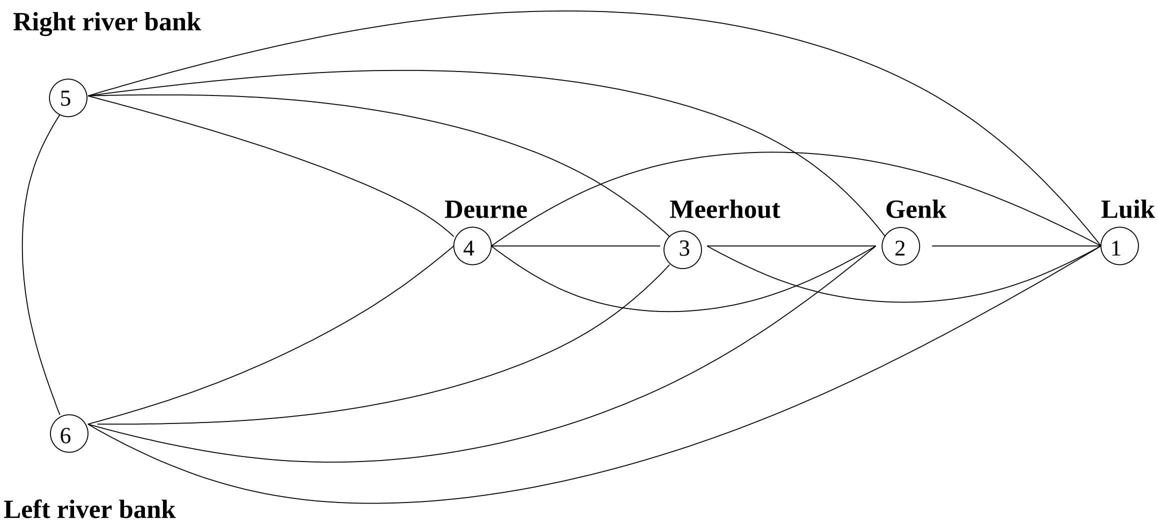

Figure 3: Hinterland network along Albert Canal

Table 1: Set of products - Albert Canal on Tuesday

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

Cost information has been obtained from contacts with inland barge terminals. Base costs f^k of possible roundtrips k consist of the cost of chartering the smallest vessel on a daily basis, cooperation costs in the hinterland and a waiting cost at lock systems in the port area. The cost of chartering the smallest vessel varies per terminal, as given in table 2. A waiting cost of 400 euro is associated with arcs connecting port nodes and a cooperation cost of 400 euro is charged for each stop at an intermediate terminal, thus for each arc connecting inland nodes.

Table 2: Base cost for chartering smallest vessel one-way - Albert Canal

Terminal	Cost
Deurne	500
Meerhout	1000
Genk	1200
Luik	1400

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

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

These transportation costs stand for the additional cost of chartering a larger vessel. The vessel size x is expressed in TEU. The nonlinear function captures economies of scale obtained by bundling freight flows. A larger vessel size results in lower costs per container when a volume of at least 100 TEU is reached. Vessel size is expressed in the model formulation as the sum of freight flows and freight imbalance on a link $(i, j) \in A^B$:

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

The time frame of the analysis is a single day. It is assumed that a vessel can make a roundtrip within this time window. For connections between the terminal at Deurne and the port area this discrete cost function is divided by two. Due to its very near location to the port area, vessels can make a roundtrip in half a day.

Three cooperation scenarios are identified along the Albert Canal on Tuesday. The first scenario in figure 4 represents the current situation in which terminals operate independently. The numbers next to the arrows represent the flow (expressed in TEU) on each arc in the network.

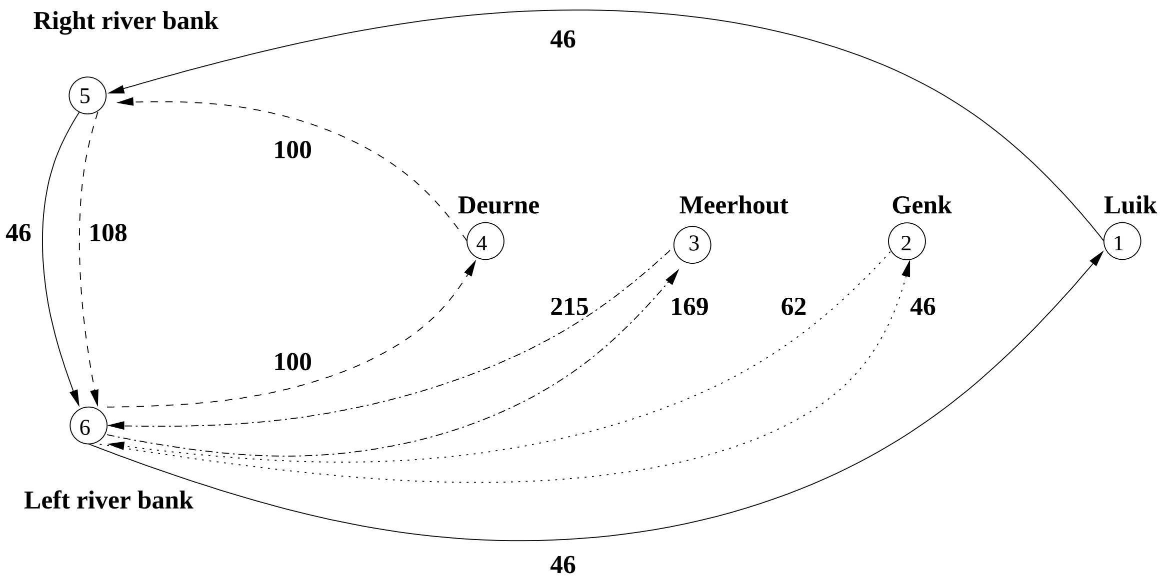

Figure 4: Albert Canal: Cooperation scenario 1 on Tuesday

In the second scenario the terminals of Luik, Genk and Deurne jointly operate two roundtrips. In the first joint roundtrip freight is bundled for the right river bank. The second roundtrip collects freight to and from the left river bank. The terminal of Meerhout operates its own roundtrip to the left river bank. This is depicted in figure 5.

The third scenario implies cooperation between Luik, Genk and Deurne in a single roundtrip serving both clusters of sea terminals, as shown in figure 6. These three inland terminals represent smaller freight flows and may benefit from cooperation. The terminal of Meerhout has enough volume to reach economies of scale on its own and thus may benefit less from cooperating with other terminals with the objective to charter a larger vessel. On the other hand, cooperation with other terminals would enable the terminal of Meerhout to further increase its frequency of service.

Table 3 compares the costs of these cooperation scenarios. For each scenario roundtrips and associated base costs f^k are given. Next, variable costs ϕ_{ij} are deducted from the flow on links between port nodes and inland nodes.

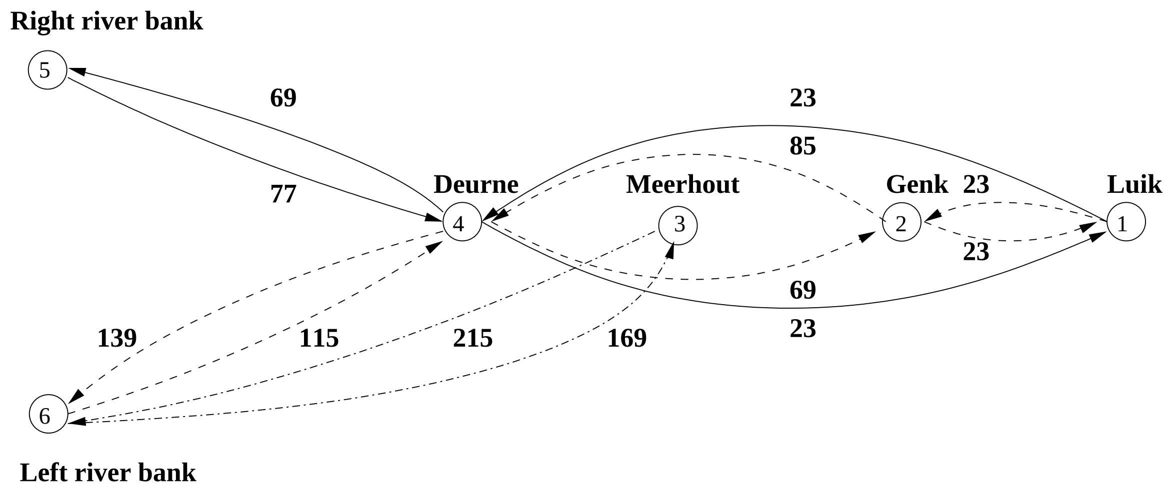

Figure 5: Albert Canal: Cooperation scenario 2 on Tuesday

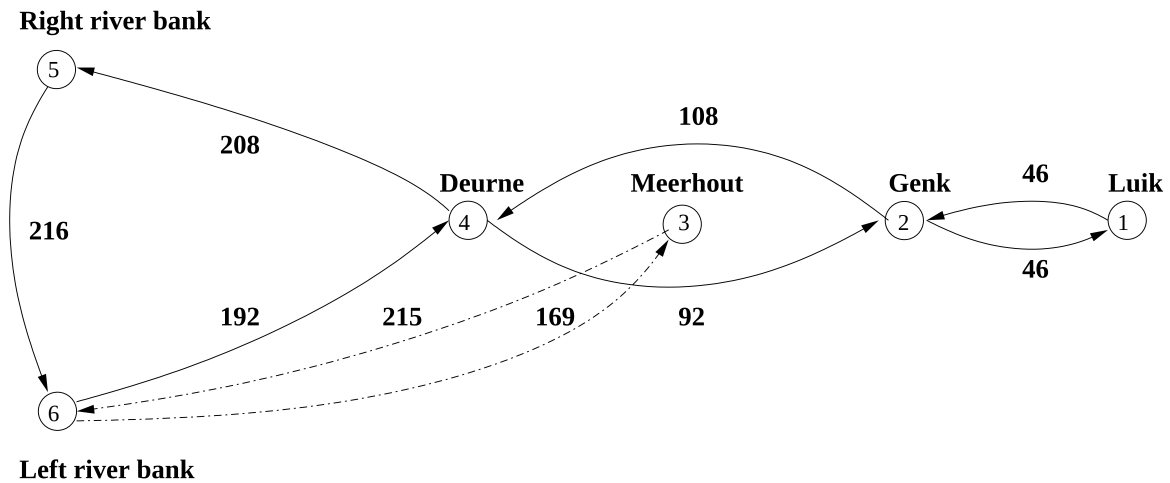

Figure 6: Albert Canal: Cooperation scenario 3 on Tuesday

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

The same methodology is applied for each day of the week, leading to the selected cooperation scenarios in table 4. The table mentions the roundtrips performed per day in order to minimize total costs of the network as a whole. Terminals 1 and 2 in Luik and Genk cooperate on each weekday. These terminals are closely located to each other but have a relatively long sailing time to the port of Antwerp. Their freight volumes are smaller due to the daily frequency of service. An opportunity exists to bundle their flow and reach economies of scale, while still main-

Table 3: Cost comparison of cooperation scenarios along Albert Canal on Tuesday

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

taining the same service schedule. Terminal 3 in Meerhout attracts enough volume to achieve economies of scale by bundling its own freight. Roundtrips are organized to either the right river bank or the left river bank. Terminal 4 in Deurne may cooperate with terminals 1 and 2 (Tuesday and Wednesday) or with terminal 3 (Thursday). However, as stated in the scenario analysis of Tuesday, this terminal has less financial incentives to cooperate due to its nearby location to the port area.

Table 4: Selected cooperation scenarios along Albert Canal

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

4.2 Brussels-Scheldt Sea Canal

Three inland terminals offer regular departures along the Brussels-Scheldt Sea Canal, as shown in figure 7. The terminal at Herent is left out of the analysis since it is situated along the Canal

Leuven-Dijle, which is only navigable for vessels up to 600 tons. Each terminal offers a daily service to the port of Antwerp, resulting in relatively small individual freight volumes. Table 5 presents average volumes transported from the three inland terminals to both clusters of sea terminals in the port of Antwerp on Monday in TEU. Table 6 mentions the cost of chartering the smallest vessel departing from each terminal. A waiting cost of 400 euro is assumed along arcs connecting port nodes and a cooperation cost of 400 euro is incurred when selecting arcs between inland nodes. Variable costs on arcs connecting the port area with the hinterland are represented by the same discrete cost function along all three waterway axes in the hinterland of the port of Antwerp.

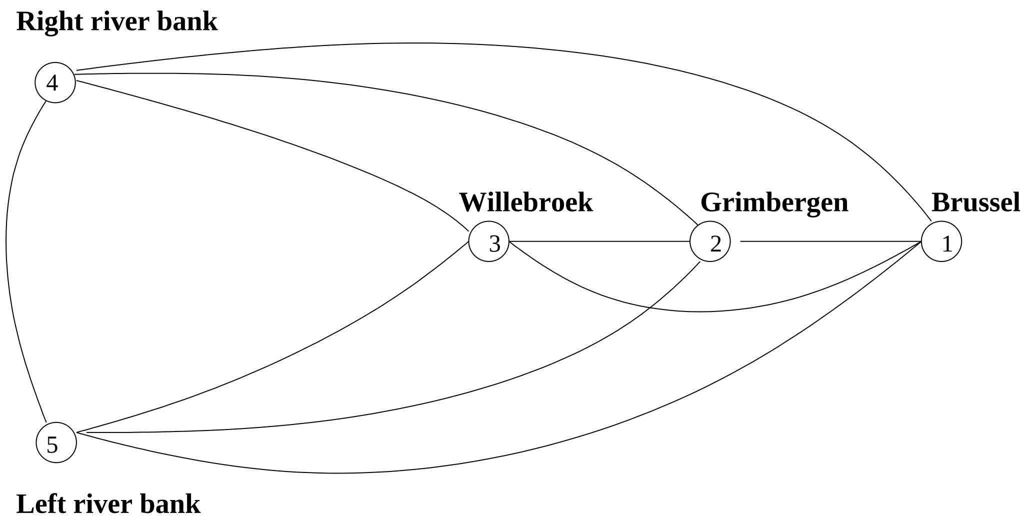

Figure 7: Hinterland network along Brussels-Scheldt Sea Canal

Table 5: Set of products - Brussels-Scheldt Sea Canal on Monday

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

Three cooperation scenarios are investigated for departures on Monday. In the first scenario each terminal organizes its own shuttle service, as depicted in figure 8.

Table 6: Base cost for chartering smallest vessel one-way - Brussels-Scheldt Sea Canal

Terminal	Cost
Willebroek	750
Grimbergen	1000
Brussel	1000

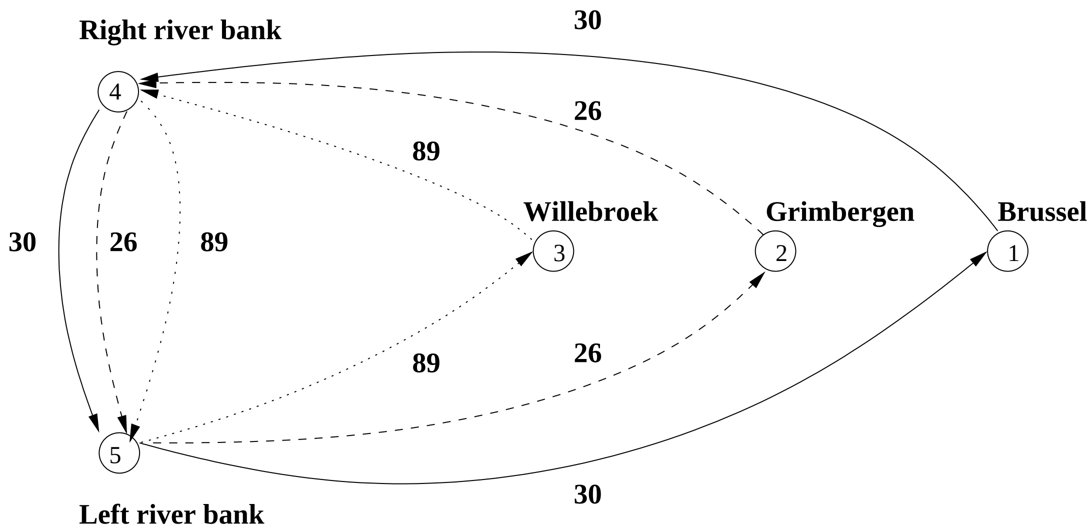

Figure 8: Brussels-Scheldt Sea Canal: Cooperation scenario 1 on Monday

The second scenario consists of two separate roundtrips in which the three terminals cooperate, but bundle freight with the same origin or destination in the port area. The first roundtrip sails to and from sea terminals on the right river bank, the second roundtrips serves sea terminals on the left river bank. This situation is shown in figure 9.

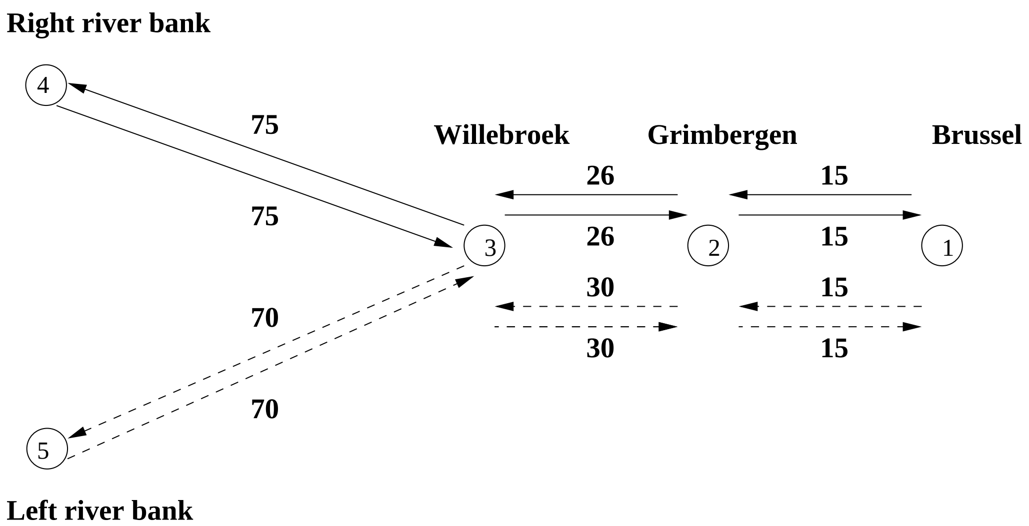

Figure 9: Brussels-Scheldt Sea Canal: Cooperation scenario 2 on Monday

The final scenario represents full cooperation in a single roundtrip sailing to the right and left river bank (figure 10).

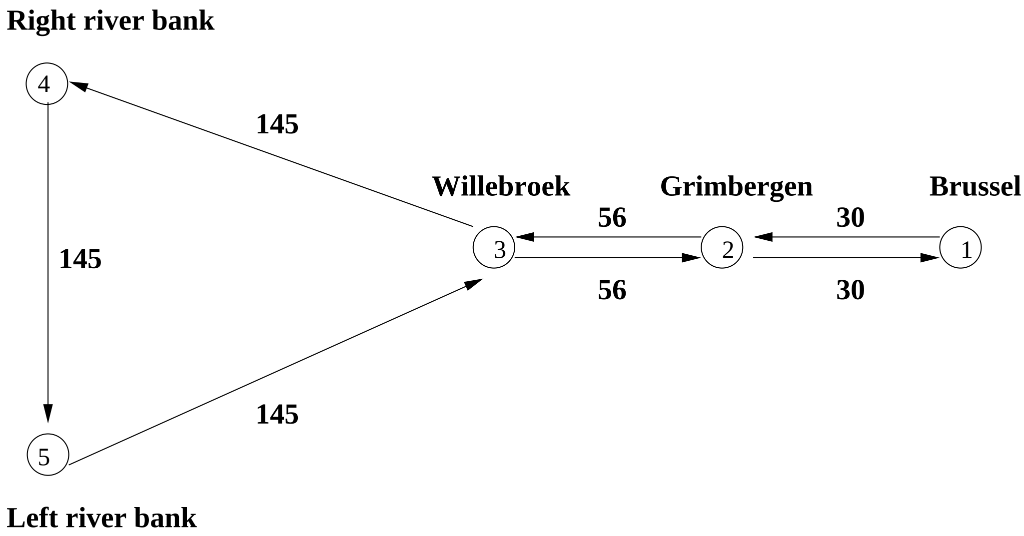

Figure 10: Brussels-Scheldt Sea Canal: Cooperation scenario 3 on Monday

A cost comparison of these three cooperation scenarios is presented in table 7. Total costs are minimized in the third scenario, implying full cooperation in a single roundtrip. Terminals 1 and 2 in Brussel and Grimbergen carry high costs in the current scenario due to their small volumes and daily schedules. By bundling their freight with terminal 3 at Willebroek in a single roundtrip only one vessel needs to be chartered instead of three. The inland terminal at Willebroek gathers more volume on its own and thus has less tendency to cooperate than the other two terminals. In the second cooperation scenario the gain of avoiding waiting costs at lock systems in the port area does not outweigh the additional cost of chartering an extra vessel. Similar analyses on other weekdays lead to the conclusion that full cooperation between the three terminals in a single roundtrip is always the most beneficial scenario along the Brussels-Scheldt Sea Canal when optimizing the complete waterway network.

4.3 Upper Scheldt and river Leie

Three inland terminals are located in the Western part of the Belgian hinterland of the port of Antwerp. The network structure is depicted in figure 11. The terminals at Wielsbeke and Avelgem are very near to each other but along a different waterway axis. Each may organize a corridor network with the terminal at Gent. The terminal at Gent could also function as an inland hub, but this would require extra handling of containers between barges. In contrast, line bundling only requires containers to be added onto the vessel and thus no extra handling. An overview of average transport demand on Wednesday in TEU between the three terminals and the port of Antwerp is given in table 8. Costs of chartering the smallest vessel are summarized in table 9. All other costs are assumed to be the same as in the analyses of the Albert Canal and the Brussels-Scheldt Sea Canal.

Table 7: Cost comparison of cooperation scenarios along Brussels-Scheldt Sea Canal on Monday

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

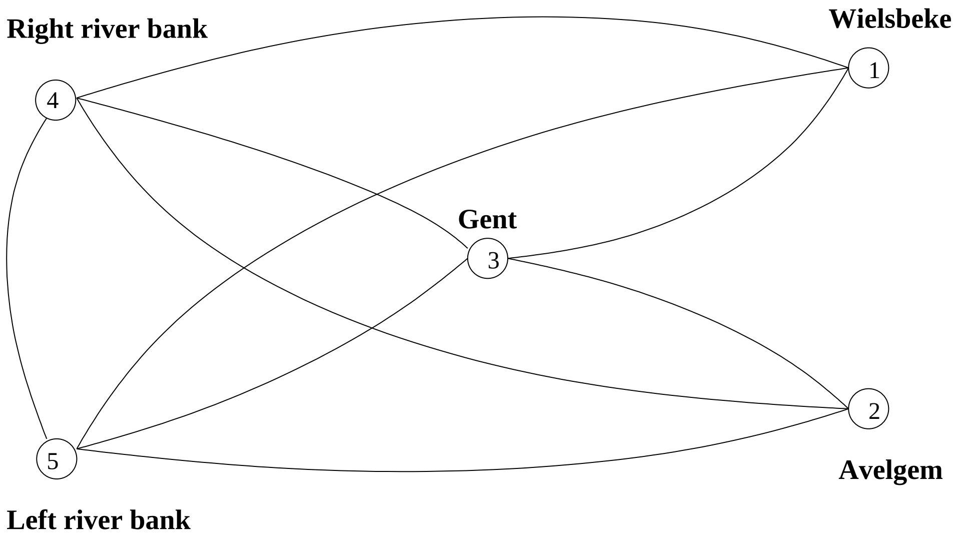

Figure 11: Hinterland network along Upper Scheldt and river Leie

Three cooperation scenarios are identified in the hinterland network on Wednesday. In the first scenario each terminal offers its own roundtrip to customers. Figure 12 shows the resulting roundtrips and freight flows. In the second scenario Wielsbeke and Gent organize a joint roundtrip, while Avelgem maintains its own shuttle service. This situation is depicted in figure 13.

Table 8: Set of products - Upper Scheldt and river Leie on Wednesay

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

Table 9: Base cost for chartering smallest vessel one-way - Upper Scheldt and river Leie

Terminal	Cost
Gent	1000
Wielsbeke	1200
Avelgem	1400

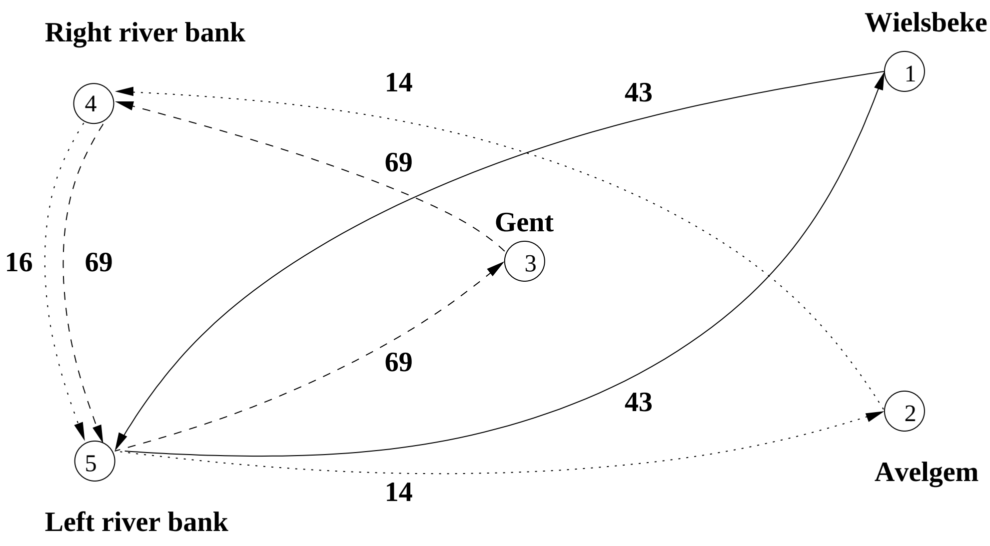

Figure 12: Upper Scheldt and river Leie: Cooperation scenario 1 on Wednesday

Avelgem and Gent set up a corridor network in the third cooperation scenario, while Wielsbeke organizes its own shuttle service (figure 14). The three cooperation scenarios on Wednesday are compared in table 10. Scenarios two and three require the same number of roundtrips. The third scenario is the most interesting from a network perspective. The terminal of Wielsbeke only has to visit sea terminals on the left river bank. Waiting costs in the port area are less in this scenario

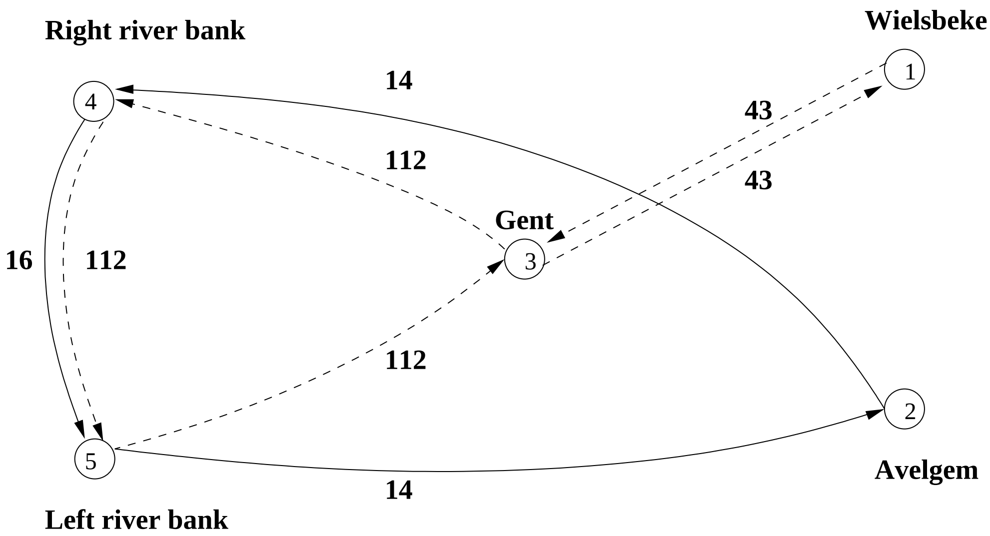

Figure 13: Upper Scheldt and river Leie: Cooperation scenario 2 on Wednesday

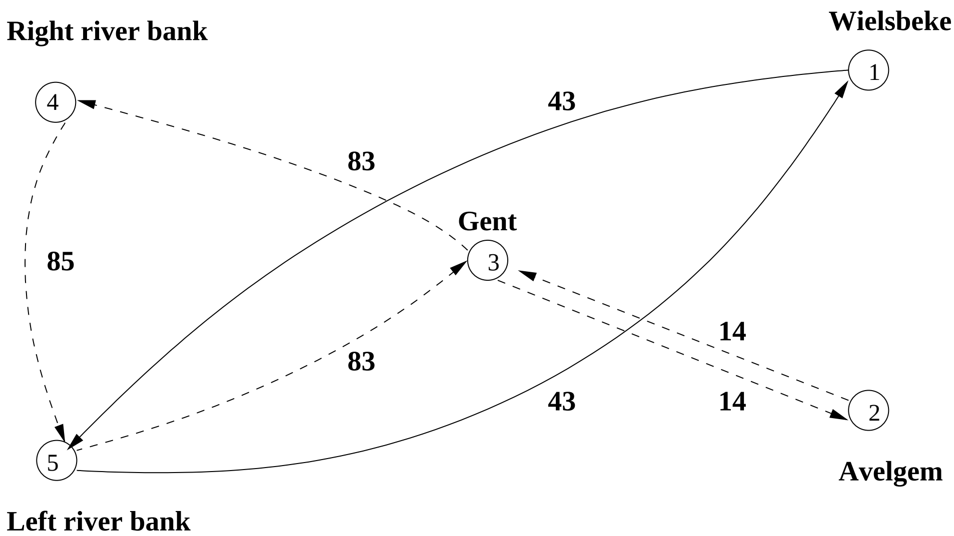

Figure 14: Upper Scheldt and river Leie: Cooperation scenario 3 on Wednesday

compared to the second scenario.

The cost comparison depends on the assumptions made about the discrete cost function representing economies of scale, coordination costs and waiting costs. However, the methodology allows to analyze line bundling given any changes in cost structure. In scenarios two and three cooperation between two terminals still does not lead to bundling large volumes of freight. Opportunities to achieve economies of scale related to the port of Antwerp are not large in this region of the hinterland. In both scenarios total costs after cooperation are less than or equal to the current operations. Departures are also organised on Monday and Friday. Terminal three in Gent does not ship any containers to the port of Antwerp on these days, so no line bundling opportunities exist. Resulting roundtrips are presented in table 11.

Table 10: Cost comparison of cooperation scenarios along Upper Scheldt and river Leie on Wednesday

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

Table 11: Selected cooperation scenarios along Upper Scheldt and river Leie

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

5 COMPARING BUNDLING IN THE HINTERLAND WITH BUNDLING IN THE PORT AREA

The selected cooperation schemes from section 4 are modelled in a new simulation scenario for the SIMBA model, as described in Caris et al. (2009). The SIMBA model covers the hinterland waterway network of the port of Antwerp. The operations of the inland navigation network are modeled in detail. This enables us to examine ex-ante the effects of alternative ways of organization of container barge transport. The objective of the simulation model is to assess the impact of policy measures on performance measures such as turnaround time of vessels, waiting time of barges in the port area and handling time of inland barges at sea terminals. In the new line bundling scenario, inland barges stop at intermediate terminals to consolidate freight in the Belgian hinterland of the port of Antwerp. The same approach as in Caris et al. (2010) is applied to compare results with the current situation in which no bundling takes place. For each scenario ten simulation runs of 672 hours are performed. Table 12 reports on the average turnaround times of all inland terminals, expressed in hours, in the current scenario and cooperation scenario.

Performance measures in the port area are given in table 13. The average and maximum

Table 12: Average turnaround times current situation and bundling in hinterland

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

waiting time before handling, expressed in hours, are measured at the sea terminals on the right and left river bank. Secondly, the table mentions the average and maximum utilization of quays on the right and left river bank.

Table 13: Performance measures in the port area: current situation and line bundling in hinterland

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

In table 14 paired-*t* confidence intervals are constructed to compare the results. An overview is given of the 95% confidence intervals which report a significant difference between the current situation and the cooperation scenario.

Table 14: Confidence intervals comparing the current situation with line bundling in hinterland

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

Table 14 shows a significant increase in the turnaround time of a number of terminals. Terminals engaging in a cooperation scheme have to take a longer turnaround time into account. This may reduce the delivery speed and thus the competitive position of intermodal barge transport compared to unimodal road transport. First, cooperation between inland terminals implies extra stops along the route. The extra stops have to be anticipated in the departure time of barges. The more terminals involved in a corridor network, the more stops are required in a corridor network. A solution may be to organize an inland collection/distribution network in which a single terminal serves as an inland hub. Secondly, terminals which already consolidate freight to a single cluster of sea terminals see their turnaround time increase when both clusters of sea terminals are served in the cooperation scenario. Table 13 and 14 show only small or no improvements in performance measures in the port area.

Cooperation along river axes in the hinterland offers less efficiency gains at the sea terminals compared with the bundling scenarios in the port area studied in Caris et al. (2010). Freight may be bundled in the port area at a dedicated quay for inland vessels, representing an intermodal barge hub. The introduction of an intermodal barge hub in the port area results in an uncoupling of collection and distribution services in the port area from trunk haul services to the hinterland Konings (2007). Such a network concept may be categorized as a connected hubs design in the generic terminology of Woxenius (2007). By doing so inland barges do not have to call at multiple sea terminals. They only visit the intermodal barge hub and the inland terminal. This leads to a reduction in turnaround time of vessels serving the hinterland. In the collection/distribution network containers with the same origin or destination can be bundled. This enables a more efficient and prompt handling of barges at sea terminals. In Caris et al. (2010) four alternative bundling scenarios are analysed with the SIMBA model for the port of Antwerp.

In corridor networks freight of a limited number of inland terminals is bundled, while remaining the same service level offered to customers. More opportunities to attain economies of scale may exist when reducing the number of sailings per week, given current transport volumes. From these results it can be concluded that the main motivation for setting up a corridor network in the hinterland is to attain economies of scale for inland terminals or to increase their frequency of service. No major impact is recorded on average waiting times of inland barges in the port area, but an improvement in maximum waiting times at peak moments may be observed. At present the observed inland terminals are owned by different private companies. However, sea terminal operators are gradually taking a share in inland terminal operations. This new tendency opens perspectives for future cooperation between inland terminals. Inland terminals are thinking about cooperation, but at the same time competitiveness issues exist and questions are raised about organizational issues and the distribution of benefits.

6 CONCLUSIONS

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

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

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

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