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# Optimal shipping routes and vessel size for intermodal barge transport with empty container repositioning<sup>1</sup>

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## Abstract

Despite the growing role of barge transportation in the hinterland access of major seaports in Northwestern Europe, service network design for intermodal barge transportation has received little research attention. In this paper, a decision support model for service network design in intermodal barge transportation is presented. The model determines optimal shipping routes for roundtrip services between a major seaport and several hinterland ports located along a single waterway. Vessel capacity and service frequency decisions may be analyzed by the model. A case study on the hinterland network of the port of Antwerp in Belgium is discussed. The decision support model is applied from the perspective of barge operators as well as from the perspective of shipping lines that offer door-to-door transport services. In the latter case, empty container repositioning decisions are taken into account. Numerical experiments are presented to indicate how the model may be used in practice.

## Keywords

Intermodal barge transportation, service network design, decision support, empty container repositioning

## 1. Introduction

This paper studies the transportation of containers by barge between a seaport and container terminals at a number of hinterland ports. During the last two decades intermodal barge transport has gained market share in Northwestern Europe, with annual growth figures up to 15% [1]. Currently, barge transport plays an important role in the hinterland access of major seaports in this region. For the port of Antwerp in Belgium, the share of barge transport in the modal split rose from 22.5% to 34.8% between 1999 and 2009 [2]. Although many interesting contributions to literature have been made, Caris et al. [3] indicate several intermodal planning problems that need further research attention, like service network design for intermodal barge transportation.

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Crainic and Laporte [4] state that service network design is an important issue at the tactical decision level for intermodal transportation. It is involved with the selection of routes on which services are offered and the determination of characteristics of each service, particularly its frequency. State-of-the-art reviews on service network design in freight transportation are presented by Crainic [5] and Wieberneit [6]. An overview of models for service network design in intermodal transportation may be found in Crainic and Kim [7]. Research on service network design specifically for intermodal barge transportation is scarce. Main decisions in the context of barge transportation include decisions on shipping routes, vessel capacity and service frequency. Additionally, it may be analyzed how and when empty container repositioning needs could be taken into account [5].

Woxenius [8] presents six different types of network design for intermodal transport. For geographical reasons, barge transportation is mainly based on a corridor network or line bundling design: a high-density flow along an artery with short capillary services to nodes off the corridor. Caris et al. [9] consider service network design for such corridor networks in barge transport. The authors study advantages of cooperation between hinterland terminals and different bundling strategies for barge transportation in the hinterland of the port of Antwerp. The feasibility of hub-and-spoke networks in intermodal barge transportation is analyzed by Konings [10]. Groothedde et al. [11] study the design of such a hub-and-spoke network for transporting palletized fast moving consumer goods by barge and road transport. Finally, empty container repositioning in the context of service network design for intermodal barge transportation is studied by Maraš [12]. The author adapts a model introduced by Shintani et al. [13] for service network design in maritime shipping. A mathematical model is proposed to determine the optimal barge shipping route for a single vessel along a linear network while taking empty container repositioning movements into account. Any fraction of transport demand may be satisfied and the start and end port are fixed in advance. Maraš [12] is able to find optimal solutions by using commercial software. The author finds the profit maximizing routes for five types of vessels for a single transport demand situation.

In this paper, a decision support model for service network design in the context of containerized barge transportation is proposed. A corridor network design is assumed. This means that vessels bundle freight of several ports located along a single waterway. The model may be used by barge operators or shipping lines that want to charter a vessel to offer regular roundtrip barge services between a number of ports located along a waterway. When considering a roundtrip service, vessel capacity and frequency of roundtrips have to be defined. For each service type (capacity and frequency) the model determines the optimal shipping routes (the ports to be visited) and the number of containers to be transported. The decision maker may use this information to evaluate all possible types of service and choose the best among them. An application on the hinterland network of the port of Antwerp in Belgium is presented. The versatility and flexibility of the model is demonstrated by applying it in two different problem contexts.

First, the model is applied from the perspective of inland barge operators. Assuming transport demand is known and may be foregone, the objective of inland barge operators is to determine roundtrip barge services which maximize profits. Inland barge operators generally do not operate an own fleet of containers and are therefore not concerned with empty container repositioning needs. Second, the model is applied from the perspective of shipping

lines which operate a fleet of containers. When containers are transported under the carrier haulage principle, door-to-door services are provided by shipping lines. Shipping lines arrange both the maritime and inland transport part. In that case, shipping lines are responsible for both the design of barge services and for empty container repositioning. In barge transportation, these repositioning movements are made by using excess capacity of container vessels [12,14]. Hence, empty container repositioning needs may be taken into account when determining shipping routes.

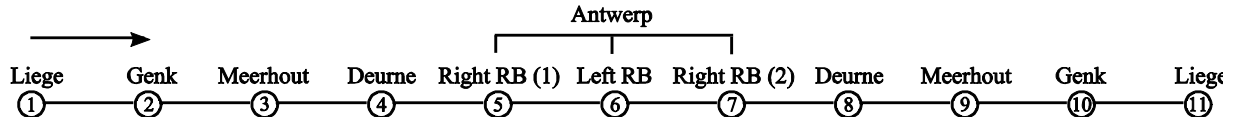
The proposed model differs from the one of Maraš [12] in several ways. Two problem contexts are considered, the start and end port are not defined in advance, more realistic assumptions regarding fulfilling transport demand are made, transport demand may vary over the weeks and multiple vessels might be used to offer roundtrips.

The outline of the paper is as follows. Section 2 describes the general framework of the model and how it is applied to the hinterland network of the port of Antwerp. In the following two sections (Sections 3 and 4), the application of the model for the two problem contexts described above is presented. Finally, conclusions and ideas for further research are discussed in Section 5.

## **2. Model framework and application**

The decision support model is applied to the situation of the Albert Canal in Belgium. The Albert Canal connects the port of Antwerp with hinterland ports in Deurne, Meerhout, Genk and Liege. Vessels start their roundtrips at a port in the hinterland, travel to the port of Antwerp and finally return to the same hinterland port. In between, several other hinterland ports may be visited. In the port area of Antwerp, two clusters of sea terminals may be identified, one on the right river bank (RRB) and one on the left river bank (LRB). Both clusters are separated by three lock systems. The Albert Canal flows into the river Scheldt in the port area on the right river bank. This means that vessels coming from the Albert Canal have to pass a lock in the port area twice when visiting the cluster on the left river bank. Because traveling between both clusters may take two and a half hours, they are considered as separate nodes in the network. It is assumed that there is a central hub terminal at each river bank which the vessels may visit. This resembles the concepts proposed by Konings [15] and Caris et al. [16] to split barge services in a hinterland service and a collection/distribution service in the port area to avoid barges having to call at multiple terminals in the port area. If both hub terminals in the port of Antwerp are visited, the order of visiting should be free to choose since this may have an impact on the outcome of the model. In order to preserve the linear representation of the ports, a duplicate node is created for the terminal at the right river bank. All hinterland ports are duplicated as well to facilitate the formulation of the problem. The final network representation is shown in Figure 1. The port of Liege is represented by nodes 1 and 11, Genk by nodes 2 and 10, Meerhout by nodes 3 and 9, Deurne by nodes 4 and 8, Antwerp right river bank by nodes 5 and 7 and finally Antwerp left river bank by node 6.

Figure 1: Network representation



A vessel starts its roundtrip at one of the hinterland ports and can only travel from a node to another node with a higher number. The end port should be the same as the start port and at least one of the river banks in Antwerp is visited during a roundtrip. Since distances on the Albert Canal are rather small, vessels may perform several roundtrips per week. Therefore, in this paper, a service type is defined by the capacity of the vessel(s) and its/their weekly number of roundtrips.

A six day working week is assumed and transport demand is modeled as follows. Each day at each hinterland port a number of clients may request (loaded) containers to be transported from the hinterland port to one of the river banks in Antwerp. Similarly, each day other clients may request containers to be transported from one of the river banks of the port of Antwerp to a hinterland port. Transport demand between two hinterland ports is not assumed. When a service type is considered, the model determines in a preprocessing step which transport demand may be satisfied by which roundtrip. Finally, for clarity purposes only a single container type is considered. To take multiple container types into account, slight modifications to the problem formulation are required.

Two problem characteristics which influence the model formulation and solution complexity may be identified. The proposed model is able to deal with all combinations of problem characteristics although the formulation and solution complexity will differ.

First, it could be assumed that each client has the same transport demand every week or it could be assumed that weekly transport demand is variable. The latter may occur when some clients have a weekly transport demand while others only demand containers to be transported every two or three weeks. When considering a constant weekly demand, roundtrips will be the same every week (since it is assumed that when the transport demand of a client is fulfilled in one week, it has to be fulfilled in all weeks). Therefore, it suffices to model only a single week. On the other hand, when demand varies over the weeks, the planning period has to be extended to take this into account. The planning period will be equal to a single demand cycle (each demand occurs at least once). Differences with the single week model are that roundtrips do not have to be the same each week. However, for customers with a weekly demand, the constraint that the demand of all weeks needs to be met if any, is still valid. Although the formulation of the model is very similar as for the constant weekly demand, solution complexity will be larger.

Second, the model formulation and solution complexity depend on whether only a single vessel is used to provide services or whether multiple vessels are employed. In all cases, it is assumed that transport demand may be fulfilled by only a single roundtrip of each vessel (the first after the demand was raised) which means transport demand cannot be transferred to a later roundtrip of the same vessel. When a single vessel is used, it is possible to establish a many-to-one relationship between transport demands and roundtrips, i.e. each transport demand can only be performed by a single roundtrip. When multiple vessels are used, this is not the case and solution complexity increases.

### 3. Perspective of barge operators

This section describes how the proposed model may be used by a barge operator. First, the model formulation is presented (Section 3.1) Next, random instances are generated and numerical experiments are presented in Section 3.2.

#### 3.1 Model formulation

Based on forecasted transport demand for loaded and empty containers, barge operators provide roundtrips between a number of hinterland ports and the seaport on a fixed schedule. Roundtrips are planned with the objective to maximize profit. Barge operators do not manage an owned or leased fleet of containers. As a consequence, they are generally not concerned with empty container repositioning decisions. Empty containers are only transported when this is demanded by shippers or shipping lines. Since the model takes the viewpoint of a single company and the objective is to maximize profit, unprofitable transport demand may be turned down.

Revenues are generated by transporting loaded and empty containers. Freight rates for loaded containers are generally higher than for transporting empty containers. For each pair of ports, transport demand consists of the sum of the demand of several clients. Either all transport demand of a particular client is satisfied (during the total planning period) or all transport demand is turned down. Costs included in the model are daily charter and crew costs, distance-related fuel and maintenance costs, port entry costs and container handling costs at the ports. No costs for turning demand down are assumed. The major constraints are related to vessel capacity and maximum roundtrip duration. Maximum roundtrip duration of a vessel is determined by dividing the number of days per week (six) by the weekly number of roundtrips of the vessel.

First, the formulation of the model for the case with a single vessel and constant weekly demand is presented. Each transport demand may be fulfilled by only a single roundtrip and the length of the planning period is a single week. Next, it is discussed how the model may be adapted to situations with varying weekly demand or multiple vessels. The following notation is used:

$N = \{1, \dots, 11\}$  = set of nodes (indices  $i, j, k$ )

$c_i^e$  = entry cost at node  $i$  (€)

$c_i^h$  = handling cost at node  $i$  (€/TEU)

$t_i^m$  = sum of mooring and unmooring time at node  $i$  (h)

$t_i^h$  = handling time at node  $i$  (h/TEU)

$L = \{(i, j) | i \in N, j \in N, i < j, i \neq 5 \text{ or } j \neq 7\}$

$d_{ij}$  = distance between nodes  $i$  and  $j$  (km)

$t_{ij}$  = travel time between nodes  $i$  and  $j$  (h)

$f_{ij}^l$  = freight rate for loaded containers between nodes  $i$  and  $j$  (€/TEU)

$f_{ij}^e$  = freight rate for empty containers between nodes  $i$  and  $j$  (€/TEU)

$R = \{1, \dots, r\}$  = set of roundtrips

$Cap^r$  = capacity of the vessel performing roundtrip  $r$  (TEU)

$c_{char}^r$  = charter and crew costs for the vessel performing roundtrip  $r$  (€/day)

$c_{fuel}^r$  = fuel and maintenance costs for the vessel performing roundtrip  $r$  (€/km)

$t_{max}^r$  = maximum duration of roundtrip  $r$  (days)

$B = \{1, \dots, b\}$  = set of clients

$dem_{ij}^{bl}$  = loaded container transport demand of client  $b$  on link  $(i, j)$  (TEU)

$dem_{ij}^{be}$  = empty container transport demand of client  $b$  on link  $(i, j)$  (TEU)

$w_{ij}^{rb} = \begin{cases} 1 & \text{if demand of client } b \text{ on link } (i, j) \text{ may be performed by roundtrip } r \\ 0 & \text{else} \end{cases}$

$WNR$  = weekly number of roundtrips performed by the vessel

$TNR$  = total number of roundtrips performed by the vessel over the planning period

$M$  = a large number

The following binary decision variables are introduced:

$a_{ij}^{rb} = \begin{cases} 1 & \text{if transport demand of client } b \text{ on link } (i, j) \text{ is fulfilled during roundtrip } r \\ 0 & \text{else} \end{cases}$

$z_i^r = \begin{cases} 1 & \text{if node } i \text{ is visited during roundtrip } r \\ 0 & \text{else} \end{cases}$

$pre_i^r = \begin{cases} 1 & \text{if a node is visited before node } i \text{ during roundtrip } r \\ 0 & \text{else} \end{cases}$

$suc_i^r = \begin{cases} 1 & \text{if a node is visited after node } i \text{ during roundtrip } r \\ 0 & \text{else} \end{cases}$

To simplify the notation additional variables are introduced:

$D^r$  = distance traveled during roundtrip  $r$  (h)

$T_{hour}^r$  = number of hours the vessel is used during roundtrip  $r$  (h)

$T_{day}^r$  = number of days the vessel is used during roundtrip  $r$  (days)

$x_{ij}^r$  = number of loaded containers transported on link  $(i, j)$  during roundtrip  $r$  (TEU)

$y_{ij}^r$  = number of empty containers transported on link  $(i, j)$  during roundtrip  $r$  (TEU)

The problem is formulated as follows:

$$\begin{aligned} \max \sum_{r \in R} \sum_{(i,j) \in L} & \left( x_{ij}^r \cdot f_{ij}^l + y_{ij}^r \cdot f_{ij}^e \right) - \sum_{r \in R} c_{char}^r \cdot T_{day}^r - \sum_{r \in R} c_{fuel}^r \cdot D^r - \sum_{r \in R} \sum_{i \in N} z_i^r \cdot c_i^e \\ & - \sum_{r \in R} \sum_{(i,j) \in L} (x_{ij}^r + y_{ij}^r) \cdot (c_i^h + c_j^h) \end{aligned} \quad (1)$$

Subject to

$$x_{ij}^r = \sum_{b \in B} dem_{ij}^{bl} \cdot a_{ij}^{rb} \quad \forall r \in R, \forall (i, j) \in L \quad (2)$$

$$y_{ij}^r = \sum_{b \in B} dem_{ij}^{be} \cdot a_{ij}^{rb} \quad \forall r \in R, \forall (i, j) \in L \quad (3)$$

$$D^r = \sum_{i \in \{2,3,4,5\}} d_{i-1,i} \cdot pre_i^r + (d_{5,6} + d_{6,7}) \cdot z_6^r + \sum_{i \in \{7,8,9,10\}} d_{i,i+1} \cdot suc_i^r \quad \forall r \in R \quad (4)$$

$$\begin{aligned} T_{hour}^r = & \sum_{i \in \{2,3,4,5\}} t_{i-1,i} \cdot pre_i^r + (t_{5,6} + t_{6,7}) \cdot z_6^r + \sum_{i \in \{7,8,9,10\}} t_{i,i+1} \cdot suc_i^r \\ & + \sum_{i \in N} t_i^m \cdot z_i^r + \sum_{(i,j) \in L} (x_{ij}^r + y_{ij}^r) \cdot (t_i^h + t_j^h) \end{aligned} \quad \forall r \in R \quad (5)$$

$$24 \cdot T_{day}^r \geq T_{hour}^r \quad \forall r \in R \quad (6)$$

$$T_{day}^r \leq t_{\max}^r \quad \forall r \in R \quad (7)$$

$$2 \cdot a_{ij}^{rb} \leq (z_i^r + z_j^r) \cdot w_{ij}^{rb} \quad \forall r \in R, \forall b \in B, \forall (i, j) \in L \quad (8)$$

$$\sum_{\substack{(i,k) \in L \\ i \leq j \\ k > j}} (x_{ik}^r + y_{ik}^r) \leq Cap^r + (1 - z_j^r) \cdot M \quad \forall r \in R, \forall j \in N \quad (9)$$

$$pre_1^r = 0 \quad \forall r \in R \quad (10)$$

$$suc_{11}^r = 0 \quad \forall r \in R \quad (11)$$

$$2 \cdot pre_i^r \geq pre_{i-1}^r + z_{i-1}^r \quad \forall r \in R, \forall i \in \{2,3,4,5\} \quad (12)$$

$$2 \cdot suc_i^r \geq suc_{i+1}^r + z_{i+1}^r \quad \forall r \in R, \forall i \in \{7,8,9,10\} \quad (13)$$

$$z_5^r + z_7^r \leq 1 \quad \forall r \in R \quad (14)$$

$$pre_2^r = suc_{10}^r \quad \forall r \in R \quad (15)$$

$$pre_3^r = suc_9^r \quad \forall r \in R \quad (16)$$

$$pre_4^r = suc_8^r \quad \forall r \in R \quad (17)$$

$$pre_5^r = suc_7^r \quad \forall r \in R \quad (18)$$

$$a_{ij}^{rb} = \{0,1\} \quad \forall r \in R, \forall (i, j) \in L, \forall b \in B \quad (19)$$

$$z_i^r = \{0,1\} \quad \forall r \in R, \forall i \in N \quad (20)$$

$$pre_i^r = \{0,1\} \quad \forall r \in R, \forall i \in N \quad (21)$$

$$suc_i^r = \{0,1\} \quad \forall r \in R, \forall i \in N \quad (22)$$



The objective is to maximize profit (1). Revenues are generated by transporting loaded and empty containers. Four types of costs are considered. Charter and crew costs depend on the number of days a vessel is used. Fuel and maintenance costs are proportional to the total distance traveled. The number of nodes visited determines port entry costs while the number of loaded and empty containers transported determines handling costs. The number of loaded containers and the number of empty containers transported between two nodes are calculated by respectively constraint (2) and (3). Total roundtrip distances are calculated by constraint (4) while total roundtrip durations are calculated by constraints (5) and (6). Maximum roundtrip duration is imposed by constraint (7) and depends on the number of weekly roundtrips. Transport demand of a client can only be fulfilled by a specific roundtrip and containers can only be transported if both the origin and destination nodes are visited (8). Constraint (9) ensures that vessel capacity is respected. Constraints (10) to (13) make sure that variables  $pre_i^r$  and  $suc_i^r$  take on the appropriate values. The cluster on the right river bank of the port of Antwerp can only be visited once during each roundtrip (14) and the start and end port of a roundtrip should be the same (15-18). Finally, constraints (19) to (22) define the domain of the decision variables.

For problems with varying weekly demand,  $R$  represents the set of roundtrips performed by the vessel over the total planning period. Three extra constraints (23-25) are added to the model to ensure that the transport demand of a client is either fulfilled every week or never. In all three constraints  $q = r - WNR$  i.e.  $q$  represents the roundtrip scheduled one week before roundtrip  $r$ .

$$a_{ij}^{rb} = a_{ij}^{qb} \quad \forall r \in R, r > WNR, \forall (i, j) \in L, i \notin \{5, 7\}, j \notin \{5, 7\}, \forall b \in B \quad (23)$$

$$a_{5j}^{rb} + a_{7j}^{rb} = a_{5j}^{qb} + a_{7j}^{qb} \quad \forall r \in R, r > WNR, \forall (7, j) \in L, \forall b \in B \quad (24)$$

$$a_{i5}^{rb} + a_{i7}^{rb} = a_{i5}^{qb} + a_{i7}^{qb} \quad \forall r \in R, r > WNR, \forall (i, 5) \in L, \forall b \in B \quad (25)$$

When considering a problem in which multiple vessels will be used to offer roundtrip services,  $R$  represents the set of roundtrips performed by all vessels. A transport demand may now be fulfilled by multiple roundtrips i.e.  $\forall (i, j) \in L, \forall b \in B: \exists r, r' \in R: w_{ij}^{rb} = w_{ij}^{r'b} = 1$ . Constraints (26), (27) and (28) are added to the model to ensure that each transport demand is satisfied by at most one roundtrip.

$$\sum_{r \in R} a_{ij}^{rb} \leq 1 \quad \forall (i, j) \in L, \forall b \in B \quad (26)$$

$$\sum_{r \in R} (a_{5j}^{rb} + a_{7j}^{rb}) \leq 1 \quad \forall (7, j) \in L, \forall b \in B \quad (27)$$

$$\sum_{r \in R} (a_{i5}^{rb} + a_{i7}^{rb}) \leq 1 \quad \forall (i, 5) \in L, \forall b \in B \quad (28)$$

### 3.1 Numerical experiments

In this section illustrative numerical experiments are presented. No real-life decisions or conclusions may be based on the results of these experiments. Numerical experiments are set up to show how the model may be used in practice to support the decision making process related to service network design in barge transportation. In order to use the model in practice, accurate cost and demand information is required. Furthermore, other factors like customer preferences on service frequency, may impact final decisions.

Three types of vessels with capacities of 100 TEU, 150 TEU and 300 TEU are considered. It is assumed that the first two types can make two or three roundtrips per week, while the largest vessel can make one or two roundtrips per week. Cost data are mainly based on a recent report commissioned by the Dutch government agency 'Rijkswaterstaat' of the Ministry of Infrastructure and the Environment [17]. Other sources for time and cost data include [18-21] and personal communication. Ten instances of transport demand are generated randomly according to the following intervals:

- total weekly downstream demand for container transports: 300-600 TEU,
- total weekly upstream demand for container transports: 50-150% of downstream demand,
- percentage loaded containers of total transport demand: 70-80%,
- number of days per week with transport demand to/from a hinterland port: 2-6,
- daily number of clients with demand at a hinterland port: 0-3.

For all instances, transport demand is equally distributed over the two clusters in the port of Antwerp. The model is implemented in AIMMS and solved using CPLEX 12. Three scenarios are tested: (1) a single vessel and constant weekly demand, (2) a single vessel and varying weekly demand and (3) multiple vessels and constant weekly demand.

Results for the first scenario are shown in Table 1. Six different service types are considered as shown in the first row. They are indicated by the vessel capacity and the weekly number of roundtrips. For example, column 300/1 represents a vessel of 300 TEU sailing in a single roundtrip per week. The second row shows the average weekly profit over all instances. The third row indicates the percentage of possible roundtrips that are actually performed. In some situations, performing a roundtrip may not be profitable. This is especially the case when vessel capacity is large and the number of weekly roundtrips is high (and thus maximum roundtrip time is small). In such cases, there might not be enough time for loading and unloading sufficient containers in order to yield enough revenues to offset the costs. No roundtrip will be performed and the corresponding profit is zero. The following rows in Table 1 present average results over all instances for the roundtrips that are actually performed. The average percentage of the maximum roundtrip time that is used by a vessel during a roundtrip is shown in the fourth row. The fifth row presents the average capacity usage of the vessel when it enters and leaves the port area in Antwerp. Finally, the last two rows indicate the percentage of empty container transports and average computation time.

Table 1: Results for scenario one

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly profit (€)	15825	10485	12212	7990	10151	9595

Roundtrip service performed (%)	100.0	70.0	95.0	66.7	95.0	86.7
Available time used (%)	55.1	86.7	74.5	92.7	65.4	89.0
Vessel capacity used (%)	86.2	60.3	77.7	58.5	80.6	70.8
Weekly container transports (TEU)	517	506	443	351	306	368
Empty container transports (%)	4.3	9.5	6.3	10.5	2.9	10.5
Average computation time (s)	1.0	1.0	1.0	1.0	1.0	1.0

A first observation that can be made from Table 1 is that for each type of vessel the best results are obtained when the number of weekly roundtrips is low. A reason is that when the number of roundtrips is high, a lot of time is spent on sailing between ports which causes time available for loading and unloading containers to be limited as explained above. Offering more weekly roundtrips also involves higher fuel and maintenance costs. For example, average profit is much higher for service type 300/1 than for 300/2. For service type 300/2 only 70.0 percent of the roundtrips are profitable, mainly due to limited time. For the roundtrips that are performed, average time used is high (86.7%) while the capacity of the vessel is not fully utilized at all (60.3%). In contrast, vessel capacity is used much more efficiently for service type 300/1. A second observation is that using a larger vessel seems to offer better results. This can clearly be seen when comparing service types 300/1, 150/2 and 100/3 which all have a weekly capacity of 300 TEU. The reasons are similar to those for the first observation. Finally, the portion of empty container transports in total container transport (2.9 to 10.5%) is much lower than the portion of empty container transport demand in total transport demand (20 to 30%). This may be explained by the fact that freight rates for empty containers are lower than for loaded containers.

Although the results favor using larger vessels and making less roundtrips, it should be taken into account that besides profit other factors will influence the final decision of a barge operator on the services to offer. Clients may prefer a higher frequency of roundtrips, so offering more roundtrips by smaller vessels may lead to a rise in transport demand or may justify higher freight rates.

Table 2 shows the results of the second scenario in a similar way as Table 1. The same transport demand instances as for scenario one are used but it is assumed that 30% of the clients request containers to be transported only every two weeks. The planning period is fixed at two weeks. Average weekly profits are much lower for this scenario. A reason is that total transport demand is lower since some clients only have a two-weekly demand and therefore some roundtrips might not be profitable anymore. As a result, the average number of roundtrips performed is much lower as can be seen from the third row in Table 2. When comparing results of the different service types, similar observations as for the first scenario may be made.

Table 2: Results for scenario two

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly profit (€)	19141	10627	13305	10008	11457	10825
Roundtrip service performed (%)	95.0	52.5	77.5	55.0	85.0	56.7
Available time used (%)	48.0	73.4	65.5	81.2	60.5	86.7

Vessel capacity used (%)	66.0	46.3	62.1	46.6	63.6	61.7
Weekly container transports (TEU)	410	316	322	257	238	232
Empty container transports (%)	8.7	8.9	12.1	11.3	11.5	10.8
Average computation time (s)	1.0	1.0	1.0	1.0	1.0	1.0

In the third scenario multiple vessels are employed to offer roundtrips while transport demand is assumed to be constant over the weeks. Numerous types of service may be considered in this case. In total twenty-one service types with two vessels are analyzed. Table 3 gives an overview of the six service types which offered the best results in terms of profit. On average, a vessel of 300 TEU with one weekly roundtrip and a vessel of 100 TEU with two weekly roundtrips offers the best results. However, the appropriate service type highly depends on the expected transport demand. For example, the abovementioned service type is only the best in four out of the ten instances.

Table 3: Results for scenario three

Service type	300/1	300/1	300/1	300/1	300/1	150/2
	300/1	300/2	150/2	150/3	100/2	100/3
Weekly profit (€)	18003	17120	18115	17912	18713	18319
Roundtrip service performed (%)	75.0	36.7	60.0	45.0	83.3	62.5
Available time used (%)	43.3	61.7	56.3	58.1	47.5	59.2
Vessel capacity used (%)	66.9	82.7	74.9	68.2	69.7	68.2
Weekly container transports (TEU)	413	523	351	350	254	260
Empty container transports (%)	3.3	3.9	3.0	4.3	5.1	5.4
Average computation time (s)	1.0	1.0	1.0	1.0	1.0	1.0

#### 4. Perspective of shipping lines

The decision support model may be applied from the perspective of shipping lines as well. When containers are transported under the carrier haulage principle, door-to-door services are provided by shipping lines. Currently the percentage of carrier haulage is on average about thirty percent of all maritime container transports. According to Notteboom [22], shipping lines seek to increase the portion of carrier haulage on the European continent. They want to increase organizational control over hinterland transport since it is an important strategy to control the logistic chain and to generate cost reductions and additional revenues [23]. Shipping lines that are successful in achieving cost reductions through better managing inland container logistics may have a competitive advantage. According to van den Berg and Langen [24] shipping lines should be involved in the organization of barge and rail services in the hinterland, although they do not have to operate these services themselves. Instead, strategic partnerships with barge and terminal operators may be established [22,24]. The decision support model, which is proposed in this paper, may be applied by shipping lines or their strategic partners to develop regular roundtrip barge services.

Two main differences between the problem from the perspective of barge operators and the problem from the perspective of shipping lines are identified. A first difference is related to transport demand. Since it is assumed that the shipping line is responsible for the inland

transportation part, they have to make sure that all loaded containers are transported from the seaport to their final destinations and from the shippers' locations to the seaport. Hence, all transport demand for loaded containers should be fulfilled by the shipping line. In case capacity of the chartered vessel(s) is not sufficient, alternatives have to be considered. Containers may be transported between hinterland ports and the port of Antwerp by barges of independent barge operators or they may be transported by truck. In this paper, it is assumed that no capacity restrictions on these alternative transport options exist and that these transports are at least as fast as transporting containers by the chartered vessel(s). Finally, the cost of an alternative transport is assumed to be high compared with the cost of transporting a container by a chartered vessel. For clarity purposes, only alternative transportation of containers by truck is considered in the remainder of this paper.

A second difference is related to container management. Shipping lines operate their own fleet of containers or have some long term leasing arrangements. They are responsible for efficiently managing this container fleet. To avoid empty container shortages at certain ports and empty container excesses at others, empty containers will have to be repositioned between ports [25]. In barge transportation, these repositioning movements are generally made by using excess capacity of container vessels which transport loaded containers [12,14]. Two options to plan empty container repositioning movements may be identified. The first option consists of planning barge services based on loaded container transport demand in a first step. The model described in Section 3 may be used for this purpose. Only the truck transportation option and the constraint that all transport demand has to be satisfied, should be added to the model. In a second step, empty container repositioning needs are determined. Based on information on excess capacity of the vessel(s), the same model may be used to find the most efficient way to perform these repositioning movements. Shipping routes and loaded container transports are assumed to be fixed during this step. A second option is to take empty container repositioning needs directly into account when planning barge services and loaded container transports. In the following paragraphs the model for this option is described in detail. Both options are compared in Section 4.2.

Empty container repositioning needs may be included in the model by imposing balancing constraints at each port. These balancing constraints impose total container inflow to equal total container outflow for each port over the planning period. Besides, at any time sufficient empty containers should be available at each port for export purposes. This is accounted for by maintaining an inventory of containers at each port. Costs for storing containers at a port are taken into account. Each port has an initial inventory of containers at the beginning of the planning period. This initial inventory is modeled as a variable (i.e. the model decides the best value), although it may also be fixed to a certain value in advance. During the planning period, the stock of available containers at each port will fluctuate. At the end of the planning period, the inventory level should be equal to the initial inventory level. A distinction is made between regular ports and ports also acting as an empty container hub. The former have a rather limited storage space for containers which is modeled by imposing a maximum inventory level. The latter have no such restriction. Only both terminals in the port of Antwerp are assumed to act as an empty container hub in this paper. Finally, it is assumed that a loaded container arriving at a port is unavailable for three days. This ensures that there is enough time to transport the loaded container to its final customer, unload it and return it to

the port empty. Similarly, three days before a loaded container transport takes place, a container should be available at the port of origin.

#### 4.1 Model formulation

The formulation of the model is similar as in Section 3.1, although some adaptations are required. Only transport demand for loaded containers is considered. All demands should be satisfied, either by the chartered vessel(s) or by truck. Variable  $a_{ij}^{rb}$  is no longer a binary decision variable. Instead  $a_{ij}^{rb}$  is a continuous decision variable which indicates the fraction of transport demand of client  $b$  on link  $(i, j)$  that is fulfilled by roundtrip  $r$ . Similarly, the new continuous decision variable  $\hat{a}_{ij}^{rb}$  indicates the fraction of transport demand of client  $b$  on link  $(i, j)$  which is fulfilled by truck at the same moment of roundtrip  $r$ . Helping variable  $x_{ij}^r$  still indicates the number of loaded containers transported by the chartered vessel on link  $(i, j)$  during roundtrip  $r$ . Helping variable  $\hat{x}_{ij}^r$  represents the number of loaded containers transported by truck on link  $(i, j)$  (at the same moment of roundtrip  $r$ ). The number of empty containers to be transported is a decision. As a result,  $dem_{ij}^{be}$  is no longer used. Integer decision variables  $y_{ij}^r$  and  $\hat{y}_{ij}^r$  represent the number of empty containers transported on link  $(i, j)$  during roundtrip  $r$  respectively by the chartered vessel and by truck. The cost of a transport by truck on link  $(i, j)$  is indicated by  $\hat{c}_{ij}$  and is expressed in euro per TEU. Finally, the time that a container is unavailable before and after a loaded container transport is expressed in the number roundtrips and indicated by  $u$  (since three days of unavailability are assumed  $u = 2$  if  $WNR = 3$  and  $u = 1$  otherwise).

To take empty container repositioning into account, the inventory of containers at each of the six ports (Liege, Genk, Meerhout, Deurne, Antwerp RRB, Antwerp LRB) should be maintained. The following notation is used:

$P = \{1, \dots, 6\}$  = set of 6 unique ports (index  $p$ )

$\delta^-(p)$  = index for the downstream node of port  $p$  (e.g.  $\delta^-(1) = 1, \delta^-(2) = 2$ )

$\delta^+(p)$  = index for the upstream node of port  $p$  (e.g.  $\delta^+(1) = 11, \delta^+(2) = 10$ )

$c_p^s$  = daily storage cost at port  $p$  (€/TEU)

$inv_p^{max}$  = maximum container inventory level at port  $p$

$inv_p^r$  = number of containers in inventory at port  $p$  before roundtrip  $r$  (TEU)

The formulation of the problem with a single vessel and constant transport demand is as follows:

$$\begin{aligned}
\min & \sum_{r \in R} c_{char}^r \cdot T_{day}^r + \sum_{r \in R} c_{fuel}^r \cdot D^r + \sum_{r \in R} \sum_{i \in N} z_i^r \cdot c_i^e \\
& + \sum_{r \in R} \sum_{(i,j) \in L} (x_{ij}^r + y_{ij}^r) \cdot (c_i^h + c_j^h) + \sum_{r \in R} \sum_{(i,j) \in L} (\hat{x}_{ij}^r + \hat{y}_{ij}^r) \hat{c}_{ij} \\
& + \sum_{r \in R} \sum_{p \in P} inv_p^r \cdot c_p^s \cdot 6 / WNR
\end{aligned} \tag{29}$$

Subject to

(4) – (18)

(20) – (22)

$$\sum_{r \in R} (a_{ij}^{rb} + \hat{a}_{ij}^{rb}) = 1 \quad \forall (i, j) \in L, \forall b \in B \tag{30}$$

$$x_{ij}^r = \sum_{b \in B} dem_{ij}^{bl} \cdot a_{ij}^{rb} \quad \forall r \in R, \forall (i, j) \in L \tag{31}$$

$$\hat{x}_{ij}^r = \sum_{b \in B} dem_{ij}^{bl} \cdot \hat{a}_{ij}^{rb} \quad \forall r \in R, \forall (i, j) \in L \tag{32}$$

$$y_{ij}^r \leq Cap^r \cdot z_i^r \quad \forall r \in R, \forall (i, j) \in L \tag{33}$$

$$y_{ij}^r \leq Cap^r \cdot z_j^r \quad \forall r \in R, \forall (i, j) \in L \tag{34}$$

$$\sum_{r \in R} \left[ \begin{aligned} & \sum_{(j, \delta^-(p)) \in L} \left( x_{(j, \delta^-(p))}^r + y_{(j, \delta^-(p))}^r \right. \\ & \quad \left. + \hat{x}_{(j, \delta^-(p))}^r + \hat{y}_{(j, \delta^-(p))}^r \right) \\ & + \sum_{(j, \delta^+(p)) \in L} \left( x_{(j, \delta^+(p))}^r + y_{(j, \delta^+(p))}^r \right. \\ & \quad \left. + \hat{x}_{(j, \delta^+(p))}^r + \hat{y}_{(j, \delta^+(p))}^r \right) \\ & - \sum_{(\delta^-(p), j) \in L} \left( x_{(\delta^-(p), j)}^r + y_{(\delta^-(p), j)}^r \right. \\ & \quad \left. + \hat{x}_{(\delta^-(p), j)}^r + \hat{y}_{(\delta^-(p), j)}^r \right) \\ & - \sum_{(\delta^+(p), j) \in L} \left( x_{(\delta^+(p), j)}^r + y_{(\delta^+(p), j)}^r \right. \\ & \quad \left. + \hat{x}_{(\delta^+(p), j)}^r + \hat{y}_{(\delta^+(p), j)}^r \right) \end{aligned} \right] = 0 \quad \forall p \in P \tag{35}$$

$$\begin{aligned}
& inv_p^r + \sum_{(j, \delta^-(p)) \in L} \left( x_{(j, \delta^-(p))}^v + y_{(j, \delta^-(p))}^r + \hat{x}_{(j, \delta^-(p))}^v + \hat{y}_{(j, \delta^-(p))}^r \right) \\
& + \sum_{(j, \delta^+(p)) \in L} \left( x_{(j, \delta^+(p))}^v + y_{(j, \delta^+(p))}^r + \hat{x}_{(j, \delta^+(p))}^v + \hat{y}_{(j, \delta^+(p))}^r \right) \\
& - \sum_{(\delta^-(p), j) \in L} \left( x_{(\delta^-(p), j)}^w + y_{(\delta^-(p), j)}^r + \hat{x}_{(\delta^-(p), j)}^w + \hat{y}_{(\delta^-(p), j)}^r \right) \\
& - \sum_{(\delta^+(p), j) \in L} \left( x_{(\delta^+(p), j)}^w + y_{(\delta^+(p), j)}^r + \hat{x}_{(\delta^+(p), j)}^w + \hat{y}_{(\delta^+(p), j)}^r \right) \\
& = inv_p^{r+1}
\end{aligned}$$

$$\text{with } inv_p^{TNR+1} = inv_p^1,$$

$$v = \begin{cases} r - u & \text{if } r > u \\ r - u + TNR & \text{else} \end{cases} \quad \text{and} \\ w = \begin{cases} r + u & \text{if } r \leq TNR - u \\ r + u - TNR & \text{else} \end{cases} \quad \forall p \in P \quad (36)$$

$$inv_p^r \leq inv_p^{max} \quad \forall r \in R, \forall p \in P \quad (37)$$

$$a_{ij}^{rb} \geq 0 \quad \forall r \in R, \forall (i, j) \in L, \forall b \in B \quad (38)$$

$$\hat{a}_{ij}^{rb} \geq 0 \quad \forall r \in R, \forall (i, j) \in L, \forall b \in B \quad (39)$$

$$y_{ij}^r \geq 0 \text{ and integer} \quad \forall r \in R, \forall (i, j) \in L \quad (40)$$

$$\hat{y}_{ij}^r \geq 0 \text{ and integer} \quad \forall r \in R, \forall (i, j) \in L \quad (41)$$

$$inv_p^r \geq 0 \text{ and integer} \quad \forall r \in R, \forall p \in P \quad (42)$$

The objective of the model is to minimize total costs of fulfilling all transport demand for loaded containers and balancing the network by repositioning empty containers. The first four terms in objective function (29) indicate respectively charter and crew costs, fuel and maintenance costs, port entry costs and container handling costs, similar as in the model in Section 3.1. The fifth term represents the cost of transporting loaded and empty containers by other means than the chartered vessel. The last cost term represents storage costs for containers at each port. These costs depend on container inventory levels and the time between two roundtrips which is indicated by  $6/WNR$  i.e. the number of days per week divided by the number of roundtrips per week. Revenues from transporting loaded containers are no longer considered since it is assumed that all transport demand should be fulfilled and hence revenues are constant. Revenues from transporting empty containers are not considered either since repositioning movements happen at the responsibility and expense of the shipping line itself. Constraints (4) to (18) and (20) to (22) are identical to those in the model in Section 3.1. Constraint (30) ensure that all transport demand is satisfied, either by the chartered vessel or by truck. The number of loaded containers transported on each link during a roundtrip is calculated by constraints (31) and (32). Constraints (33) and (34) indicate that empty containers may only be transported by barge between two nodes if both nodes are visited. Constraint (35) imposes container balancing at each port over the planning period while container inventories during the planning period are controlled by constraints (36) and (37). Finally, constraints (38) to (42) restrict the domain of the decision variables.

For problems with varying weekly demand, no changes have to be made to the formulation. When considering a problem in which multiple vessels will be used to offer roundtrip services, a small modification to the formulation is required. Since different vessels may arrive at ports at different moments during the day and week, it is no longer possible to take daily inventories into account. Hence all inventory-related parameters ( $c_p^s, inv_p^{max}$ ), variables ( $inv_p^r$ ) and constraints (36), (37) and (42) as well as the last term of objective function (29) are removed from the formulation. Constraint (35) still ensures container balancing over the total planning period.



## 4.2 Numerical experiments

Shipping lines have two options to plan empty container repositioning movements when organizing their own barge services. One option is to plan barge services based on loaded container transport demand in a first step and empty container movements separately in a second step. The second option is to plan barge services and empty container movements simultaneously by solving the model described in the Section 4.1. In this section, numerical experiments are presented for both options. The same ten random problem instances as in Section 3.2 are used. All transport demands are assumed to be loaded container transport demands. Again three scenarios are tested: (1) a single vessel and constant weekly demand, (2) a single vessel and varying weekly demand and (3) multiple vessels and constant weekly demand.

Results for the first scenario are presented in Tables 4 and 5 for respectively separately and simultaneously planning barge services and empty container repositioning. Six service types are considered as shown in the first row. For each of them, the second row indicates average weekly costs. The third row shows the percentage of total transport demand which is satisfied by barge. The remainder is satisfied by road transport. Row four presents the percentage of available time used by the vessel on average. The capacity usage by loaded containers when entering and leaving the port area of Antwerp is shown in row five. The percentage of empty container transports in total transports and average computation times are indicated in rows six and seven. Finally, average cost reductions through the simultaneous planning of barge services and empty container repositioning movements are indicated in the last row of Table 5.

Table 4: Results for scenario one: separate planning

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly cost (€)	109926	121358	121138	155636	145527	155019
Transports by barge (%)	63.6	64.4	57.2	39.4	38.3	37.3
Available time used by vessel (%)	72.3	98.1	94.0	93.0	76.3	95.9
Vessel capacity used (loaded) (%)	97.1	59.4	90.1	55.7	95.2	75.6
Empty container transports (%)	30.9	32.7	33.6	31.4	33.8	32.7
Average computation time (s)	1.0	1.0	1.0	1.0	1.0	1.0

Table 5: Results for scenario one: simultaneous planning

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly cost (€)	108065	114590	118494	142900	138900	146784
Transports by barge (%)	66.9	66.7	58.5	49.4	44.6	43.4
Available time used by vessel (%)	74.1	98.6	93.8	99.7	83.8	98.7
Vessel capacity used (loaded) (%)	92.7	52.3	85.2	46.3	88.9	62.7
Empty container transports (%)	29.4	31.3	32.7	30.6	32.1	31.2
Average computation time (s)	1.0	1.0	1.4	1.5	2.0	2.2
Average cost reduction (%)	1.7	5.6	2.2	8.2	4.6	5.3

Similar observations as for the problem from the perspective of barge operators may be made from Tables 4 and 5. For each vessel type, the service type with the lowest number of weekly roundtrips leads to the best use of available vessel capacity and lowest costs. A high number of weekly roundtrips generally results in situations with inefficient capacity usage due to time constraints. Average time and capacity usage are higher than in Section 3.2 since in this section fractions of transport demand of a client may be satisfied by barge transport while the remainder of the transport demand is satisfied by road transport. The portion of empty container transports in total transports ranges around 30% which is considerably higher than in Section 3.2. This is a result of the container balancing constraints that are imposed. The fraction of transports performed by barge ranges on average between 43 to 67% of all transports. Finally, simultaneously planning barge services and empty container repositioning movements results in cost reductions of one to eight percent, mainly due to the fact that different shipping routes are chosen for both options.

Average results for the second scenario are shown in Tables 6 and 7. The same transport demand instances as for scenario one are used but it is assumed that 30% of the clients have demand only every two weeks. Average weekly costs are lower for this scenario due to lower total transport demand. As a consequence, average percentage of transports by barge are slightly higher than for the first scenario. Other results are similar to those of scenario one.

Table 6: Results for scenario two: separate planning

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly cost (€)	76096	88854	88317	107456	100349	106475
Transports by barge (%)	72.5	73.1	62.1	47.9	47.9	45.2
Available time used by vessel (%)	64.4	88.3	84.0	86.3	73.4	86.1
Vessel capacity used (loaded) (%)	80.5	45.0	72.5	45.9	84.9	63.2
Empty container transports (%)	30.1	33.3	34.7	31.8	35.3	33.1
Average computation time (s)	1.0	1.0	1.0	1.0	1.0	1.0

Table 7: Results for scenario two: simultaneous planning

Service type	300/1	300/2	150/2	150/3	100/2	100/3
Weekly cost (€)	72574	81790	82785	96400	95909	97883
Transports by barge (%)	76.6	78.7	67.9	59.9	51.9	54.5
Available time used by vessel (%)	66.0	92.6	89.4	95.5	79.2	97.4
Vessel capacity used (loaded) (%)	78.5	42.7	72.5	41.9	79.3	57.3
Empty container transports (%)	29.3	31.8	33.0	30.6	32.7	32.0
Average computation time (s)	1.3	1.7	5.2	5.7	26.1	13.5
Average cost reduction (%)	4.6	8.0	6.3	10.3	4.4	8.1

Again twenty-one service types with two vessels are analyzed for the third scenario. Results of the six service types which offer on average the lowest costs are presented in Tables 8 and 9. Since two vessels are employed, a larger portion of total transports are performed by barge compared with the first scenario. As a result, less costly road transports are required and weekly costs are on average lower than when a single vessel is employed. On the other hand, the percentage of empty containers in total transports increases compared with scenario one.

This is caused by the fact that daily container inventories are not taken into account and only container balancing constraints over the total planning period are imposed in the third scenario. This offers more flexibility for empty container repositioning. Although the percentage of empty containers in total transport increases, the portion of these empty container transports which is carried out by costly road transportation is reduced drastically from 36 to 15%. Finally, average cost reductions from simultaneously planning barge services and empty container repositioning movements are much larger for the third scenario compared with scenarios one and two. The reason is as follows. When barge services are planned only based on loaded container transport demand, for some instances it is better not to perform all roundtrips of both vessels. If capacity usage during a roundtrip would be too small, it might be more cost-efficient not to make a roundtrip, thereby saving charter and fuel costs, while transporting containers by truck. In case empty container repositioning needs are taken into account, capacity usage of the vessels will be higher and performing these roundtrips might in some cases be cheaper than transporting all containers by truck.

Table 8: Results for scenario three: separate planning

Service type	300/1	300/1	300/1	300/2	150/2	150/2
	300/2	150/2	150/3	150/2	150/2	150/3
Weekly cost (€)	122257	122892	123833	133714	125177	125049
Transports by barge (%)	85.1	79.3	78.8	75.2	76.3	74.8
Available time used by vessel (%)	70.5	64.1	74.6	81.4	80.0	86.7
Vessel capacity used (loaded) (%)	63.8	74.7	64.4	67.6	77.4	72.8
Empty container transports (%)	45.6	45.5	45.3	45.7	45.2	36.5
Average computation time (s)	1.7	2.8	2.1	1.2	2.1	3.6

Table 9: Results for scenario three: simultaneous planning

Service type	300/1	300/1	300/1	300/2	150/2	150/2
	300/2	150/2	150/3	150/2	150/2	150/3
Weekly cost (€)	105946	108486	108865	106238	111093	111233
Transports by barge (%)	93.7	87.0	88.2	90.8	82.5	83.0
Available time used by vessel (%)	76.9	73.9	82.6	88.4	81.8	89.5
Vessel capacity used (loaded) (%)	53.3	66.8	51.7	58.1	69.0	58.6
Empty container transports (%)	44.4	44.4	44.5	44.4	44.4	35.7
Average computation time (s)	3.0	8.5	9.8	7.3	38.4	18.3
Average cost reduction (%)	13.3	11.7	12.1	20.6	11.3	11.1

As shown in the previous paragraphs, the proposed model may be used by shipping lines to determine the best service type and the corresponding shipping routes for a given demand scenario while taking empty container repositioning into account. A sensitivity analysis on costs and freight rates may be performed as well. Additionally, the model may be applied for supporting long term strategic decisions. For example, the effect of changes in the network and service network configurations on the hinterland transport chain may be analyzed, as explained in the following paragraph.

In the numerical experiments described in this paper, it is assumed that empty container hubs are only located at both river banks in the port of Antwerp while all hinterland ports have a maximum storage capacity of twenty containers. The starting inventory at these hinterland ports is chosen by the model. Examples of strategic decisions that may be analyzed include increasing or reducing container storage capacity of hinterland ports and the establishment of an empty container hub at one of the hinterland ports. For example, for the instances used in this paper, a decrease of the storage capacity at the hinterland ports to ten containers reduces profits on average by 1.21%, while establishing an empty container hub at the hinterland port in Genk yields an average increase in profits of 1.50%. To correctly interpret the magnitude of these changes, it is necessary to have information on the cost of implementing the decisions.

## **5. Conclusions and future research**

In this paper, a tactical planning model for service network design in barge transportation along a single waterway is proposed. The model may be used as a decision support tool for barge operators and shipping lines that want to offer roundtrip barge services between a major seaport and several hinterland ports. It allows to calculate optimal shipping routes for a given vessel capacity and roundtrip frequency. A case study on the hinterland network of the port of Antwerp in Belgium is presented. To demonstrate the versatility and flexibility of the model, it is applied from the perspective of barge operators as well as from the perspective of shipping lines that offer door-to-door transport services. In the latter case, empty container repositioning decisions should be taken into account. Numerical experiments for three scenarios are presented to indicate how the model may be used in practice. Results indicate that shipping lines may reduce costs by simultaneously planning barge services and empty container repositioning movements instead of planning empty container repositioning movements in a post-optimization phase.

Future research could focus on how uncertainty regarding transport demand could be taken into account by the model. Reserving a portion of vessel capacity for unexpected increases in transport demand may be an opportunity. Similar to the concept of safety stock in inventory theory, the amount of capacity to be reserved should depend on the variability of transport demand. Furthermore, additional numerical experiments may be performed to analyze whether the model can still be solved efficiently for larger problem instances (increase in number of ports, vessels, clients or weeks). Finally, the model may be tested on real-life problem instances in order to compare its results with decisions made in practice. It may be analyzed to what extent the model improves the current decision making process and whether additional elements may be introduced in the model to further improve its applicability in practice.

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