Coordination and analysis of barge container hinterland networks

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Coordination and Analysis of Barge Container Hinterland Networks

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Abstract

We analyze the import hinterland supply chain from the perspective of both the inland terminal operator and of the shippers. In the hinterland supply chain, the interests of capital-intensive terminal operators are not aligned with the interests of shippers. Therefore, we define the joint shipment quantity for container freight distribution that counts for the specific nature of barge transportation. We consider the direct and the tour coordination policies. Based on empirical data, the cost-effectiveness and the performance of these policies is evaluated in detail. Analytical results give insights into the trade-off between the variable transportation costs and the inventory holding costs.

Keywords: Hinterland network coordination, Container transportation, Barge transportation, Inventory depletion

1 Introduction

Container-based transportation has grown very fast over the last decades, driven by a general expansion in intercontinental transport following the growth in world trade. Moreover, an increasing share of global transport is being containerized, primarily to reduce handling costs and to increase flexibility in the use of multiple modes of transportation. The performance of container-based trade substantially influences regional development: efficient and large container ports facilitate trade and hence lead to economic growth. Consequently, ports and container terminals have been investing in modification of their operations and facilities to be able to cope with the growing use of containers.

We study the container freight supply chain from the perspective both of the inland terminal operator who distributes and handles containers along the hinterland and of freight forwarders, consignees or end-shippers that need the containers to be transported between the port area and terminal location (we refer from now on to these parties as shippers). In the hinterland supply chain, the interests of capital-intensive terminal operators are not aligned with the interests of the shippers. While terminal operators are focused on increasing the utilization of their expensive facilities, shippers want short and reliable lead times. The frequency of services should be reasonable to satisfy the needs of shippers, but at the same time should be justified by sufficient container volume (Notteboom, 2004). The latter implies the growth of vessel capacity or the growth of the time at the terminal required to collect, load and unload the appropriate amount of

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containers. Both factors affect the time a container spends in the system and, as a consequence, the inventory holding costs for shippers.

Our aim is to define the shipment quantity for barge container transportation for import flows that takes into account the timing issue. The importance of timing issue in the hinterland transportation leg has been increased recently due to the tight inventory policy of shippers. To study the influence of time on shipment quantity we consider the following barge coordination policies: a direct coordination policy and a tour coordination policy. The time of shipping a container depends not only on network coordination policies, but also on network structural characteristics, such as number of nodes being served and duration of connections between them.

The problems of network design and network coordination have received most attention in academic literature with the focus of optimizing the operations of an individual carrier firm. Baumol and Vinod (1970) study the theoretic inventory model of freight transport demand, where the total in-transit carrying costs and the recipient's inventory costs are considered. Early works of Blumenfeld et al. (1985) and Hall (1985) examine routing policies of goods from manufacturing plans to final destination. The optimization method determines optimal routes and shipment sizes for networks with a consolidation terminal and concave cost function. Then, they analyze the trade-off between inventory and fixed costs. Inventory holding costs are calculated for an average batch size that is the LTL or full load of the truck. Burns et al. (1985) develop a method that determines the optimal dispatching frequency for collecting goods from suppliers that are equally served. They use an approximation of distance traveled to pick up goods from different suppliers, and the probability that a particular customer is served during the track dispatch. Decision variables are shipment size and peddling region size. Since the work is based on spatial density of customers rather than on the demands of specific customers in precise locations, there is no need to specify network configuration and corresponding flows. McCann (2001) discusses the relationship between the optimum vehicle-vessel size, the haulage distance and the haulage quantity and incorporates the transport cost structure into analysis presented. He concludes that the relationship between the optimum vehicle-vessel size and the haulage distance depends on the static relationship between vehicle-vessel movement costs and carrying capacities. By calculating the optimal shipment size on the basis of vehicle movement costs it is noticed that transport costs per ton shipped are directly related to the square root of the haulage distance and inversely related to the haulage quantity per time period. Hsu and Hsieh (2007) formulate a two-objective model to determine the optimal liner routing, ship size and sailing frequency for container carriers by minimizing shipping costs and inventory costs in a hub-and-spoke network. Based on the trade-off between shipping costs and inventory costs, Pareto optimal solutions of the two-objective model are determined. The authors show that a hub system is more efficient as port charges decrease. Caris et al. (2011) provide analysis and comparison of alternative types of container bundling networks in the port area of Antwerpen. They develop a discrete event simulation model that examines the effects of alternative ways of organization of container barge transport. We refer to Kelle et al. (2007) and Gheidar et al. (2009) for models of total supply chain costs, when both retailer and supplier are taken into account simultaneously. We adopted these ideas and apply them to the hinterland of a port environment where both a carrier and a shipper tend to maximize their revenue, causing the impact on costs of other player.

The contribution of this paper is a new analytical model, that defines the transportation order quantity for container transportation. We incorporate the specific nature of container freight transportation by barge. Thereto, we model the depletion of shipper's inventory along the route originating from a port and leading to inland terminals. The inventory level of a shipper changes at every unloading stop of a barge. Further on, we examine the trade-off of inventory and transportation costs of container distribution process. We repeat the analysis for the direct and the tour coordination policies and derive the set of inequalities that define their cost-effectiveness. The model is tested on several examples driven by real-life applications of container barge transportation.

A complete model of the hinterland supply chain network is presented in Section 3. We include the shipper and the inland terminal operator perspectives and their joint perspective. The cost functions are formulated for the direct and tour shipping policies. Section 4 presents a numerical example that demonstrates the usefulness of the proposed model. Finally, conclusions are presented in Section 5.

2 Modeling the hinterland supply chain

2.1 Model description

We consider a hinterland supply chain with a single deep-sea port and a number of hinterland locations operated by the service provider. This situation is similar to the environment examined by Van Rooy (2010) who investigated the structure of the Port of Rotterdam hinterland barge network in Brabant, in the Netherlands.

The inland terminal operator is involved with two kinds of activities along the hinterland container supply chain. Its main activity is container handling, which consists of moving containers along the stacking area and loading and unloading them from and to the various modes of transportation. Nowadays, inland terminal operators expand their role by executing transportation of containers between inland and deep-sea terminals. Consequently, in addition to their primary activity of container handling, terminal operators bring containers from deep-sea port terminals to the hinterland by barges and have to decide upon the routing and the frequency of such services.

Let P be the set of locations the terminal operator has available in its distribution network. These locations are called inland terminals and denoted by p_i ($i = \{1, \dots, M\}$). The deep-sea port terminal is denoted by p_0. The hinterland supply chain can be coordinated in two ways. Either the terminals are connected directly to the deep-sea port or they are visited as part of a tour in which multiple inland terminals are visited. Figure 1 illustrates both coordination policies. We assumed that the barge routing is predetermined for either topology of the network as the direct accessibility is limited by the geographical

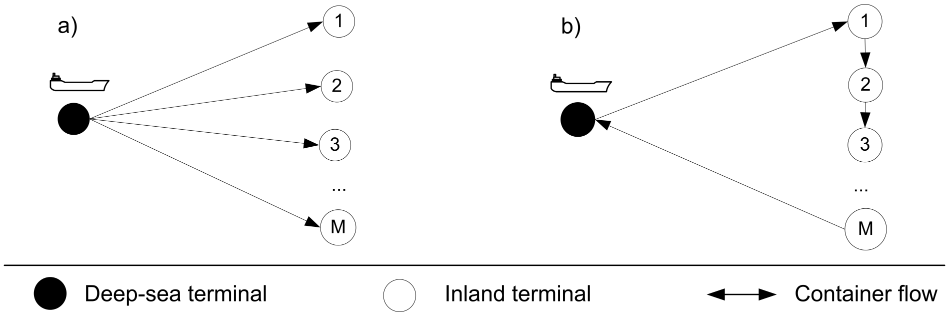


Figure 1: Network coordination policies: a) Direct b) Tour.

restrictions, the length and the capacity of waterways. Therefore, a barge visits terminals according to their sequential order.

A shipper faces demand of D_i containers at location i. We assume that shortages are not allowed. The shipper incurs an inventory holding costs at the rate of h€ per container per time unit and pays F€ per shipment to the inland terminal operator as the freight charge. The shipper determines its optimal shipment quantity Q_i and the best frequency f_i^S to minimize his distribution and inventory holding costs. Then, he places a transportation order to the inland terminal operator to ship Q_i containers from the deep-sea terminal p_0 to the inland terminal p_i $(i = \{1, \dots, M\})$.

In the direct coordination policy we denote the sailing time between the deep-sea terminal p_0 and the inland terminal p_i as t_i, where $i = \{1, \dots, M\}$. In the tour coordination policy we denote the sailing time as $t_{i,suc(i)}, (t_{i,suc(i)} > 0)$, where :

$$suc(i) = \begin{cases} i+1 & \text{if } 0 \leq i \leq M-1 \\ 0 & \text{otherwise} \end{cases}$$

The inland terminal operator provides the service of distributing containers between the locations and handling containers at the inland terminals. The vessel v with capacity C is loaded at the deep-see port p_0 and sails to the inland terminal p_i. There, containers are unloaded and the vessel continues its route, dependent on the network coordination policy used (i.e. direct or tour). The costs associated with transportation activities consist of fixed and variable costs. The former depends on the type of barge tenancy (leasing or ownership) and provides possible economies of scale. The variable transportation costs include expenditures on fuel, lubricant or oil and maintenance. These costs are related to either distance or time. The variable transportation costs increase at the rate c, while the fixed transportation costs are payed per time unit at rate b.

The handling operations of a terminal operator are measured in the number of moves per time unit, which includes the number of crane moves from the quayside to the vessel and back. We denote a rate of handling operations as h. This rate is dependent on machinery used by a terminal operator and can considerably varies between large and small terminals.

While the operator of the barge will be focused on minimizing its operating cost, costs associated with the time a container spends in the system are typically incurred by the shipper. We assume that the different stakeholders in the hinterland supply chain follow a profit maximizing behavior. In what follows, we formulate the total shipping costs of the inland terminal operator, TRC^T and the total relevant costs for the shipper, TRC^S. Then, we introduce the total relevant costs of the hinterland supply chain as a whole, denoted as TRC. We do this analysis for both proposed network coordination policies.

Refer to Table 1 for an overview of all the variables and parameters used in this paper.

Data	Description	Measurements
P	Set of locations	-
p_i	Inland terminal, when $i = \{1, \dots, M\}$ or deep-sea port terminal, when $i = 0$	-
r	Handling rate	containers/hour
C	Vessel capacity	cont.
h	Costs of an hour of handling at any inland terminal	€/hour
b	Fixed transportation costs	€/month
c	Variable transportation costs	€/hour
D_i	Shipper's demand at the location i	containers/month
t_i	One-way travel time between the terminals p_0 and p_i	hour/shipment
$t_{i,suc(i)}$	Travel time between any two successive terminals p_i and p_j, $i, j \in P, i \neq j$	hour/shipment
Q_i	Shipment quantity to terminal i	containers/shipment
H	Inventory holding charge of shipper	€/hour/container
f_i^S	Frequency of shipper orders to the $i - th$ inland terminal	shipment/month
f_i^T	Frequency of the $i - th$ inland terminal service	shipment/month
F	Freight charge	€/container
C	Capacity of the vessel	containers
TRC^S	Total relevant costs of shipper	€/month
TRC^T	Total relevant costs of inland terminal operator	€/month
TRC	Total logistic costs of freight container supply chain	€/month

Table 1: Parameters and variables used.

2.2 The direct coordination policy

In the direct coordination policy, the deep-sea terminal p_0 is directly connected to each of the inland terminals p_i. Since demand between inland terminals is independent of each other, we divide the network into a number of subnetworks each containing a single route. Similar to (Hall, 1985), we obtain the total costs of the original network as the cost summation of the different subnetworks. To simplify the notation, we drop, in what follows, the index i referring to an inland terminal.

The total relevant costs of the shipper

The total relevant costs of the shipper consists of shipping and holding inventory costs. Since shortages are not allowed, the inventory holding costs are minimized when the replenishment of inventory takes place each time the inventory level reaches zero (Figure 2).

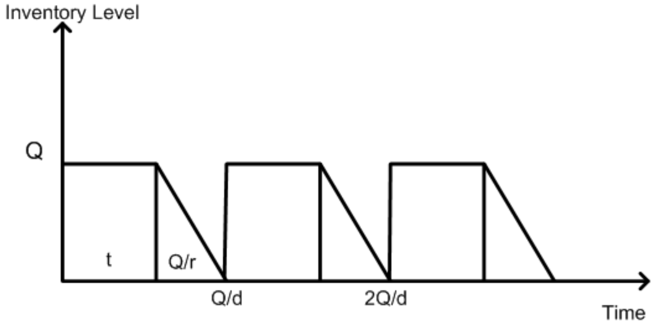


Figure 2: Shipper's inventory in the direct coordination policy.

The length of the cycle is $t + Q/r$ time units, consisting of the sailing time to the terminal p and the time required to unload the vessel at the terminal. Then, the average inventory depletion per cycle is split into two phases. The first phase characterizes the average inventory during the sailing time t. It stays equal to Q containers from the beginning of the route till the moment a vessel reaches an inland terminal. The second phase is the process of vessel unloading that takes Q/r time units per cycle. During this time, the inventory level decreases from Q to 0 containers, implying that the average inventory is equal to $Q/2$ containers. Following this logic, the inventory holding costs per cycle are equal to $H(Qt + Q^2/2r)$. Next to the inventory holding costs, the shipper also incurs freight transportation costs. These costs are proportional to the number of containers transported during the cycle and equal to FQ, where F is the freight charge.

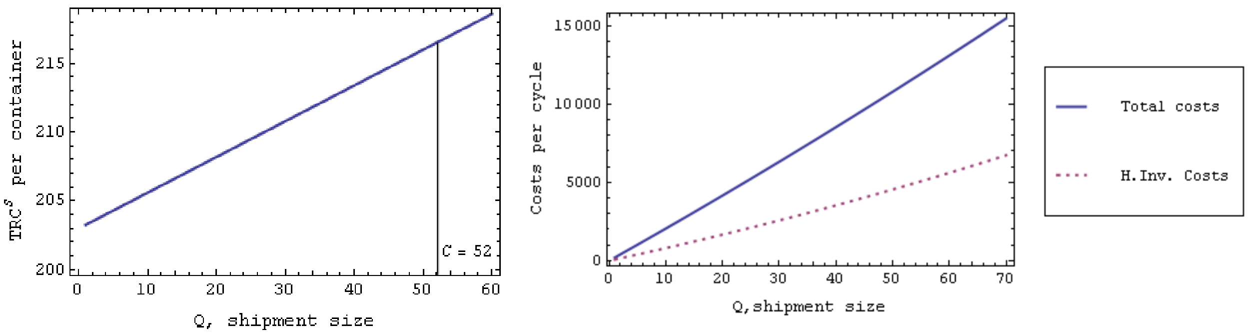
The shipper's relevant costs per cycle are obtained by summing the transportation costs and the inventory costs:

$$\text{Cost per cycle} = FQ + H\big(Qt + \frac{Q^2}{2r}\big) \tag{1}$$

The total relevant costs per time period, TRC^S, are the costs incurred by shipper during the cycle multiplied with the number of trips $\frac{d}{Q}$ needed to satisfy the demand of this inland terminal.

$$TRC^S \quad = \quad \frac{FDQ}{Q} + \frac{DH}{Q}\big(Qt + \frac{Q^2}{2r}\big) = FD + DHt + \frac{DHQ}{2r} \tag{2}$$

Figure 3 is a graphical representation of TRC^S. The lower bound for the shipment quantity is one container per sailing trip, the upper bound is restricted by the vessel capacity. The larger the quantity of containers needed to be shipped, the higher are the holding costs.



(a) Total relevant costs per container

(b) Total costs per cycle and inventory holding costs per cycle

Figure 3: Shipper's total relevant costs per container during the time period as formulated in Eq. 2 is presented in (a). Shipper's total costs per cycle as formulated in Eq. 1 and inventory costs per cycle vs. shipment size is presented in (b). Data is taken from Table 2.

The total relevant costs of the terminal operator

The hinterland supply chain from the perspective of the terminal operator has a cyclic pattern as well. Each cycle has a length of two-way sailing time $2t$ and unloading time at the inland terminal $\frac{Q}{r}$. The relevant costs for the inland terminal operators are a combination of the variable and fixed transportation costs and the costs incurred during container handling operations. Then the relevant cost per cycle can be expressed as:

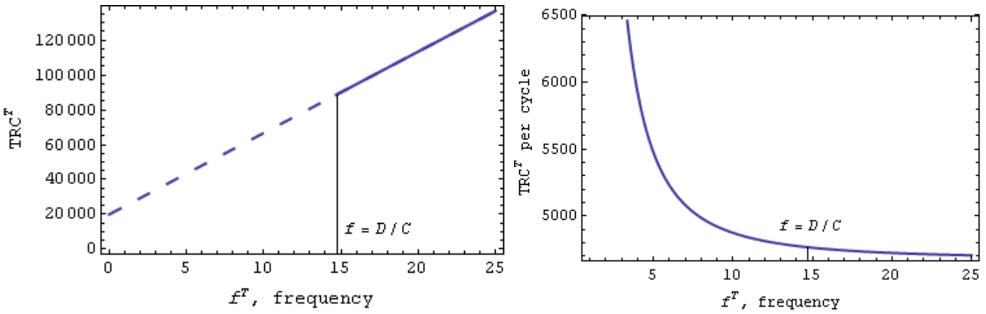
$$\text{Cost per cycle} = c(2t + \frac{Q}{r}) + \frac{Db}{Q} + \frac{hQ}{r} \tag{3}$$

The first term in Eq. 3 is the variable transportation costs spent for operating the route during the cycle, the second is the fixed transportation costs incurred during the cycle. The third part represents the handling cost. The handling costs of unloading the vessel are proportional to the shipment size and vary inversely to the rate of unloading the vessel.

The total relevant costs, TRC^T, for the inland terminal operator per time period are:

$$TRC^T \quad = \quad \frac{Dc}{Q}(2t + \frac{Q}{r}) + b + h\frac{DQ}{Qr} = \frac{Dc}{Q}(2t + \frac{Q}{r}) + b + \frac{Dh}{r} \tag{4}$$

We refer to Fig. 4 for a graphical representation of the total relevant costs for the inland terminal operator. The total relevant costs are increasing with the number of trips. The function of costs reaches its minimum value for $f = 0$, then only fixed transportation costs are paid for. A more realistic lower bound for frequency is equal to $f^T = \left\lceil \frac{D}{C} \right\rceil$. In Fig. 4 (b) the total relevant costs per cycle are presented. This relationship is quite intuitive as more cycles lead to more spreading of the fixed transportation costs.



(a) Total relevant costs

(b) Total relevant costs per trip

Figure 4: Total relevant costs of the inland terminal operator as a function of frequency. The minimum frequency needed to satisfy the demand of the node $D = 764$ TEU is calculated based on vessel capacity $C = 52$ TEU. Data is taken from Table 2.

The total relevant costs of the hinterland supply chain

To capture the costs of both parties in the container supply chain, both perspectives are combined into one equation and the total relevant costs are redefined by the sum of the shipping and handling costs from the inland terminal operator perspective and the inventory holding costs from the shipper perspective. In the joint perspective setting, the freight charge the shipper incurs during a time period is equal to the inland terminal operator costs. As we take a cost perspective (the margin of the terminal operator is not included), the total relevant costs of the hinterland supply chain per time period are:

$$TRC = \frac{Dh}{r} + b + \frac{Dc}{r} + \frac{2Dct}{Q} + \frac{DHQ}{2r} + DHt \tag{5}$$

After taking the first order condition and setting it equal to zero we receive the optimal shipment size and optimal frequency for joint decision for direct shipping policy:

$$\frac{dTRC}{dQ} = \frac{Dh}{2r} - \frac{2Dct}{Q^2} \tag{6}$$

$$Q^* = 2\sqrt{\frac{crt}{H}} \tag{7}$$

$$f^* = \frac{D}{2}\sqrt{\frac{H}{ctr}} \tag{8}$$

To obtain the optimal total shipping costs formulation we have to insert the optimal value for shipment size Q^* in Eq. 5:

$$TRC^* = b + 2D\sqrt{\frac{Hct}{r}} + D\left(\frac{h}{r} + \frac{c}{r} + Ht\right) \tag{9}$$

2.3 The tour coordination policy

As in section 2.2, we formulate the total costs of the system as the sum of the inventory holding costs from the shipper perspective and the transportation and handling costs from the inland terminal operator perspective.

The total relevant costs of the shipper

We start our analysis with the following assumptions: the shipper has the same demand of containers on every inland terminal, $D_i = D_j, i \neq j, \quad i,j = \{1,\ldots,M\}$. A second assumption is that the vessel capacity is equally divided between the shipments dedicated to each of the inland terminals on the tour, $Q_i = \frac{C}{M} \quad i = \{1,\ldots,M\}$.

Let us designate Q the sum of the shipments Q_i dedicated to each of the inland terminals i, i.e. $Q = \sum_{i=1}^{M} Q_i$. As mentioned above, the total relevant costs of the shipper consists of inventory holding and transportation costs. The prime difference between the direct and the tour coordination policy is the time a container (or bundle of containers) spends in the system. The latter affects the inventory holding costs of the shipper. As in the previous section, the review of the system inventory depletion follows a cyclic pattern. Each cycle is divided into $2M$ phases and corresponds to one barge tour. Please refer to Fig. 5, where the average inventory depletion is presented for the network with 2 inland terminals.

The average inventory of the end shipper is equal to the sum of the bundles of containers $Q_1 + Q_2$ while they are shipped for $t_{0,1}$ time units from the deep-sea terminal to the first inland terminal. Then, at the first inland terminal, the bundle of Q_1 containers is unloaded and the shipper's average inventory drops to the level of $(Q_2 + Q_1)/2$ containers. This procedure lasts for Q_1/r time units. So far, the inventory holding costs are equal to $H\big((Q_1+Q_2)t_{0,1} + Q_1(Q_1+2Q_2)/2r\big)$. This pattern is replicated until the cycle is completed, resulting in the following relevant costs per cycle for the network containing 2 nodes:

$$\begin{aligned} \text{Costs per cycle} &= F(Q_1+Q_2) + H\left((Q_1+Q_2)t_{0,1} + \frac{Q_1(Q_1+2Q_2)}{2r} + Q_2 t_{1,2} + \frac{Q_2^2}{2r}\right) \\ &= FQ + H\left(\frac{Q^2}{2r} + Qt_{0,1} + \frac{Qt_{1,2}}{2}\right) \end{aligned} \tag{10}$$

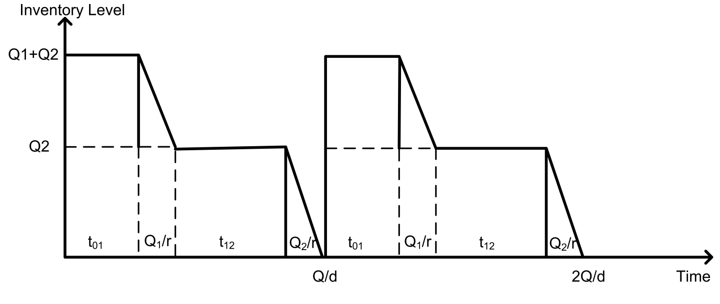


Figure 5: Shipper's inventory in tour shipping policy.

The general form of the relevant costs per cycle is:

$$\text{Costs per cycle} \quad = \quad F \cdot Q + H\Big(\sum_{i=1}^{M} \frac{Q \cdot i}{M} t_{M-i,M+1-i} + \frac{Q^2}{2r}\Big) \tag{11}$$

The total relevant costs for the shipper per time unit Q/D are:

$$TRC^S = F \cdot D + \frac{DH}{Q}\Big(\sum_{i=1}^{M} \frac{Q \cdot i}{M} t_{M-i,M+1-i} + \frac{Q^2}{2r}\Big) \tag{12}$$

The total relevant costs of the terminal operator

The cost structure of the inland terminal operator is similar to the one described in section 2.2. The unit of frequency in this case is equal to tour. The time the barge of the inland terminal operator spends in the system per cycle is equal to the sailing time $\sum_{i=0}^{M} t_{i,suc(i)}$ and unloading time Q/r at all terminals on tour. Then, the costs per cycle are:

$$\text{Cost per cycle} = c\big(\sum_{i=0}^{M} t_{i,suc(i)} + \frac{Q}{r}\big) + \frac{Db}{Q} + h\frac{Q}{r} \tag{13}$$

The total relevant costs, TRC^T, for the inland terminal operator per time period are:

$$\begin{aligned} TRC^T \quad &= \quad \frac{D}{Q}c\big(\sum_{i=0}^{M} t_{i,suc(i)} + \frac{Q}{r}\big) + b + h\frac{DQ}{Qr} \\ &= \quad \frac{D}{Q}c\big(\sum_{i=0}^{M} t_{i,suc(i)} + \frac{Q}{r}\big) + b + \frac{Dh}{r} \end{aligned} \tag{14}$$

The first term in Eq. 14 is the variable transportation costs, and is proportional to the transit time in the network, which consists of actual traveling time and unloading time. The second term in Eq. 14 is the fixed transportation costs per time unit. The third term is the handling costs. These costs are incurred by inland terminal operator and with margin constitute the freight charge available for customers on the market.

The total relevant costs of the hinterland supply chain

To model the joint perspective of both parties in the hinterland supply chain, we combine their cost formulations and redefine the total relevant costs as shipping and handling costs from the inland terminal operator perspective and holding costs from the shipper perspective. The total relevant costs of the hinterland supply chain are:

$$TRC = \frac{D}{Q}c\Big(\sum_{i=0}^{M} t_{i,suc(i)} + \frac{Q}{r}\Big) + b + \frac{Dh}{r} + \frac{DH}{Q}\Big(\sum_{i=1}^{M} \frac{Q \cdot i}{M} t_{M-i,M+1-i} + \frac{Q^2}{2r}\Big) \tag{15}$$

After taking the first derivative and setting it equal to zero we obtain the optimal shipment size and optimal frequency for the joint decision under the tour shipping policy:

$$\frac{dTRC}{DQ} = \frac{HD}{2r} - \frac{Dc(\sum_{i=0}^{M} t_{i,suc(i)})}{Q^2} \tag{16}$$

$$Q^* = \sqrt{\frac{2cr(\sum_{i=0}^{M} t_{i,suc(i)})}{H}} \tag{17}$$

$$f^* = D\sqrt{\frac{H}{2cr(\sum_{i=0}^{M} t_{i,suc(i)})}} \tag{18}$$

To receive the optimal total relevant costs formulation we insert the optimal shipment size Q^* in Eq. 15:

$$TRC^* = b + 2D\sqrt{\frac{cH(\sum_{i=0}^{M} t_{i,suc(i)})}{2r}} + D\left(\frac{h}{r} + \frac{c}{r} + H\Big(\sum_{i=1}^{M} \frac{i \cdot (t_{M-i,M+1-i})}{M}\Big)\right) \tag{19}$$

2.4 The direct coordination policy versus the tour coordination policy

In this section, we compare the direct coordination policy and the tour coordination policy. We derive a set of conditions that define the cost-effectiveness of the tour over the direct coordination policy. We look at the difference of total relevant costs obtained from the difference of the total relevant costs for the direct and the tour policies, i.e. Eq. 9 − Eq. 19. If Inq. 20 holds, then the performance of the tour coordination policy is better than the direct coordination policy.

$$\begin{aligned} f\tfrac{c}{M}\Big((M-2)t_{0,1} - 2\textstyle\sum_{i=2}^{M} t_{0,i}\Big) + \tfrac{DH}{M}\Big((M-1)t_{0,1} - \textstyle\sum_{i=2}^{M} t_{0,i}\Big) > \\ -fc\big(\textstyle\sum_{i=1}^{M} t_{i,suc(i)}\big) - \tfrac{DH}{M}\Big(\textstyle\sum_{i=1}^{M-1} \tfrac{i}{M} t_{M-i,M+1-i}\Big), \quad c > 0, H > 0 \end{aligned} \tag{20}$$

The first part of Inq. 20 considers the variable transportation costs and the inventory holding costs for the direct coordination policy. The second part describes the costs accumulated during the sailing along the inland terminals, resulting from the tour coordination policy. Since the cost parameters (c, H) are time dependent, the influence of c and H on the total relevant costs is conditioned by the difference in duration of the different connecting links $t_{i,suc(i)}$ and the corresponding direct links t_i. For the direct coordination policy the variable transportation costs accumulate slower than for the tour coordination policy. The number of inland terminals and the frequency determines the cost-effectiveness of the two policies in terms of transportation costs. When the duration of connection links $(\sum_{i=1}^{M} t_{i,suc(i)})$ approaches the value of the term $((M-2)t_{0,1} - 2\sum_{i=2}^{M} t_{0,i})$, then the variable transportation costs of the direct coordination policy are lower than the tour coordination policy. The inventory holding costs accumulate faster under the direct coordination policy than under the tour policy. When the values of H and M are low $(H < 1)$, the difference between the time terms $((M-1)t_{0,1} - \sum_{i=2}^{M} t_{0,i})$ and $(\sum_{i=1}^{M-1} \frac{i}{M} t_{M-i,M+1-i})$ is small as well. Hence, the direct coordination policy is more profitable as the total costs of transporting containers are lower.

3 Numerical Study

In this section, we apply the proposed model and illustrate the managerial insights. Consider a hinterland container supply chain consisting of one shipper and one inland terminal operator. The inland terminal operator ships containers on a network of canals and can choose between the direct coordination policy or the tour coordination policy. For our numerical results, we use real-life data collected from four inland terminals located in the hinterland of the port of Rotterdam, The Netherlands. The key data used in this numerical study is summarized in Table 2.

Name	Description	Measurements	Data
N	Number of terminals	-	2
D_i	Demand of a node of the network	containers/month	1500
r_i	Handling rate	containers/hour	25
h	Costs of an hour of handling	€/hour	125
b	Rent of a barge	€/month	20 000
c	Variable transportation costs of TO	€/hour	55
H	Inventory holding coefficient of jth shipper	€/hour/container	2.9

Table 2: Data used for the numerical results.

The hinterland network consists of two inland terminals that are directly connected to the port, as shown in Fig. 1a. Table 3 gives the sailing times of the different links in the network. Demand for containers at the different inland terminals is equal to 1500 containers.

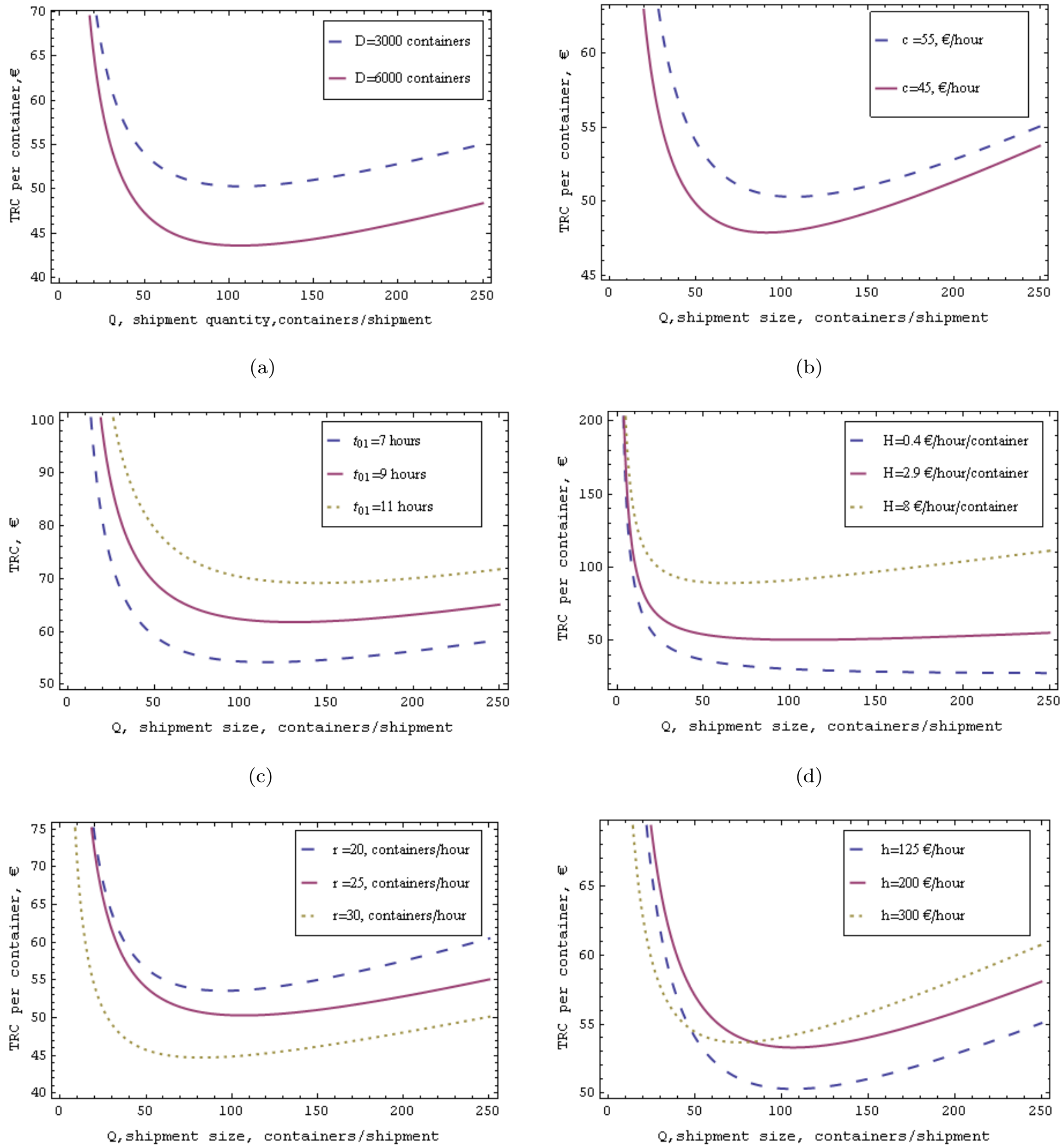
Link	Travel time (hours)
$0, 1$	$t_{0,1} = 6$
$1, 2$	$t_{1,2} = 3$
$0, 2$	$t_{0,2} = 11$

Table 3: Barge sailing times.

The focus of this section is on the joint decision making of shippers and terminal operators. Clearly, individually, the shipper would reduce its inventory holding costs and would as such request very high frequencies. On the other hand, the terminal operator wants to use his resources as efficiently as possible, hence highly utilized barges. This latter leads to a low frequency operated network. These two extreme situations are less interesting than the joint decision making perspective. This section is structured along the same lines as our previous section. First, we discuss the direct coordination policy, then we consider the tour coordination policy. Subsequently, we evaluate and compare both policies and identify when it is better to utilize them.

3.1 The direct coordination policy

In this section, we describe the performance of the direct coordination policy. Figures 6a - 6f show the sensitivity of the total relevant costs (expressed per container) to the total demand D, the variable transportation costs c, the sailing time t, the inventory holding charge H, the handling rate r, and the handling costs h, respectively. The optimal values of shipment size, frequency and total relevant costs for the direct coordination policy are calculated according to Eq. 7, 8 and 9, respectively, with parameter values taken from Table 2.



(a) (b)

(c) (d)

(e) (f)

Figure 6: Sensitivity analysis for the direct coordination policy.

The direct coordination policy is cost-effective for high container volumes. To justify the extra inventory costs for the shipper, containers have to be transported in a short time. As such, the terminal operator cannot wait to fill up the barge to full capacity. Consequently, the terminal operator increases the freight charges per container to keep the level of revenues from the barge trip. Sensitivity on the variable transportation costs, given in Fig. 6b, shows that, low variable transportation costs provide lower values of the total relevant costs per container. As the variable transportation costs approach zero, the shipment size approaches the value of one container that coincides with the lower bound of the shipment size (see also Section 2.2). Furthermore, the closer the port and the destination inland terminal, the lower the total relevant costs per container. A decrease in sailing time provides significant decreases of the total relevant costs, as can be seen from Fig. 6c. This is explained by the fact that both variable transportation costs and the inventory holding costs depend on time, thus a drop in sailing time results in decrease of costs. Figure 6a shows that for increasing demand, the total relevant costs per container decrease. This illustrates the benefits of shipment consolidation: higher volumes of containers in the network results in lower total relevant costs per container, as fixed transportation costs are redistributed on a larger number of containers. Besides lower transportation costs, increasing shipment sizes, also lead to an increase of unloading time, causing the increase of time a container spends on the quay side and in the container supply chain in general.

Figure 6e shows that a low handling rate increases the total relevant costs per container and forces the costs to grow with the increase of the shipment size. Next, Fig. 6f provides insights in the influence of the handling operations costs on the direct coordination policy cost-effectiveness. Expensive machinery is justified for the handling of direct shipments up to 50 containers. Shipment sizes starting from 50 containers and more should be handled by less expensive machinery in order to minimize the costs. Of course, this threshold value depends on several parameters and it moves to the right along the horizontal axis with an increase of travel time between the port and the inland terminal and increase of variable transportation costs. Additionally, Fig. 6f shows that the total relevant cost function is sensitive to the value of parameter h around the optimal value of costs, supporting the trade-off between transportation and handling costs described in Notteboom (2004). Important for the shipper is the inventory holding charge. In case of perishable products, the value of goods decreases in time while they are transported to the terminal. Thus, in order to minimize losses, the shipper is interested in shorter delivery lead times. Reliable and frequent services offered by the inland terminal operator implies shorter lead times. The latter influences the company's inventory in pipeline and amount of available funds. This being extremely crucial in case of high-value and low-packaging density products, such as electronic home appliances.

To illustrate the influence of inventory holding charge on total relevant costs we consider three types of products. The first type can be characterized by high-packaging density and low-value. An example of such product is paper. In this case, the transportation costs constitutes the main part of the total relevant costs. The value of 0.4€/hour/container is assigned to the inventory holding charge of such product. The second type is characterized by average packaging density and relatively high value density with $H =$ 2.9€/hour/container. Any perishable goods, such as dairy products and fruits, can serve as an example of such type of product. The last type are high-value, low-packaging density products such as electronic appliances. Consequently, the inventory holding charge for such product is high, $H = 8€$/hour/container. Figure 6d shows that, as the inventory holding charge H increases, the total relevant costs per container become more sensitive to the shipment size. These curves indicate that it is important to determine the optimal shipment size and to further use it for the distribution of expensive goods with high holding inventory charge.

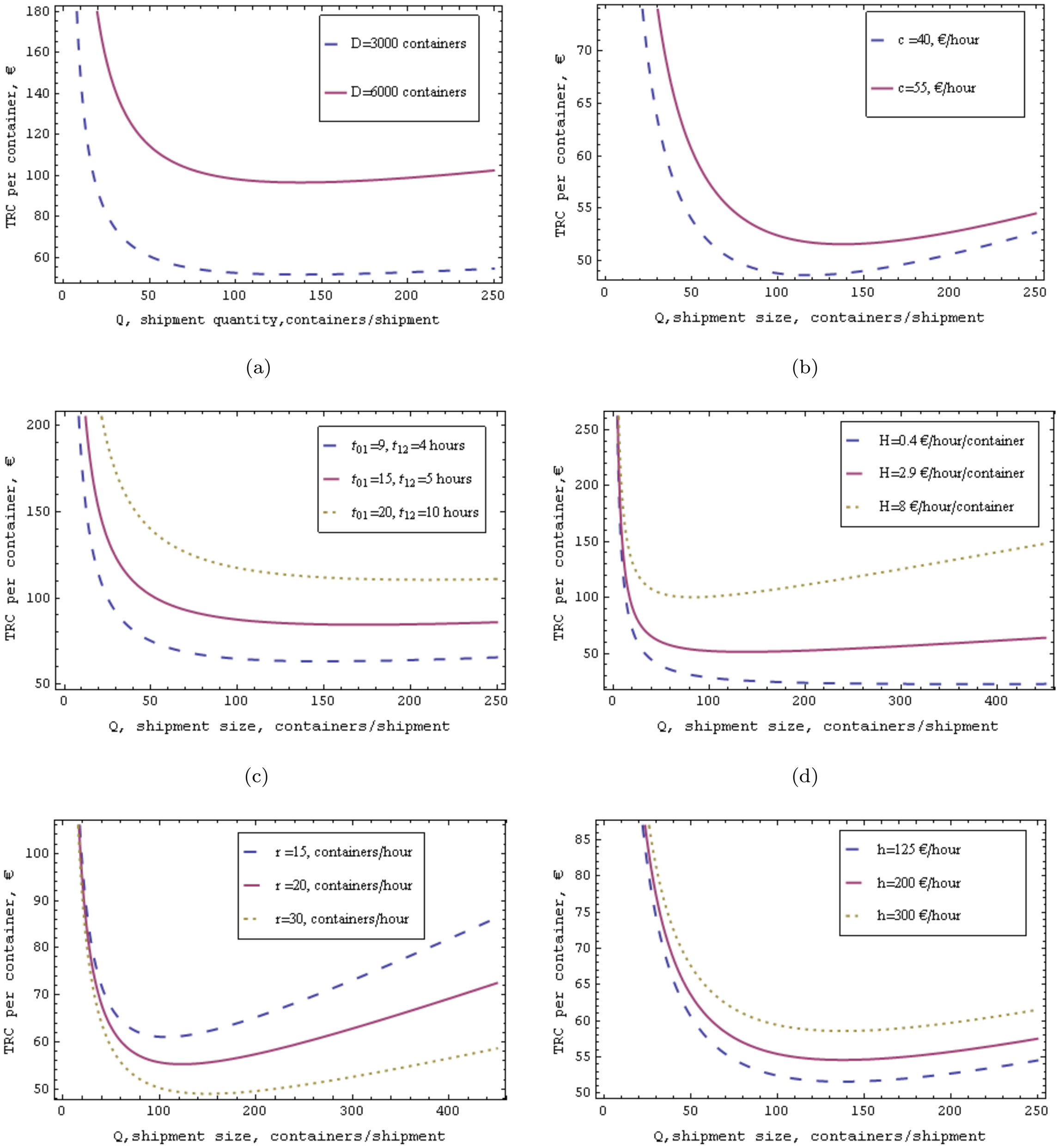
3.2 The tour coordination policy

In this section, we describe the performance of the tour coordination policy. Refer to Fig. 1b for a graphical representation. Figures 7a - 7f show the sensitivity of the total relevant costs (expressed per container) to the total demand D, the variable transportation costs c, the sailing time t, the inventory holding charge H, the handling rate r, and the handling costs h, respectively. The optimal values of shipment size, frequency and total relevant costs per container for tour coordination policy are calculated according to Eq. 17, 18 and 19 respectively with parameter values taken from Table 2.

The sensitivity curves of Fig. 7b show that low variable transportation costs lead to low total relevant costs per container. Both coordination policies (direct and tour) are robust against variable transportation cost fluctuation. Furthermore, shorter sailing times lead to lower total relevant costs per container, as shown in Figure 7c. Increasing the tour duration raises the optimal shipment size, but the total relevant costs is relatively insensitive (Figure 7c). Higher demand gives an increase of the total relevant costs per container (Figure 7a). Since the vessel capacity is highly utilized in the tour coordination policy, an increase of the number of containers does not provide similar economies of scale as in the direct coordination policy. Fig. 7e shows that high and low handling rate results in same values of TRC for small shipment sizes. With increase of shipment size, high handling rates lead to lower costs per container. Figure 6f shows that the TRC is sensitive to the handling operation costs. In contrast to the direct coordination policy, the use of expensive handling machinery gives an increase in the total relevant costs per container with any shipment size. As for the direct coordination policy, three types of products were chosen to illustrate the influence of holding inventory charge on total relevant costs per container. The results are similar to direct coordination policy. The inventory holding charge H positively influences the rise of total relevant costs(Fig. 7d). The costs per container are more sensitive with respect to shipment size, when the rate values are high.

3.3 The direct coordination policy versus the tour coordination policy

This section is based on the analysis of Inq. 20. First, we focus the case where the number of inland terminals equals two ($M = 2$), then we also analyze the impact of the number of terminals on the total relevant costs per container.



(a) (b)

(c) (d)

(e) (f)

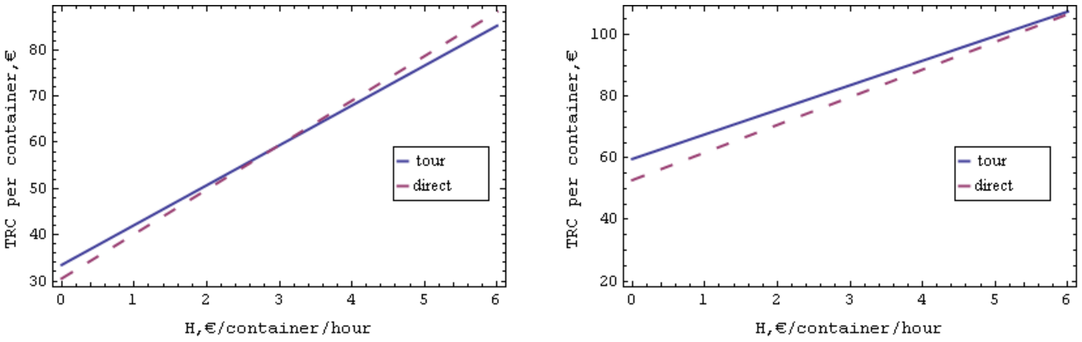
Figure 7: Sensitivity analysis for the tour coordination policy.

Two inland terminals

For $M = 2$, Inq. 20 reduces to:

$$f\frac{t_{1,2}}{2}(2c + Hq) > \frac{DH}{2}(t_{0,2} - t_{0,1}) \tag{21}$$

We start our analysis with the inventory holding costs. The results show that the total relevant costs function is sensitive to the shipment size, when the holding inventory costs are increasing. Figures 8a and 8b present the situations where the inventory holding charge H varies between 0 and 6 for fixed values of the shipment size, $Q = 56$ and $Q = 24$, respectively. The intersection point of TRC graphs represents equal costs and the indifference point between both coordination policies. When the shipment size increases, this intersection point will move to 0, meaning that for large shipments the tour coordination policy is always preferred over the direct coordination policy (Fig. 8a). For smaller shipment sizes, the indifference point moves towards increasing values of the rate (Fig. 8b). Therefore, high-value goods have to be sent in smaller shipments and directly to the dedicated inland terminal.



(a) TRC versus H, Q=56

(b) TRC versus H, Q=24

Figure 8: Inventory holding costs comparing direct versus tour coordination policies.

In practice, the inventory holding rate, the average inventory and the lead time influence the inventory holding costs. Lead time corresponds to the time that is necessary to satisfy the call of the inland terminal. If $t_{1,2} + t_{0,1} > t_{0,2}$ then it is less costly to transport container by direct coordination policy. The cost-effectiveness of the direct coordination policy stays valid till the moment the $t_{1,2} + t_{1,0} < t_{0,2}$. In reality, it means that the link between first and second inland terminal has the same duration as serving the second node directly. Consequently, there is no use in bundling containers and ship them in a tour. Figure 9 shows that the direct coordination policy is more profitable than the tour coordination policy for smaller shipment sizes, when the link $t_{1,2} + t_{1,0} > t_{0,2}$. Starting from 60 containers in the shipment size the tour coordination policy outperforms the direct coordination policy.

Looking at the variable transportation costs, Fig. 11 indicates both policies perform similar for small shipment sizes. We fix the values of the shipment size to 24 and 56 containers, as it is depicted in Fig. 10a and Fig. 10b. These figures provide an insight on the interdependency of the variable transportation costs, time and inventory holding charge and their influence on the TRC for small and moderate shipment sizes. For time values $t_{1,2} + t_{0,1}$ substantially smaller than $t_{0,2}$ the tour coordination policy is more profitable comparing to the direct with any value of the inventory holding charge. Figures 10a and 10b reveal the dependency of the total relevant costs per container on the variable transportation costs, the inventory

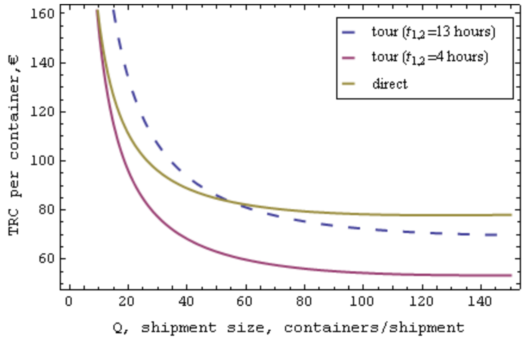
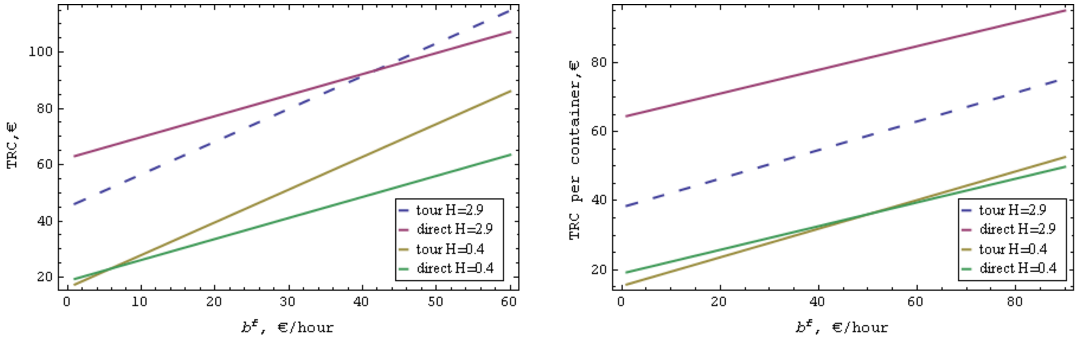


Figure 9: Sailing times comparing direct versus tour coordination policies.

holding charge, and on the duration of sailing times.



(a) TRC versus c, Q=24 containers/shipment, H=2.9 and H=0.4, $t_{1,2} = 10$ hours, $t_{0,2} = 11$ hours

(b) TRC versus c, Q=56 containers/shipment, H=2.9 and H=0.4, $t_{1,2} = 4$ hours, $t_{0,2} = 11$ hours

Figure 10: Variable transportation costs comparing direct versus tour coordination policies.

M inland terminals

More inland terminals leads to an increase of time the container stays in the system. Indeed, the number of terminals is important, and directly connects to the duration of links $t_{i,suc(i)}$. If the sailing time of the tour connection is close to the direct connection, then, the difference of the variable transportation costs for the direct and tour coordination policy is small (see Fig. 12b and Fig. 12d). In Fig. 12b the duration of a tour is almost the same as the summation of direct links. Next, for the direct coordination policy the variable transportation costs are smaller than for the tour, but the inventory holding costs accumulates much faster. For Fig. 12d the duration of the tour is much smaller the summation of direct links. In this case, for the direct coordination policy the variable transportation costs are higher than for tour. The behavior of inventory holding costs functions stays the same. To conclude, the duration of links and number of inland terminals plays a great role on policy performance measures. Besides time and network design,

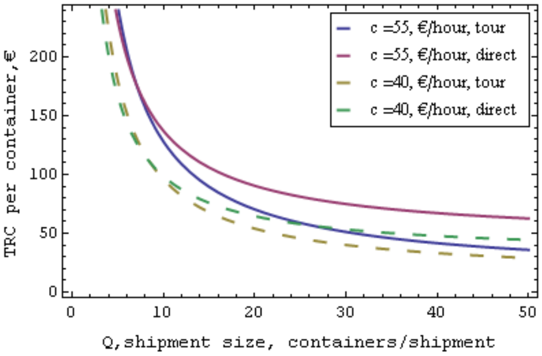
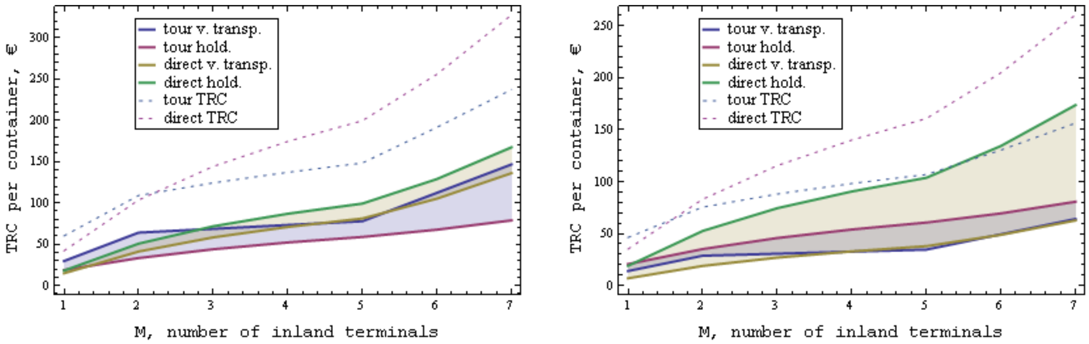


Figure 11: Total relevant costs per container vs shipment size for $c = 40$ €/hour and $c = 55$ €/hour. The joint decision making for both tour and direct coordination policy is taken into account. Graphs are based on data from Table 2, if other is not mentioned on the legend plot.

the shipment size is influential on coordination policy performance. For instance, Fig.12a and Fig. 12b provide result for shipment size $Q = 24$ containers/shipment, while Fig.12c and Fig. 12d for $Q = 56$ containers/shipment. Though the inventory holding costs keep the same dynamic for both shipment sizes, the behavior of transportation costs differs. For smaller shipment sizes the transportation costs bring higher impact on TRC indifferent to the policy. To complete the picture we need to add the value of goods, expressed in value of inventory holding charge (Baumol and Vinod, 1970). The results provide the idea that the direct coordination policy is cost-effective for low and high value goods, shipped in small and moderate sizes for small networks, consisting up to 3 inland terminals (as it is shown on Fig. 13a - 13d).

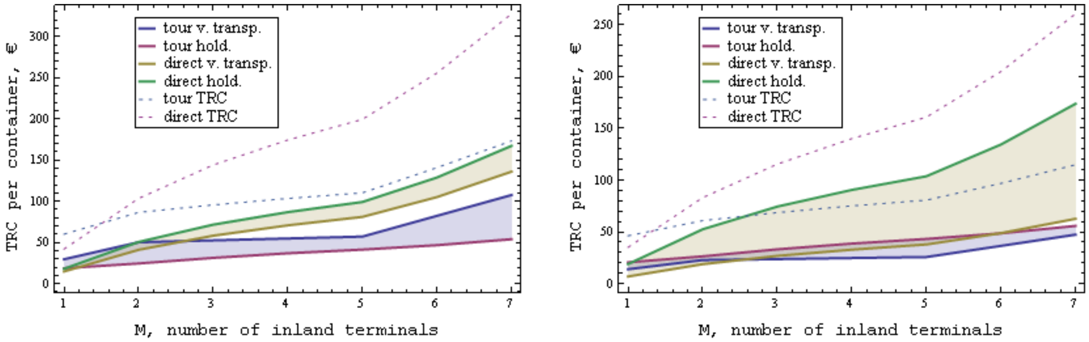
4 Conclusions

In this paper, we addressed the problem of network coordination strategies in barge container hinterland transportation. We developed an analytical model that takes into account the specific nature of barge transportation. This is reflected in inventory depletion of containers along the transportation route. Furthermore, we distinguish between the direct and tour coordination policies used in barge transportation. Our numerical results indicate that the inventory costs of the shipper drive the container supply chain. The time aspect is very important in defining the trade-off between variable transportation and inventory holding costs. The second characteristic is the number of inland terminals in the supply chain. The tour coordination policy outperforms the direct coordination policy on networks with more than 3 inland terminals. The trade-off between the variable transportation costs and the inventory holding costs depend on the duration of connections between the terminals. For the network structures with 2 inland terminals the direct coordination policy outperforms the tour for small shipments and high frequencies. This study contributes to the literature where the hinterland networks of main ports are analyzed. The model developed here can be applied to



(a) Variable and inventory holding costs versus M, Q=24 containers/shipment,H=2.9, time big

(b) Variable and inventory holding costs versus M, Q=56 containers/shipment, H=2.9, time big



(c) Variable and inventory holding costs versus M, Q=24 containers/shipment,H=2.9, time small

(d) Variable and inventory holding costs versus M, Q=56 containers/shipment,H=2.9, time small

Figure 12: Variable transportation costs and inventory holding costs and TRC per container, for given values of q, H and different durations of links $t_{i,suc(i)}$. The joint decision making for both tour and direct coordination policy is taken into account. Graphs are based on data from Table 2, if other is not mentioned on the legend plot. Nodes are serviced in sequential order.

generate managerial insights to making decisions on shipment size and frequencies of service for direct and tour coordination policies.

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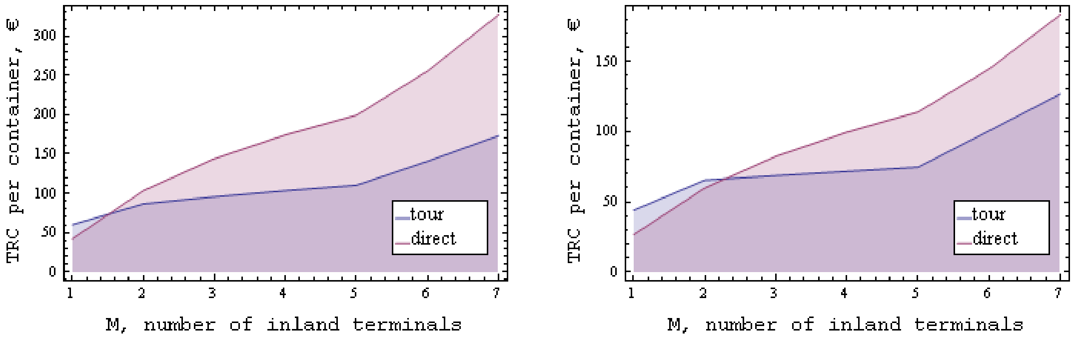
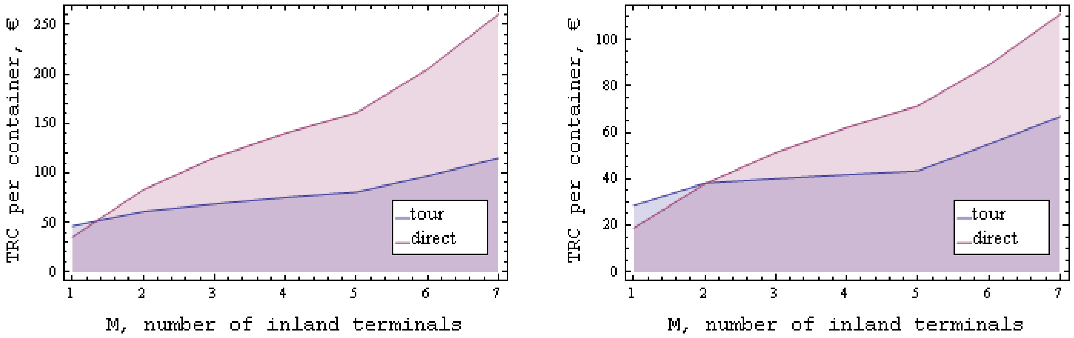


(a) TRC versus M, Q=24 containers/shipment, H=2.9 (b) TRC versus M, Q=24 containers/shipment, H=0.4



(c) TRC versus M, Q=56 containers/shipment, H=2.9 (d) TRC versus M, Q=56 containers/shipment, H=0.4

Figure 13: Total relevant costs per container sensitivity to the variable transportation costs, for given values of q and H. The joint decision making for both tour and direct coordination policy is taken into account. Graphs are based on data from Table 2, if other is not mentioned on the legend plot. Nodes are serviced in sequential order.

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