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Fazi, Stefano; Roodbergen, Kees Jan

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Effects of demurrage and detention regimes on dry-port-based inland container transport

Stefano Fazi*, Kees Jan Roodbergen

University of Groningen, Faculty of Economics and Business, Nettelbosje 2, 9747 AE Groningen, The Netherlands

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ABSTRACT

Increase of congestion at container deep seaports and shortage of capacity has led inland transport systems worldwide to rely more and more on inland terminals, and on the use of high capacity modes of transport to generate economies of scale and reduce negative effects of trucking. In this setting, planning the transport of maritime containers between a deep seaport and a final inland destination must also consider due dates and soft time windows, the latter known as Demurrage and Detention (D&D). In this paper, we formalize the concept of D&D, model the multimodal planning problem, and assess the impact of different D&D regimes on the emerging inland transport systems. By means of an experimental framework, we compare different D&D policies and provide managerial insights. The experiments highlight the effects of existing D&D regimes on transport efficiency and provide guidelines for their choice in practice. D&D are shown to have a twofold effect: first to limit consolidation opportunities and force the use of trucks as buffer, and second to push containers to dwell unnecessarily at the seaports.

1. Introduction

Increase of congestion at container deep seaports, road traffic and lack of handling capacity has led transport systems worldwide to rely more and more on inland terminals for inland transport. Inland terminals have become a sort of extension of seaports, as containers can be stored and wait here to be picked up. This fact favors the use of high capacity modes of transport, such as barges and trains, against trucking, since containers can be moved more easily in bulk. This concept is also known as “dry port” and has been implemented extensively by several seaports, such as Rotterdam, Los Angeles and Long Beach (Zuidwijk and Veenstra, 2014; Roso, 2007).

Scheduling maritime containers for inland transport entails the trade-off between using primarily high capacity but slow barges or trains, to achieve economies of scale, and the need to be on-time (Zuidwijk and Veenstra, 2014). Additionally, containers, while inland, are subject to soft time windows and related fees provided by shipping lines, who lease the containers to shippers and try to stimulate short return times. In general, for the time a shipper holds a container at or outside the seaport, the container is said to be respectively in Demurrage and Detention. For both conditions, a free period is granted by the shipping line; exceeding it results in a homonym daily fee (Veenstra, 2015).

Many reports indicate that D&D are devised to induce shippers to move their containers out of the seaport terminal areas as quickly as possible. From 2000, some articles reported serious congestion problems at seaports in the USA due to idle containers, which was reportedly dealt with by a decrease in the number of free demurrage days, see Mongelluzzo (2000a,b). In 2005, Leach (2005) reports that Maersk, one of the major shipping lines, announced substantial increases in D&D fees and reductions of free

* Corresponding author.

E-mail addresses: s.fazi@rug.nl (S. Fazi), k.j.roodbergen@rug.nl (K.J. Roodbergen).

demurrage days as to limit a common behavior of shippers to use seaport premises as storage space. A few years later, [Bonney \(2015\)](#) reports that the Federal Maritime Commission asked for evidence of unreasonable demurrage and detention fees. Nevertheless, the particular structure of D&D is suspected to impact scheduling decisions and to limit the use of high-capacity modes of transport. In this regard, [Veenstra \(2015\)](#) and [Ypsilantis et al. \(2014\)](#) report that D&D can cause a general delay, because it is common for shippers to use all available free demurrage days at the seaport, before initiating inland transport. The motivation is to gain more flexibility during the detention period. Thereby, D&D can reduce opportunities of consolidation, and consequently hinder dry-port-based inland transport.

This paper addresses the following operational problem. Given a set of containers and information on their release and due dates in a time-frame, an appointed local carrier schedules the inland transport from the seaport to the inland terminal, and from the inland terminal to empty container depots. For both transport legs, the decision maker must allocate all containers to the available fleet, preferably consolidating and assigning to high capacity means of transport, thus limiting the use of trucks. This allocation problem considers costs reflecting economies of scale and Demurrage and Detention (D&D) costs. Different release and due dates may entail that pairs of containers are incompatible; for example, a late release of one may cause a delay for the other, due to delayed departure. Finally, D&D typically drive the decision on when to move the containers from the seaport ([Veenstra, 2015](#)).

In the scientific literature, container systems and related problems have been discussed extensively. See, for example, [Vis and de Koster \(2003\)](#) for a review of operations at container terminals, [Christiansen et al. \(2013\)](#) and [Wang and Meng \(2017\)](#) respectively for review of ship routing and container liner fleet deployment, and finally [Konings et al. \(2013\)](#) for evaluation of container transport networks. In terms of emerging technologies, several contributions have focused on the improvement and control of container logistics in various aspects, based on new concepts and systems. For example, with concern to inland transport, [Bhattacharya et al. \(2014\)](#) focus on an efficient organization of intermodal transport; the proposed system, in a two-step approach, predicts road congestion and assigns the flow to the best transport option. The aim is to reduce excessive use of road infrastructures by better exploiting transport alternatives, such as rail or barge. [Nabais et al. \(2015\)](#) propose a cooperative approach between hub managers and transport providers to better use available transport capacity at hubs, i.e. inland terminals, and in order to achieve imposed modal split goals. The system consists of a predictive model to assess evolving situation of cargo at the hub and of the allocation of cargo to available capacity, constrained by due dates. Similarly, [Crainic et al. \(2015\)](#) and [Li et al. \(2015\)](#) investigate intermodal freight transport planning problems; the former paper defines optimal routes and schedules for vehicles providing transportation services in a dry-port-based intermodal system with a service network design approach; whereas the latter proposes a multi-level freight transport planning approach to assign container flow in a multimodal network.

In this context, D&D have never been directly addressed. The terms are mentioned in a few qualitative studies as a fact, without an in-depth analysis, see descriptions in [Frémont and Franc \(2010\)](#) and [Fransoo and Lee \(2013\)](#). However, recently, [Veenstra \(2015\)](#) emphasized the possible negative impact on inland container transport, thereby hinting towards further investigation. Some papers addressing tactical decisions in container shipping refer to demurrage as an inventory cost ([Crainic et al., 2015](#)) or waiting cost ([Song and Dong, 2012](#)). The problem is not directly tackled also at an operational level. Mathematical models have been developed to model specific aspects of the transport chain, for example routing of trucks through depots and sea terminals ([Zhang et al., 2010](#)), multimodal trade-off decisions ([Fazi et al., 2015](#)) and shuttling ([Wang and Yun, 2013](#)). Proposed models usually include time windows or due dates, which can be implicitly a means to model the free demurrage and detention periods. However, as is demonstrated in this paper, D&D have a decisive role in the scheduling decisions, and a fixed time window does not properly reflect the interplay between free periods, demurrage fees, and detention fees. Therefore, the presence of an integrated decision scheme that takes the D&D system into account is required.

The aim of this paper is threefold. Firstly, we formalize the concepts of demurrage and detention, describing the system, the stakeholders involved and real-world fees. Secondly, we develop a modeling framework and a heuristic technique to approach a typical transport problem in a dry port setting with different D&D policies. Finally, by means of numerical experiments based on real-world data, we generate insights for practice by exploring the effects of D&D on the dwell times in seaports and the use of sustainable modes of transport, and in general, on the concept of dry port. We also assess the effect of information availability on planning and propose an alternative tariff. As support for this study, we consider the case of the Port of Rotterdam region for which data concerning inland transport is available from a transport provider, owning an inland terminal.

2. Problem setting

The aim of this section is to provide a description of the main dynamics of demurrage and detention (D&D) in relation to a typical inland container transport.

2.1. Setting of inland transport networks

In recent years, inland container transport systems have experienced an evolution in terms of network and supply chain, called regionalization ([Notteboom and Rodrigue, 2005](#)). From decentralized and independent systems, seaports are integrating their functions with the hinterland by means of inland terminals. Inland transport networks are increasingly “terminalized” and inland terminals operate as operational buffer with the aim of reducing capacity pressure at seaports, increase throughput and make better use of available land ([Rodrigue and Notteboom, 2009](#); [Li et al., 2015](#)).

From an operational point of view, inland terminals act as barge, truck or train operators and provide seamless shuttle services to the seaport ([Rodrigue and Notteboom, 2009](#)). Thus, inland terminals establish long term contracts for the constant availability of the

Fig. 1. The transportation process.

fleet in the specific corridor and they exclusively plan the transportation of their own corridor.

From a network perspective, the seaport is composed of (sea) terminals and each terminal can have several docks (i.e. quays) where containers are positioned. Containers either arrive to the seaport by means of sea-vessels or are transported to the seaport from the hinterland. In both cases, the container can be destined to any dock.

Considering barge transport, the barge operator has to make “calls” to each sea terminal, declaring in advance the containers that are going to be picked. During the route, a barge typically visits a seaport terminal only once and the sequence of docks to visit is predefined either by guidelines of the seaport or by the sequence on the waterway. This implies that a barge should follow a so-called master route (Fazi et al., 2015). Additionally, the amount of docks to be visited may be limited both by the port itself, due to congestion and mooring time, and by the planner to avoid the creation of excessive delays or costs due to the docking process, which can make trucks a cheaper alternative, see Caris et al. (2011) and Konings et al. (2013). For example, the Port of Rotterdam suggests that small size calls may be detrimental for efficiency and bring to higher costs per container handled (Port of Rotterdam, 2013).

In general, a barge travels to the sea port from a starting location to pick up containers and bring them to a destination in the hinterland, such as an inland terminal. Here, containers may be temporarily stored and then processed at an agreed due date by the final receiver. Once the container is returned to the inland terminal, it is transported to the seaport at an agreed dock or at the empty container depot. A small example of this process is depicted in Fig. 1.

In this paper, we model such a transportation setting. Throughout the paper we will consider the case of the Port of Rotterdam.

2.2. A description of demurrage and detention

We refer to all activities that occur between the container’s pick-up from the seaport until its delivery at the final destination as *inland transport*. D&D fees only have impact on this part of the total journey of a container. In general, a container is said to be in *demurrage* for the time it is positioned at a seaport. Each container is usually granted a free demurrage period, after which additional days at the seaport are penalized with a daily demurrage fee. A container is said to be in *detention* once it has left the seaport and is in the hinterland, until it is returned empty to the shipping line’s empty container depot or to an agreed seaport terminal. A free detention period is usually granted, and exceeding it results in a daily detention fee.

A generic description of the different stages of the relevant inland transport problem is as follows and is provided along with numbers that match the time line depicted in Fig. 2. A container may reach a seaport by means of a sea-vessel (1). The demurrage period starts at the release date, i.e. when the container becomes physically available for inland transport (2). Once the container leaves the seaport (dispatch), the demurrage period ends and the detention period starts (3). The dispatch may take place before or after the end of the free demurrage period (4). The container is supposed to arrive to the inland terminal on or before a due date (5). The due date is the time the receiver wishes to pick up the container from the inland terminal and is usually strict (Zuidwijk and Veenstra, 2014). Once the container is picked and processed (i.e. unpacked), it is returned to the inland terminal (6). A container is usually to be returned to an agreed seaport terminal; as soon as it arrives there, the detention period ends (7). The final delivery may occur before or after the end of the free detention period (8). If the dispatch (3) occurs after the end of the free demurrage period (4), the shipper is charged a demurrage fee. If the container return (7) occurs after the end of the free detention period (8), the shipper is charged a detention fee.

The reason to include inland terminals as destination for containers is twofold. First, it is a necessary node for barge or train transport. Second, inland terminals can operate as operational buffer, as they offer free temporary storage before the due date, as

Fig. 2. Transportation flow and D&D windows on a time line.

incentive to move containers earlier from the seaport (Rodrigue and Notteboom, 2009).

In practice, two types of D&D are applied: “separated D&D” and “combined D&D”. The *separated D&D* is the most common policy and corresponds to the situation just described. A *combined D&D* consists of a single free period for both demurrage and detention taken together; in the time line of Fig. 2, this period starts at (2) and ends at (8). An additional differentiation may take place. In order to favor the use of sustainable modes of transport, such as barges and trains, shipping lines may grant additional free days if a container is moved from the seaport by one of these modalities. For the separated D&D, this means that the detention period is extended. In the numerical section, results will show the effects of such differentiation.

In Table 1, we report some typical free days regimes for the Port of Rotterdam traffic from the major shipping lines and the respective fees, as reported in Veenstra (2015).

2.3. Container transport planning under demurrage and detention

A container can be transported either under carrier haulage or merchant haulage (Iannone, 2012; Nabais et al., 2015). If goods are transported under *carrier haulage*, the shipper entrusts the shipping line to organize the entire transport of the container until its final destination. Under *merchant haulage*, the shipping line is only responsible for the sea transport; typically, the shipper appoints a *local*

Table 1

Free D&D days and daily fees in case of excess. The amount of free detention days may vary if either barges or trains are used to move the container out of the seaport. Data related to the Port of Rotterdam traffic (Veenstra, 2015).

Shipping line	Separated D&D				Combined D&D			
	Free demurrage days	Fee	Free detention days		Fee	Free days		Fee
			Truck	Train/Barge		Truck	Train/Barge	
APL	5	16€	3	6	10€			
CSAV	4	45€	6	6	30€			
CSCL	3	15€	2	10	10€			
Evergreen	3	14€	2	6	4€			
Hapag Lloyd	5	22€	2	6	25€			
Maersk	3	45€	3	5	35€			
MOL	3	25€	3	5	15€			
Nyk Line	4	28€	6	6	15€			
OOCL	3	40€	2	6	25€			
Yang Ming	4	15€	3	3	5€			
COSCO						7	7	30€
CMA CGM						7	7	12€
Hamburg Süd						7	7	20€
MSC						3	7	10€

carrier for the inland transport. The main advantage for the shipper in this case is more contractual power, which allows for rate negotiations for the inland transport. Both under carrier haulage and under merchant haulage, the shipping line has no control over the container for part of the time. For carrier haulage, this entails only the unloading of the container at the receiver. For merchant haulage, this concerns the entire inland transport as well as the unloading.

In this scenario, shippers would typically relay any D&D fee to the local carrier in case the delay is caused by transport inefficiencies and not by explicit request. In fact, local carriers, besides their goal of reducing transport costs and meeting due dates set by the shippers, also need to avoid potential D&D fees. At first sight, the allotted free demurrage and detention periods may appear to provide flexibility in transport planning. After all, a container may wait without charge for a number of days to connect to a suitable transport mode. However, as we will demonstrate in this paper, the fee structure of D&D may trigger behavior that is not favoring sustainability nor enhancing overall supply chain efficiency.

3. Mathematical model

We model the problem of transporting containers from the seaport to an inland terminal and back. We assume the presence of a single decision maker, a local carrier, who has information on arriving and available containers at the seaport. The information concerns location at the port, release dates, due dates, free demurrage and detention periods and D&D fees.

The local carrier aims to minimize transport costs, D&D fees and dwell times at the seaport, while on-time delivery is the only hard constraint. The cost of each ride can be considered fixed. For example, barge owners typically offer their services to the local carrier for a specific transport leg and the cost per ride is predefined by established deals.

This inland transport problem can be modeled using a generalized bin packing formulation, which can be formally defined as: a set of items must be packed into a set of bins with different capacities and selection costs, aiming for a minimum total bin-selection cost. The model takes capacities and costs into account of a fleet (i.e. bins) composed of trucks and high capacity means of transport. The costs reflect economies of scale; therefore, they are not linearly proportional to the capacities. Henceforth, for simplicity, we will refer only to barges, but the model is equally applicable to trains. Finally, when referring to both barges and trucks, the generic term “bin(s)” will be used.

Additionally, the model considers a clustered network. Each seaport terminal is a cluster with several docks; hence, a barge has to route through a selection of docks. As mentioned, barges typically follow a master route that indicates the sequence of docks.

3.1. Formulation

We characterize the mathematical model as follows. Consider a set of containers, $\mathcal{I} = \{1 \dots I\}$. Each container has size W_i , for $i \in \mathcal{I}$, referring to TEU (twenty equivalent foot unit), the standard unit of measurement for container sizes. And consider containers $i \in \mathcal{I}$, that are available at the seaport from time R_i (release date) and must be at the inland terminal not later than due date D_i , i.e. the agreed moment of pick up by the receiver.

We define $\mathcal{K}$ as the set of all bins. For each bin the cost per transport leg is C_k for $k \in \mathcal{K}$. Finally, capacity is Q_k for $k \in \mathcal{K}$. Note that for barges Q_k may be chosen to be lower than the actual capacity, if the barge needs to accommodate containers that are outside the scope of our analysis.

The bin departs from a starting location, such as the inland terminal or a waiting dock outside the port. This location has index “0”. The route of the bin follows the established route to pick up containers and finally to bring them to the inland terminal indexed as node “ N ”, where $N = I + 1$. For the return, the bin departs from the inland terminal and transports the containers to their final destinations at the seaport.

Each container i is considered as a node that identifies its reference dock at the seaport. For example, the nodes of two containers located at the same dock for pick up overlap. This modeling aspect is necessary as each container (i.e. node) has its distinguishing features (R_i, D_i). In case two containers are alike, they may be considered together. Overall, the network G has a set $\mathcal{N} = \{0 \dots N\}$ of nodes, that are ordered according to the given master route through quays. As the reference quays of the containers may differ for forward transport (seaport to inland) and backward transport (inland to seaport), we consider two distinct networks, respectively G^f and G^b , featuring distance matrices $V_{ij}^{f,k}$ and $V_{ij}^{b,k}$ expressed in times, with $k \in \mathcal{K}, i, j \in \mathcal{N}$. Binary matrices L_{ij}^f and L_{ij}^b indicate the reference dock j of container i , where $j \in \mathcal{S}$ (set of docks) and $i \in \mathcal{I}$, respectively for forward and backward leg.

Considering the case of separated D&D, the free demurrage and detention periods are denoted respectively as X_1 and X_2 (in hours), and the daily fees for exceeding them are respectively F_1 and F_2 . Parameter ϵ is an infinitesimally small cost that forces the container to be moved as early as possible from the seaport, in case all other costs are equal. Finally, U is the average time required by the receiver to unpack the container.

To characterize the assignment of containers to the bins for the forward leg (from seaport to inland terminal), we set binary assignment variable f_{ik} for $i \in \mathcal{I}$ and $k \in \mathcal{K}$ equal to 1 if container i is assigned to bin k , and equal to 0 otherwise. Similarly, b_{ik} characterizes the assignment for the backward leg. Furthermore, let z_k^f be a binary variable that keeps track whether a bin is used or not for the forward leg, and z_k^b for the backward leg. Let $x_{ij}^{f,k}$ and $x_{ij}^{b,k}$ be the binary variables, respectively for forward and backward leg, to track the routing, with $k \in \mathcal{K}, i, j \in \mathcal{N}$. They assume value 1, if arc (i, j) is covered by the means of transport k . Binary variables $u_{ij}^{f,k}$ and $u_{ij}^{b,k}$ control whether bin k visits dock j , with $k \in \mathcal{K}, j \in \mathcal{S}$. Let $t_{ij}^{f,k}$ represent, for the forward leg, the visit time of bin k at node j , and $t_{ij}^{b,k}$ for the backward leg. With variables e_{1i} and e_{2i} , we compute respectively the amount of days with demurrage and detention fees for container i , and with d_i its dwell time at the seaport. Sets, parameters and variables are summarized in Table 2.

Table 2
Sets, parameters and variables.

Sets	
$\mathcal{I}$	Set of containers 1,...,I
$\mathcal{N}$	Set of nodes 0,...,N = I + 1
$\mathcal{K}$	Set of bins (barges and trucks) 1,..., $\mathcal{K}$
$\mathcal{S}$	Set of docks 1,..., $\mathcal{S}$
Parameters	
X_1	Free demurrage period (h)
X_2	Free detention period (h)
F_1	Demurrage fee (per day)
F_2	Detention fee (per day)
D_i	Due date of container i , $\forall i \in \mathcal{I}$
R_i	Release date of container i at the seaport, $\forall i \in \mathcal{I}$
W_i	Size of container i , $\forall i \in \mathcal{I}$
U	Unpacking time
C_k	Transport cost for bin k , $\forall k \in \mathcal{K}$
Q_k	Capacity of bin k , $\forall k \in \mathcal{K}$
$V_{ij}^{f,k}$	Distance between nodes i and j , in traveling time for bin k in the forward leg, $\forall i, j \in \mathcal{N}$, $\forall k \in \mathcal{K}$
$V_{ij}^{b,k}$	Distance between nodes i and j , in traveling time for bin k in the backward leg, $\forall i, j \in \mathcal{N}$, $\forall k \in \mathcal{K}$
L_{ij}^f	Binary reference of dock j for container i in the forward leg, $\forall i \in \mathcal{I}$, $\forall j \in \mathcal{S}$
L_{ij}^b	Binary reference of dock j for container i in the backward leg, $\forall i \in \mathcal{I}$, $\forall j \in \mathcal{S}$
ϵ	A small value
α	An integer value
M	A large value
Variables	
f_{ik}	For the forward leg, set 1 if container i is allocated to bin k , 0 otherwise, $\forall i \in \mathcal{I}$, $\forall k \in \mathcal{K}$
b_{ik}	For the backward leg, set 1 if container i is allocated to bin k , 0 otherwise, $\forall i \in \mathcal{I}$, $\forall k \in \mathcal{K}$
z_k^f	For the forward leg, set 1 if bin k is used, 0 otherwise, $\forall k \in \mathcal{K}$
z_k^b	For the backward leg, set 1 if bin k is used, 0 otherwise, $\forall k \in \mathcal{K}$
$x_{ij}^{f,k}$	For the forward leg, set to 1 if bin k goes from i to j , 0 otherwise, $\forall i, j \in \mathcal{N}$, $k \in \mathcal{K}$
$x_{ij}^{b,k}$	For the backward leg, set to 1 if bin k goes from i to j , 0 otherwise, $\forall i, j \in \mathcal{N}$, $k \in \mathcal{K}$
$t_j^{f,k}$	For the forward leg, visit time of bin k at node j , $\forall k \in \mathcal{K}$, $\forall j \in \mathcal{N}$
$t_j^{b,k}$	For the backward leg, visit time of bin k at node j , $\forall k \in \mathcal{K}$, $\forall j \in \mathcal{N}$
$u_j^{f,k}$	For the forward leg, set to 1 if bin k visits dock j , 0 otherwise, $\forall k \in \mathcal{K}$, $\forall j \in \mathcal{S}$
$u_j^{b,k}$	For the backward leg, set to 1 if bin k visits dock j , 0 otherwise, $\forall k \in \mathcal{K}$, $\forall j \in \mathcal{S}$
d_i	Dwell time at the seaport of container i , $\forall i \in \mathcal{I}$
e_{1i}	Amount of days with demurrage fee for container i , $\forall i \in \mathcal{I}$
e_{2i}	Amount of days with detention fee for container i , $\forall i \in \mathcal{I}$

We now present the complete formulation with a separated D&D regime.

$$\min \sum_{k \in \mathcal{K}} (C_k z_k^f + C_k z_k^b) + \sum_{i \in \mathcal{I}} (F_1 e_{1i} + F_2 e_{2i} + \epsilon d_i) \quad (1)$$

$$\text{s.t.} \sum_{k \in \mathcal{K}} f_{ik} = 1 \quad \forall i \in \mathcal{I} \quad (2)$$

$$\sum_{i \in \mathcal{I}} W_i f_{ik} \leq Q_k z_k^f \quad \forall k \in \mathcal{K} \quad (3)$$

$$\sum_{j \in \mathcal{N}: j > i} x_{ij}^{f,k} = \sum_{j \in \mathcal{N}: j \neq i} x_{ji}^{f,k} = f_{ik} \quad \forall i \in \mathcal{I}; \forall k \in \mathcal{K} \quad (4)$$

$$\sum_{j \in \mathcal{I}} x_{0j}^{f,k} = z_k^f \quad \forall k \in \mathcal{K} \quad (5)$$

$$\sum_{j \in \mathcal{I}} x_{jN}^{f,k} = z_k^f \quad \forall k \in \mathcal{K} \quad (6)$$

$$t_0^{f,k} \geq R_i f_{ik} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (7)$$

$$t_i^{f,k} = t_0^{f,k} + \sum_{w \in \mathcal{N}} \sum_{j \in \mathcal{N}: j \leq i} V_{wj}^k x_{wj}^{f,k} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (8)$$

$$t_0^{f,k} + \sum_{w \in \mathcal{N}} \sum_{j \in \mathcal{N}} V_{wj}^{f,k} x_{wj}^{f,k} \leq D_i + (1-f_{ik})M \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (9)$$

$$d_i \geq (t_i^{f,k} - R_i) - (1-f_{ik})M \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (10)$$

$$\sum_{k \in \mathcal{K}} b_{ik} = 1 \quad \forall i \in \mathcal{I} \quad (11)$$

$$\sum_{i \in \mathcal{I}} W_i b_{ik} \leq Q_k z_k^b \quad \forall k \in \mathcal{K} \quad (12)$$

$$\sum_{j \in \mathcal{N}: j > i} x_{ij}^{b,k} = \sum_{j \in \mathcal{N}: j \neq i} x_{ji}^{b,k} = b_{ik} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (13)$$

$$\sum_{j \in \mathcal{I}} x_{0j}^{b,k} = z_k^b \quad \forall k \in \mathcal{K} \quad (14)$$

$$\sum_{j \in \mathcal{I}} x_{jN}^{b,k} = z_k^b \quad \forall k \in \mathcal{K} \quad (15)$$

$$t_0^{b,k} \geq (D_i + U)b_{ik} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (16)$$

$$t_i^{b,k} = t_0^{b,k} + \sum_{w \in \mathcal{N}} \sum_{j \in \mathcal{N}: j \leq i} V_{wj}^{b,k} x_{wj}^{b,k} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (17)$$

$$e_{1i} \geq (d_i - X_i)/24 \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (18)$$

$$e_{2i} \geq (t_i^{b,k} - t_i^{f,w} - X_i)/24 - (1-b_{ik})M - (1-f_{iw})M \quad \forall i \in \mathcal{I}, \forall k, w \in \mathcal{K} \quad (19)$$

$$\sum_{i \in \mathcal{I}} f_{ik} L_{ij}^f \leq u_j^{f,k} M \quad \forall k \in \mathcal{K}, j \in \mathcal{I} \quad (20)$$

$$\sum_{i \in \mathcal{I}} b_{ik} L_{ij}^b \leq u_j^{b,k} M \quad \forall k \in \mathcal{K}, j \in \mathcal{I} \quad (21)$$

$$\sum_{j \in \mathcal{I}} u_j^{f,k} \leq \alpha \quad \forall k \in \mathcal{K} \quad (22)$$

$$\sum_{j \in \mathcal{I}} u_j^{b,k} \leq \alpha \quad \forall k \in \mathcal{K} \quad (23)$$

$$f_{ik}, b_{ik} \in \{0,1\} \quad \forall i \in \mathcal{I}, \forall k \in \mathcal{K} \quad (24)$$

$$z_k^f, z_k^b \in \{0,1\} \quad \forall k \in \mathcal{K} \quad (25)$$

$$x_{ij}^{f,k}, x_{ij}^{b,k} \in \{0,1\} \quad \forall i, j \in \mathcal{N}, \forall k \in \mathcal{K} \quad (26)$$

$$d_i \in \mathbb{R}^+ \quad \forall i \in \mathcal{I} \quad (27)$$

$$t_i^{f,k}, t_i^{b,k} \in \mathbb{R}^+ \quad \forall i \in \mathcal{N}, k \in \mathcal{K} \quad (28)$$

$$e_{1i}, e_{2i} \in \mathbb{N}_0 \quad \forall i \in \mathcal{I} \quad (29)$$

$$u_j^{f,k}, u_j^{b,k} \in \{0,1\} \quad \forall j \in \mathcal{I}, \forall k \in \mathcal{K} \quad (30)$$

In the Objective Function (1), the first and second terms give the costs for bins usage, the third and fourth terms add demurrage and detention costs for the set of containers, the fifth term penalizes the dwell times. In particular, ϵd is the small cost that guarantees the earliest possible departure under equal D&D fees. With Constraints (2), we impose that every container is included in the forward leg and with Constraints (3) that bins capacities are not exceeded. Similarly for the backward leg, we have Inequalities (11) and (12). Inequalities (4)–(6) are flow conservation constraints for the forward leg. Additionally, Constraints (4) impose bin k to follow a master route, which is a predetermined sequence of docks. In this regard, containers are presorted according to reference dock and then ordered according to the preferred master route. Analogously, (13)–(15) apply for the backward leg.

With Inequalities (7), we constrain bin k to depart only after the latest allocated container is released. With Inequalities (8), we compute the moment bin k reaches the allocated node i . With Constraints (9), we impose that containers allocated to bin k are not late. Inequalities (10) compute the dwell time of container i . With Inequalities (16), the departure time of a bin k , for the backward

leg, must be after every allocated container becomes again available, whereas (17) compute the time the bin leaves container i at the seaport. With Constraints (18) we calculate the demurrage days to be paid, and with (19) the detention days for each container i . Finally, Constraints (20) up to (23) limit the amount of visited docks to a constant α for each leg. These constraints are practical and are not meant to limit the traveling time, which is already limited by Constraints (9), (18) and (19), but rather to avoid too many calls with few containers. This limitation can alternatively be penalized in the objective function by adding items $u_j^{f,k}$ and $u_j^{b,k}$. However, related costs are unknown and difficult to quantify. Hence, in the numerical section we will consider the reported constraints.

Finally, the mathematical model can be extended in case of constrained departure times, for example, if trains are considered. In such a case, variables $t_0^{f,k}$ and $t_0^{b,k}$ simply become parameters of the model.

The formulation as given above is valid for the case of separated D&D. When considering the other typologies of fees, the formulation needs changes. We first consider separated D&D with differentiation between detention fees for trucks and barges, which is commonly used when trying to stimulate the more environmentally friendly option of using barges. Let X_2^i denote the number of free detention days that apply to container i , depending on whether a truck or a barge is used for its transport, and $B \subset \mathcal{N}$ the set of barges. Then X_2^i can be defined as:

$$X_2^i \equiv \sum_{k \in B} f_{ik} X_2^B + \sum_{k \notin B} f_{ik} X_2^T \quad \forall i \in \mathcal{N} \quad (31)$$

where X_2^B and X_2^T are the free detention periods (in days) for using respectively either a barge or a truck in the forward leg. Now separated D&D with differentiation between detention fees for trucks and barges can simply be modeled by replacing X_2 by X_2^i in Constraints (19).

For the case of combined D&D, we remove $\sum_{i \in \mathcal{N}} F_1 e_{1i}$ from the Objective Function (1), remove Constraints (18), and replace $t_i^{f,w}$ by R_i in Constraints (19). For the combined D&D with differentiation between fees for trucks and barges, we make both the changes described for combined D&D as well as the changes described for separated D&D with differentiation between detention fees for trucks and barges.

It is important to notice that the proposed model assumes all information on container availability at the seaport to be known in advance. This may not always be the case in practice, especially when considering a long time horizon. Typically, the carrier will be able to trace the container only once it becomes available or hours before, using specific web-based software. A common method in such a setting is to employ a block sequencing approach (Han et al., 1987). In this approach, the scheduling is repeated regularly and in each scheduling run only the jobs are included that are known at that point in time. In the numerical experiments of Section 5.2, we compare the full-information and block sequencing settings.

3.2. Discussion of the model

The proposed formulation is an extended allocation model. In literature, allocation models have been widely used in many applications, for example manufacturing (Lohatepanont and Barnhart, 2004), airline planning (Chen and Pundoor, 2006), and ship routing (Fagerholt and Christiansen, 2000). However, our model integrates also capacity constraints, which align more to bin packing problems. Perboli et al. (2014) observe that “researchers have started to push towards the definition of generalizations and enrichment of the traditional packing problems” to model aspects of new logistics systems. However, to our knowledge, Crainic et al. (2016) or Fazi et al. (2012) are among the few recent attempts to use such modeling approach to practical problems.

The model generalizes the bin packing problem or, in terms of scheduling, the problem of scheduling m parallel batch processing machines (means of transport) with jobs (containers) having unequal release and due dates, with incompatible job families, precedence constraints, and where total weighted tardiness must be minimized, studied in Bilyk et al. (2014). Here, the tardiness relates to D&D extra times; the incompatibility relates to the fact that some containers may be available too late for others in the forward leg to ensure on-time delivery and also to avoid batches made of forward and backward containers; finally, the precedence constraints are to make sure that containers in the backward leg depart after their forward leg is completed. In addition, the proposed model includes the objective of minimizing machines usage costs. Finally, we notice that the compositions of batches in the forward leg bias the starts of the detention periods, thereby the “due dates” for detention are not a fixed quantity. The generalized scheduling problem proposed by Bilyk et al. (2014) and the bin packing problem are NP-hard. Hence, we propose a heuristic approach.

3.3. Analysis of demurrage and detention costs

When considering the model without Demurrage and Detention, as long as due dates can be respected, the departure time is not of interest. On the other hand, the addition of D&D constraints forces the model to find an appropriate departure time that minimizes the D&D costs. Let us consider a reduced version of the model, with one container available at time 0, and no fleet, but one bin at no cost, with transport time T and readily available at the seaport.

The main decision variable is the departure time of the container from the seaport, t . For any given t , e_1 and e_2 follow easily from the model’s constraints. We note that demurrage and detention cost functions are stepwise linear functions. The demurrage cost function is non-decreasing in t with increments of F_1 every 24 h after the free period has passed. The detention cost function is non-increasing in t and is 0 if t is equal to or larger than $D + U + T - X_2$. The sum of these two cost functions gives a stepwise linear, non-convex function, see Fig. 3 for an example.

Despite the fact that the objective function is non-linear, two aspects of the problem can ease the search of an optimal departure time t . First, the set of values is limited. In fact, we cannot move a container before its release date or after time $D - T$. Secondly, the

Fig. 3. Demurrage and detention cost functions. Their sum is a stepwise linear, nonconvex function. In this example, the demurrage and detention free periods are respectively 4 and 2 days; the due date is set at day 7 (168 h); return time 200. Departure time t can range from 0 to 158, considering a transportation time of 10 h.

search is limited to a discrete set of values, since the D&D functions change at 24 h intervals. The following lemma formalizes this statement.

First, let us define the function $\lambda(\cdot)$, a modulo function, as $\lambda(x) = x \bmod 24$. That is, $\lambda(x)$ gives for time point x the time on the day, but not the day itself. Since free demurrage and detention periods are normally multiples of 24 h, we assume $\lambda(X_1) = \lambda(X_2) = 0$. Let $D + U + T$ be r and denote the end of the transport process.

Lemma 3.1. Define parameter $\delta = \lambda(r - X_2)$. To find an optimal solution, only time points 0 and $24\tau + \delta$ need to be evaluated for $\tau \in \{0, 1, 2, \dots, \lfloor (D - T)/24 \rfloor\}$.

Proof. Let the function $c(t)$ denote D&D fees when departing the seaport at time $t \geq 0$, where $c(t) = F_1 e_1(t) + F_2 e_2(t)$ with functions $e_1(t) = \max(0, \lfloor (t - X_1)/24 \rfloor)$ and $e_2(t) = \max(0, \lfloor (r - t - X_2)/24 \rfloor)$.

Now it is straightforward to see that $e_1(t)$ is a monotone non-decreasing function in t that can (potentially) change (i.e., increment by 1) only at $t = 0 + \epsilon, 24 + \epsilon, 48 + \epsilon, 72 + \epsilon, \dots$ (assuming $\lambda(X_1) = 0$). Similarly, $e_2(t)$ is a monotone non-increasing function that can (potentially) change (i.e., decrement by 1) at $t = \delta, 24 + \delta, 48 + \delta, 72 + \delta, \dots$. Now for each $\tau, \tau \in \{-1, 0, 1, 2, \dots, \lfloor (D - T)/24 \rfloor\}$, it holds that the minimum value for $c(t)$ in the interval $[24\tau, 24\tau + 24]$ is achieved at $24\tau + \delta$, namely just at the (potential) decrease of detention cost, and beyond until $24\tau + 24$, namely just before the (potential) increase of demurrage costs. Hence the minimum is achieved on the interval $[24\tau + \delta, 24\tau + 24]$. Similarly, the maximum on the interval $[24\tau, 24\tau + \delta]$. In some cases, the maximum and minimum may be equal. If cost ϵt is considered, only the leftmost feasible point ($t \geq 0$) in the range $[24\tau + \delta, 24\tau + 24]$ for each $\tau, \tau \in \{-1, 0, 1, 2, \dots, \lfloor (D - T)/24 \rfloor\}$ must be evaluated. $\square$

The proposed Lemma states that the optimal departure can be found easily among a limited set of values. In case of a combined D & D fee, say e_3 , the cost is a fixed quantity given by: $(r - R)e_3$, where $R = 0$. As the only adjustable quantity in the objective function would be ϵt , for the combined D&D we have, theoretically, always $t = 0$.

4. A heuristic approach

The proposed heuristic to solve the model is a hybrid simulated annealing method with Tabu lists, run with constant temperatures in a multi-start approach. Specifically, we create lists that prevent the generation of non-feasible solutions and that reduce randomness in the search of local optima. Simulated annealing is one of the most used techniques in combinatorial optimization and has been found effective for a large variety of scheduling problems. The hybrid technique has been previously developed by Osman and Christofides (1994) for capacitated clustering problems and the constant temperature approach was found effective in Fazi et al. (2015).

In this section, we first present a number of conditions to ensure feasibility and a method to determine optimal departure times (Section 4.1). Specifically, a feasible solution to our problem consists of three components. First an assignment of containers to trucks and barges in the forward leg, denoted as a matrix $\bar{f} = (f_{ik})$. Second, the assignment of containers to trucks and barges, in the backward leg $\bar{b} = (b_{ik})$. And thirdly, departure times for all trucks and barges in the forward leg. Having these in place, we have all the ingredients to develop the algorithm determining an initial solution (Section 4.2), and the simulated annealing procedure (Section 4.3).

4.1. Construction and evaluation of feasible solutions

Feasible solutions can be attained by first constructing feasible transport matrices ($\bar{f}$ and $\bar{b}$), and then by setting optimal departure times. Here, we first present the conditions for feasibility.

Primarily, for a solution $\bar{f}$ to be feasible, Constraints (2), (3), (9), (20) and (22) must hold. For a solution $\bar{b}$, Inequalities (11), (12), (21) and (23) must hold. Any solution, with configurations $\bar{f}$ and $\bar{b}$ respecting these conditions, has the prerequisites of feasibility for the proposed model. Transport costs are easily computable.

The remaining variables to be set in order to achieve feasibility are the departure times for each used bin k . For the backward leg, the departure time of a bin k is immediate, namely as soon as all allocated containers become available, since no cost but detention can be affected. Thereby, the creation of a feasible configuration $\bar{b}$ prompts the definition of the end of the transportation process for each container, r_i , by following the master route for the backward leg.

The only remaining decision is related to the departure times of the bins in the forward leg from node 0: $t_0^{f,k}$. First, the total transport time, named $T^{f,k}$, is computed by following the master route. Then, the following condition for the departure time of the bin is set:

Condition 4.1. Consider a feasible solution $\bar{f}$. The departure time $t_0^{f,k}$ of a bin $k \in \mathcal{K}$ is bounded: $\max_{i \in \mathcal{I}} [f_{ik} R_i] \leq t_0^{f,k} \leq \min_{i \in \mathcal{I}} [(f_{ik} D_i) - T^{f,k}]$

For any feasible value $t_0^{f,k}$, the pickup time of a container $t_i^{f,k}$, with i such that $f_{ik} = 1$, is computable by following the master route up to container i . Then, for each $k \in \mathcal{K}$, the departure time $t_0^{f,k}$ is the value that minimizes the following function:

$$F_1 \sum_{i: f_{ik}=1} \max(0; [(t_i^{f,k} - R_i - X_1)/24]) + F_2 \sum_{i: f_{ik}=1} \max(0; [(r_i - t_i^{f,k} - X_2)/24]) \quad (32)$$

where $t_i^{f,k}$ is the value implicitly depending on $t_0^{f,k}$. As $t_0^{f,k}$ is constrained by Condition 4.1, and by Lemma 3.1 to specific values, a limited enumeration is needed.

4.2. Initial solution

The initial feasible starting solution s is constructed by an algorithm incorporating the conditions just described. Additionally, we include the following condition for the creation of non-dominated solutions. Specifically, for a barge, in order to be cost-effective against trucks, there is a minimum required amount of containers to be transported.

Condition 4.2. Any barge k with cost C_k and capacity $Q_k > 1$ is only more cost effective than employing a truck t of capacity 1 and cost C_t on the forward leg if $\sum_{i \in \mathcal{I}} f_{ik} \geq C_k/C_t$.

A similar condition can be formulated for the backward leg. Note that Condition 4.2 is only used for generating an initial solution and will not be incorporated in the simulated annealing heuristic, in order to allow a wider search in the solution state space.

The algorithm that creates the initial solution has five main steps. In the first and second step, lists are created to ease the construction of the transport matrices. In the third and fourth step, the algorithm constructs the feasible matrices, and in the fifth, departure times are computed. The algorithm works as follows.

In the first step, the algorithm sorts containers by increasing due dates, creating $list_0$. This is done because due dates are critical for the construction of a bundle.

In the second step, the algorithm simply checks which containers are suitable candidates for barge transport. The procedure takes a container and checks how many containers can be bundled with it. If there is not a bundle that respects Constraints (9), (20) and (22), and Condition 4.2 the container is put on a truck and on a permanent list, called $list_1$, and removed from $list_0$.

In the third step, the algorithm tries to form bundles for $\bar{f} = f_{ik}$. The first container in $list_0$ is selected and consolidated with the following containers, checking at each iteration capacity Constraints (3) and Constraints (9). In case no more containers can be bundled, the algorithm checks whether Condition 4.2 is respected. If so, the bundle is accepted and the containers are allocated to matrix $\bar{f}$ on a barge k and removed from $list_0$; otherwise the first selected container is moved to a truck. The algorithm processes iteratively all remaining containers in $list_0$, until all containers are allocated.

In the fourth step, $\bar{b} = b_{ik}$ is built. The algorithm bundles containers until either the capacity or the maximum amount of stops is reached. In case the amount of remaining containers is not enough to respect Condition 4.2, they are trucked.

In the fifth and final step, optimal departure times are computed via enumeration, using Function (32), Condition (4.1) and Lemma 3.1.

4.3. Simulated annealing

The simulated annealing perturbs and rebuilds the current solution and evaluates the new solution, which may become the new starting solution. Each new solution is first checked for feasibility using the conditions reported in Section 4.1. If the conditions are satisfied the heuristic searches for an optimal departure time, as previously described, and then computes the total cost. The heuristic repeats for a fixed number of iterations in a multi-start approach, with different temperatures run in parallel. Here, the structure and the operators for the hybrid simulated annealing are given.

Considering a current solution s with cost $C(s)$, two operators may be used to construct a new solution s' , named (1.0) and (1.1).

These operators will ignore containers belonging to $list_1$. For a set of iterations, only a specific transport leg will be screened. During this set, operator (1.0) is performed continuously for a certain amount of iterations, and then operator (1.1).

Operator (1.0) randomly selects a container and moves it to another randomly picked bin. If a feasible configuration is found, optimal departure times, transport costs and D&D are computed. If the new solution is worse, the specific move is put in a temporary tabu list, $list_2$; however, the solution can still be accepted in that iteration. If no feasible configuration is attainable, after trying a certain number of bins, the container index is placed on a temporary list, $list_3$, that prevents its selection for a certain number of iterations.

Operator (1.1) is an interchange process that randomly selects two containers from two different bins and swaps them. The selected containers must meet the following criteria: not being in $list_1$, not being in the same bin, not belonging to two trucks. If the containers cannot be swapped, the pair is inserted in a temporary tabu list, $list_4$. If a feasible configuration is found, new optimal departure times, transport costs and D&D are computed. If the new solution is worse, the specific move is put in a temporary tabu list, $list_5$.

Once a new feasible solution s' is found, its cost $C(s')$ is evaluated and accepted with a certain probability given by the Boltzmann distribution. The probability is computed as $P(T) = \min\left\{e^{\frac{C(s) - C(s')}{T}}, 1\right\}$, where T is the parameter called temperature that is fixed throughout the search. The algorithm stops after a predefined amount of iterations and stores throughout the search the best solution found. Finally, at the end of the computation the best performing temperature, in terms of speed and accuracy, is given with its results.

5. Numerical analysis

In this section, we show numerical experiments on the proposed mathematical model. The aim of these experiments is to assess the impact of the different D&D tariffs on departure times, transport costs and total dwell time at the seaport. We consider a data set of 5174 containers from 2015 provided by a local carrier in the port of Rotterdam region, containing information on their release date (R), due date (D) and reference docks; the carrier owns an inland terminal and is responsible for both import and export containers. As shippers pay a certain fixed fee for the transport, the main goal for the carrier is to reduce transport costs by using mainly barges and limit D&D fees.

The network represents the Port of Rotterdam setting and it consists of 2 main seaport terminals and 26 possible docks, see Fazi et al. (2015) for details. The limit for amount of docks to visit in one ride is set to 4: this number has been suggested by the local carrier, subject of this study. The inland terminal is set as starting node for the forward leg.

The experimentation is threefold. In the first, we solve a set of instances for the proposed model. In the second, we analyze the effects of information availability. In the third, we propose an alternative cost function.

The mathematical model is solved via the proposed heuristic, coded in C. CPLEX 12.6 is also used in order to assess the performances of the heuristic. All experiments are run on an Intel(R) Core(TM)2 DUO machine with 2.93 GHz and 4.00 GB RAM memory.

5.1. Results analysis

The generated instances range from 12 to 65 containers and are obtained by extracting containers belonging to similar time periods. The selection was driven by the actual allocation of the container to the same rides, identified in the data set with an alphanumerical code. Additionally, we purposely chose containers related to short time frames, as to recreate an information as close as possible to that available by the planners.

According to carrier guidelines, for barges and trucks, we consider costs respectively €900 and €140. Barge capacities are set to 15 containers. The carrier estimated an average unpacking time of 24 h. The size of the fleet is limited; we vary the amount of barges according to the size of the instance, taking into account also the need of economies of scale. In terms of trucks, the amount is considered taking into account the available fleet and the possibility of several trips back and forth during the day. In the results, the fleet was always used partially.

In the first experimentation, the set of 25 instances is solved considering a shipping line fee at a time. In other words, for each shipping line we solve the 25 instances plugging in the related fee. We report the results related to the heuristic solutions in Tables 3–6. For each shipping line we provide the total transport cost, the D&D cost and the dwell time as sum of the results obtained from the 25 instances. Each table groups shipping lines according to the type of fee: combined D&D and separated D&D, with or without

Table 3
Shipping lines with separated D&D.

Shipping line	Total cost	Transport cost	D&D cost	Total dwell time (h)
Nyk Line	116,372 (+12%)	107,340 (+3%)	9032	33,542 (+84%)
CSAV	123,010 (+18%)	111,280 (+7%)	11,730	35,442 (+95%)
Yang Ming	116,590 (+12%)	104,740 (+0.1%)	11,850	37,629 (+107%)
No D&D	104,040	104,040	0	18,210

Table 4
Shipping lines with separated D&D and differentiation when using trucks or barges.

Shipping line	Total Cost	Transport cost	D&D cost	Total dwell time (h)
Maersk	144,550 (+39%)	117,120 (+13%)	27,430	32,021 (+76%)
Hapag Lloyd	120,266 (+16%)	112,020 (+8%)	8646	40,309 (+121%)
Evergreen	110,490 (+6%)	104,440 (+0.1%)	6050	27,908 (+53%)
APL	113,006 (+9%)	105,700 (+2%)	7306	37,580 (+106%)
CSCL	108,220 (+4%)	104,580 (+0.1%)	3640	22,648 (+24%)
MOL	126,795 (+22%)	108,780 (+5%)	18,015	31,372 (+72%)
OOCL	130,410 (+25%)	112,380 (+8%)	18,030	30,036 (+65%)
No D&D	104,040	104,040	0	18,210

Table 5
Shipping lines with combined D&D.

Shipping line	Total cost	Transport cost	D&D cost	Total dwell time (h)
CMA CGM	122,040 (+17%)	106,860 (+3%)	15,180	18,210 (+0%)
COSCO	141,210 (+35%)	113,580 (+9%)	27,630	18,210 (+0%)
Hamburg Süd	131,640 (+27%)	110,320 (+6%)	21,320	18,210 (+0%)
No D&D	104,040	104,040	0	18,210

Table 6
Shipping lines with combined D&D and differentiation when using trucks or barges.

Shipping line	Total cost	Transport cost	D&D cost	Total dwell time (h)
MSC	121,740 (+17%)	106,600 (+2%)	15,140	18,572 (+2%)
No D&D	104,040	104,040	0	18,210

differentiation in free days when using trucks or barges. Additionally, we provide results for the case without D&D regimes.

The “No D&D” case is a system with complete flexibility in terms of transport timing. The carrier has the possibility of moving immediately the containers and use the inland terminal as storage space. Although, this is appealing from a cost perspective, it is impractical as shipping lines must have a control mechanism on the rented containers.

From the results, we note that the presence of D&D influences negatively the transport cost when comparing the results with the case of no D&D: from 0.1% (Evergreen) to 13% (Maersk). The fees from Evergreen, CSCL and APL (Table 4) perform better in terms of total cost. However, these shipping lines are the ones providing the lowest fees. It is interesting to notice how Yang Ming, proposing relatively small fees, generates a high total cost due to large D&D costs. The result is explained by the small amount of free days granted for barges. The highest cost of Maersk is explained by the very large fees and small amount of free days.

As previously suggested, combined fees do not compromise dwell times. However, interestingly, MSC generates a slightly larger dwell time than the “No D&D” case. Since MSC provides an incentive for barge usage, for some instances it turns out to be more profitable to use, for example, two barges not fully loaded rather than a less costly combination of a full barge and a few trucks. In such a case, the slightly larger transport cost of the first combination is compensated by the lower detention cost, but generates slightly larger dwell time. If D&D are kept separated, the dwell time is at least 24% higher than the value in case with no D&D, and can reach a maximum of +121% with the fee of Hapag Lloyd, the only one providing a lower fee for demurrage. With such a fee, the planner is pushed to keep the container at the sea terminal for more days.

For the separated D&D, on average, CSCL performs the best for dwell times; the reason is in the largest amount of free detention days granted (10 days). We also note that a reduced amount of free demurrage days may actually push containers to leave the port premises sooner. For example, by comparing results from APL and Maersk, we notice that the smaller amount of free days granted by Maersk generates lower dwell time, confirming, in a sense, the previously reported claim in Leach (2005). Yet, containers dwell for a considerable amount of time and transport cost is the largest. This can be explained for the fact that exceeding both demurrage and detention due dates is very costly. Thereby, free days are fully used and trucks are favored because of their flexibility and speed.

As a matter of fact, cutting free demurrage days must align with the need of bundling containers and the detention period must be reasonable to achieve economies of scale. Let us consider Yang Ming and Nyk Line. The larger amount of detention days granted by Nyk Line allows containers to leave the port earlier, while for Yang Ming there is a need to use almost all allotted free demurrage days, in order to avoid detention. This confirms earlier conjecture by Veenstra (2015) and Ypsilantis et al. (2014). This result can call into question the belief that by just cutting free demurrage days, carriers are urged to swiftly move the containers out of the seaport (Leach, 2005). If detention free days and fees are not balanced, this strategy can be counterproductive.

With respect to the combined D&D fee, this policy may hinder economies of scale for transport in the return leg, as there is more

Table 7
Results considering for each container the actual shipping line.

Shipping line	Total cost	Transport cost	D&D cost	Total dwell time (h)
Mixed	131,132 (+26%)	111,340 (+7%)	19,792	32,506 (+79%)
No D&D	104,040	104,040	0	18,210

pressure to return containers, due to a sudden start of the detention period. Therefore, the high transport and D&D costs from Table 5 come as no surprise. This confirms the claim by Fransoo and Lee (2013), who mention how D&D fees may force the return of empty containers early to the empty container depot, before a potential load can be identified.

Overall, the results show that combined D&D fees are a good alternative, as they generate low dwell time, together with average D &D revenues for shipping lines and average transport costs. For example, OOCL generates very similar results in terms of transport and D&D costs when compared to Hamburg Süd; however the dwell time is drastically higher. The same can be noticed for Nyk line or CSAV compared to CMA CGM, Maersk vs Cosco and so on.

Finally, we provide an experimentation considering for each container the actual shipping line in the data set. Containers related to shipping lines providing a combined fee account for 16%. The remaining relate to the shipping lines providing a separated fee, with a majority for Maersk. As a matter of fact, the results in Table 7 are in line with results from separated fees.

5.2. Effects of fragmented and dynamic information

In this section, we analyze the effects of information availability on planning. The information on containers is now assumed to arrive over time, and consequently scheduling cannot be performed for the entire time horizon simultaneously. Rather, scheduling is performed repetitively, each time for only those containers for which at the moment of scheduling the required information is available (block sequencing approach; Han et al. (1987)). We consider a time span between consecutive scheduling events of 24, 48 or 72 h. The chosen time span would in practice depend on the frequency of the shuttle service.

In Table 8, we report the effects of block sequencing for shipping line Maersk based on those of our instances that have a sufficiently long time horizon. Results are in line with the experiments reported above. Shorter time spans cause higher transportation costs, which is due to more difficult economies of scale. As truck usage increases for shorter time spans, dwell times for the “no D&D” cases *tend* to decrease. On the other hand, with D&D, with shorter time spans dwell times also tend to decrease, but to a lower extent. This can be explained from the fact that the risks of incurring fees due to early retrieval prevent a further reduction of dwell times, even when trucks are used (this will be studied more extensively in the next experiment). As a consequence, the relative disadvantage of D&D increases for shorter time spans, i.e. when a more dynamic environment is considered.

In a second experiment, we have a closer look at the effects of D&D on dwell times. Note that dwell times may be caused by either the waiting time of containers for departure of the barge, or by the presence of D&D. To remove the consolidation effect of the barges, we apply the mathematical model to one container at a time, without consideration of transport costs and assuming that a container can be picked up as soon as it is released. For a specific combination of release date (R) and due date (D), we compute the optimal departure time that minimizes D&D costs. As the combination can be shifted, moving R to point 0 in time, two containers with different values of R and D , but with the same difference $\Delta = D - R$, will generate the same result.

The computation is conducted as follows. First, we compute the optimal solutions for the existing values Δ in the data set for a specific D&D fee, given by Table 1. Then, each result is weighted to the amount of containers having the same value Δ . We repeat this procedure for each shipping line D&D fee. Results are reported in Tables 9 and 10 for separated D&D. With combined D&D fee, as explained in Section 3.3, containers, theoretically, do not need to dwell at the seaport, and can be moved at once to the inland terminal for temporary storage.

Table 8
Effects of block sequencing for shipping line Maersk. The first column indicates the time span between consecutive scheduling events, and the presence or absence of D &D costs. The percentages beside each cost in the “D&D” case indicate the gap with the respective “no D&D” case.

Time span	Total cost	Transport cost	D&D cost	Total dwell time (h)
24 h with D&D	38,715 (+25%)	34,340 (+11%)	4375	6180 (+140%)
24 h no D&D	30,820	30,820	0	2566
48 h with D&D	35,380 (+19%)	31,025 (+4%)	4355	6419 (+113%)
48 h no D&D	29,780	29,780	0	3018
72 h with D&D	33,555 (+21%)	28,960 (+5%)	4595	6834 (+108%)
72 h no D&D	27,680	27,680	0	3286
Complete with D&D	31,770 (+20%)	27,960 (+6%)	3810	6991 (+123%)
Complete no D&D	26,360	26,360	0	3140

Table 9

Average dwell time at the sea terminal for each shipping line tariff. B stands for the dwell times obtained when considering barge transport times and T for trucks. Symbol $\diamond$ accompanies fees without differentiation for barges and trucks. Part I.

	Shipping Lines									
	APL		$\diamond$ CSAV		CSCL		Evergreen		Hapag Lloyd	
	T	B	T	B	T	B	T	B	T	B
Avg Dwell time (days)	2.6	1.4	1.1	1.2	2.1	0.4	2.1	0.9	5.1	2.3

Table 10

Average dwell time at the sea terminal for each shipping line tariff. Part II.

	Shipping Lines									
	Maersk		Mol		$\diamond$ Nyk Line		OOCL		$\diamond$ Yang Ming	
	T	B	T	B	T	B	T	B	T	B
Avg Dwell time (days)	1.8	1.2	1.8	1.2	1.1	1.2	2.1	0.9	2.3	2.4

The results show the necessity of using part of the free demurrage period at the port, even without consolidation issues. Hence, it is clear how a separated fee does not fit in such a highly dynamic environment, where containers may show up suddenly while, for example, a barge is in transit. With such a tariff the planner is prevented to include these new arrivals in the ongoing ride.

5.3. An alternative cost function for D&D

Mongelluzzo (2000b) reports how free days were cut in order to encourage shippers to move their cargo earlier. As receivers are somehow motivated to use the whole free period for storage purposes or extra flexibility in successive transportation stages, a possible alternative to the current cost function can be to completely exclude free days in the D&D system.

In this section, we suggest that D&D could be transformed in a daily, smaller fees from time 0. In such a way, shippers should not have any more pressure of free days and should be more flexible for departure times. Hence, the main target is to generate a lower transportation cost. However, this new cost function should also provide D&D revenues. In fact, since shipping lines have contractual power, our target is to provide them with at least the same revenue of D&D. Finally, if possible, we should aim for lower dwelling times.

Good daily fees are found by means of an iterative procedure that tries different combinations of D&D. The boundaries of this search are: maximum fee is the halved current fee; minimum fee is 1€. We try 0.0 and 0.5 values for every integer of the selected range. The solutions concern the first 15 instances, for which optimal solutions are mostly certified by CPLEX.

In Tables 11–14, we summarize the results of this experimentation and the % errors from the actual D&D results is reported within brackets. For shipping lines that differentiate in the number of free days according to the used modality, we propose a lower daily fee when using barges. From the results we notice that it is actually possible to find cost functions that perform better in terms of total cost, transportation cost and revenue for D&D. With regard to dwell time, all new fees perform better, or equally for the combined fees, except for MSC. Due to its favorable tariff in case of barge transport, it is most beneficial *in specific cases* to send the earliest available containers by barge, as they are the ones that need a favorable tariff the most. However, these will wait a relatively long time before consolidation is reached.

In general, the performance improves for total costs, and transportation costs, and the shipping lines have still a consistent revenue. With regard to dwell times, we notice that they reduce drastically. We see that the improvements are substantial for the shipping lines with a separated D&D (from –10% to –49% decrease). Therefore, we conclude that such a daily fee can be seen as a good alternative to the separated D&D fee. On the other hand, a combined D&D with the existing fee can still be seen as a valid option.

The main issues for a daily D&D fee would be from a practical point of view. First of all, D&D bills are nowadays causing extra administrative work that is not seen positively by the clients of the shipping lines; so this should be improved first. Second of all, D&D

Table 11

Shipping lines with separated D&D. The new daily fees (€) are in brackets beside the name of the company.

Shipping Line	Total Cost	Transp. Cost	D&D revenue	Dwell time (h)
Nyk Line (5/2)	43,696 (–5%)	36,800 (–7%)	6896 (+2%)	9106 (–36%)
CSAV (8/2)	45,188 (–11%)	36,800 (–13%)	8388 (+1.3%)	9060 (–40%)
Yang Ming (5/2)	43,696 (–1%)	36,800 (–1%)	6896 (+2%)	9106 (–31%)

Table 12

Shipping lines with separated D&D and differentiation when using trucks or barges. The new daily fees are in brackets beside the name of the company; we report respectively: demurrage daily fee, detention daily fee for trucks, detention daily fee for barges.

Shipping Line	Total Cost	Transp. Cost	D&D revenue	Dwell time (h)
Maersk (12/8-4)	52,868(−15%)	37,060(−28%)	15,808(+4%)	9269(−28%)
Hapag Lloyd (7.5/2-1)	43,030(−14%)	36,800(−16%)	6230(+2%)	9043(−49%)
Evergreen (3.5/2-1)	41,114(−1%)	36,800(−1%)	4314(+5%)	9043(−16%)
APL (7.5/2-1)	43,030(−2%)	36,800(−3%)	6230(+2%)	9043(−39%)
CSC (4/1-0.5)	40,035(−1%)	36,800(−1%)	3235(+11%)	9043(−10%)
MOL (13/6-2)	48,847(−6%)	36,860(−8%)	11,987(+4%)	8954(−29%)
OOCL (12/6-2)	48,376(−12%)	36,860(−16%)	11,516(+2%)	8942(−25%)

Table 13

Shipping lines with combined D&D. The new daily fees are in brackets beside the name of the company.

Shipping Line	Total Cost	Transp. Cost	D&D revenue	Dwell time (h)
CMA CGM (4)	47,556(−2%)	36,940(−5%)	10,616(+11%)	8363(0%)
COSCO (6)	52,748(−12%)	37,220(−17%)	15,528(+5%)	8363(0%)
Hamburg Sud (5)	50,160(−8%)	37,220(−11%)	12,940(+4%)	8363(0%)

Table 14

Alternative cost function for shipping lines with combined D&D and differentiation when using trucks and barges. The new daily fees, respectively for trucks and barges, are in brackets beside the name of the company.

Shipping Line	Total Cost	Transp. Cost	D&D revenue	Dwell time (h)
MSC (5.5-3.5)	46,946(−3%)	37,060(−4%)	9886(+14%)	8822(+1.8%)

bills are in most cases a legal matter when addressing the responsible for the delays: either the client or the transport provider.

5.4. Performances and parametrization of the heuristic

The heuristic has a few values to be set: temperature ranges, size of lists, iterations. The settings were obtained through a preliminary experimentation on the 25 instances. Temperature was the most impacting parameter. Sensible temperature values ranged from 20 to 170. In general, the larger the size of the instance the lower the temperature. With concern to list sizes, apart from $list_1$, whose size is fixed and dependent on the instance, the remaining lists had to be sized. The heuristic proved to be robust and slight improvements were recorded while varying the sizes. For $list_2$ and $list_4$, we recommend a size $\lfloor \mathcal{N} \rfloor$. While for $list_3$ and $list_5$ we recommend $\lfloor \mathcal{N} \rfloor * 2$.

Finally, the heuristic runs for a maximum number of iterations. All optimal solutions were found within 10 million iterations and a maximum of 20 million was established. Every 100,000 iterations, the algorithm switches the focus of the search, from matrix $\bar{f}$ to $\bar{b}$ and vice versa. 80,000 iterations were dedicated to operator (1.0), the remaining 20,000 to operator (1.1). Assigning more iterations to operator (1.1) did not produce better results.

Statistics on the computational performances are reported in the appendix, Table 15, where we provide for every shipping line D&D fee the following averages. For CPLEX we report: average gap between best upper bounds (BI: best integer) and best lower bounds (BN: best node), average end time. For the heuristic we report: average gaps between the best solutions found and best lower bounds, and upper bounds, average standard deviation, average time to reach the best solution. In general, CPLEX is able to solve to optimality 16 instances, ranging from 12 to 26 containers, for *almost* every shipping line D&D fee. For the remaining instances, from 31 to 65 containers, CPLEX cannot find optimal solutions in most cases, with a maximum gap between BI and BN of 42%.

Overall, the heuristic is always able to find the optimal solutions certified by CPLEX. In the case CPLEX cannot certify optimality, the gaps between the heuristic solution and the lower bounds provided by CPLEX show a maximum average gap of 8%.

5.5. Discussion of the results and implications

The most important result of this paper is that D&D, in particular the separated version, do not do what they are supposed to do. Namely, they do not motivate shippers to move containers out of the seaport and use inland terminals as temporary storage. However, D&D are rather an important source of income for shipping lines, as confirmed by Storm (2011), and also necessary to control return times. Hence, discussion should be opened among stakeholders to find solutions. In this paper, we proposed a daily tariff as a possibility.

An important factor in inland container transport is dynamic information on upcoming containers. The experimentation showed the impracticability to move a container right at its release date, due to loss of free time. Hence, consolidation opportunities, also last-minute, are limited. On the other hand, combined D&D can provide the flexibility to increase barges (or trains) utilization when needed.

Our experimentation can also suggest shippers which shipping line to select, according to the provided D&D tariff that best matches their needs. A separated fee is a viable option in case a shipper: has a good control of the container, wishes to have more flexibility in re-using the container, has limitations in terms of resources for unpacking, plans to process the container quickly. A combined fee is a good option in case the shipper: has flexibility during the lease period in terms of due dates and unpacking, the shipper wishes to decrease transport costs in the forward leg and dwell times at seaports, the shipper has more possibilities for temporary storage.

In terms of modeling, this paper emphasizes the emerging role of inland terminals and the need for advanced systems to enhance control. [Rodrigue and Notteboom \(2009\)](#) argue that inland terminals are achieving an additional level of integration within supply chains that goes beyond their conventional transshipment role. The development of inland terminals permits increased throughput, better use of available land and less pressure for capacity at seaports. However, this integration requires the coordination of several actors, including shipping lines and inland terminals ([Franc and Van der Horst, 2010](#); [Nabais et al., 2015](#)). In this sense, stakeholders are more and more leaning on advanced ICT systems to share information and improve decision making ([Li et al., 2015](#)). For example, in the Netherlands, a few inland terminals have established direct connections with ICT systems of large shipping lines. Once an empty container reaches the inland terminal, the detention costs are stopped ([Barge Terminal Tilburg, 2017](#)).

In such a dry port setting, the results showed how combined fees may be more beneficial. Under the current separated D&D system, the immediate transshipment from seaports to dry ports may entail an immediate start of the detention period. The useful free demurrage days are then lost and receivers have less free days to handle containers in the hinterland, in order to avoid detention claims. Hence, the function of temporary storage of inland terminals cannot be fully exploited.

Finally, the benefit of dry port settings can be maximized with a centralization in terms of decision making. Transport providers should be granted more freedom in the operational decision making by shippers for deciding the best modality to move a container and the best timing (synchromodality). As of now, such a flexibility can be achieved only with a combined D&D regime.

6. Conclusions

In this paper, we proposed the D&D, a low explored topic in the scientific literature. D&D are fees to be paid to the shipping lines for holding the container for a period longer than an established one. In practice and in the literature, it is suspected that D&D might affect the quality of the schedules and provide several drawbacks.

By means of an experimental framework, we could assess the impact of different fees on dry-port-based inland transport; specifically, on the use of high capacity means of transport and on the dwell times of containers at the seaport. Results showed how D&D do not motivate shippers to move containers out of the seaport and that barge transport can be limited. A combined D&D regime appears a more flexible option that can provide similar results in terms of income for shipping lines, but with lower average dwell times.

For practice, the paper emphasizes the need of advanced decision support systems for planning and scheduling maritime containers in the hinterland. The proposed modeling framework can be integrated in ICT systems to improve decision making and have better control of available containers. In fact, current ICT systems are limited to signal upcoming D&D due dates or update containers' status.

From a managerial point of view, this paper provides guidelines to shippers on the selection among different types of D&D regimes. Additionally, the results suggest that D&D must be reconsidered by shipping lines and discussed together with port authorities, shippers and major consignees. Providing a combined D&D fee might be a viable and practical option, as long as shippers and consignees are willing to move containers earlier and use inland terminals as temporary storage space. In fact, dry ports in combination with combined D&D fees can be a major solution to relieve seaports from congestion and promote the use of high capacity means of transport.

The model is open to several extensions. For example, the effects of delays may be analyzed. The model can be transformed in a multistage stochastic model with recourse in a multi-scenario setting. The allocation of containers would be a first stage decision, whereas, for example, the pickup time or the arrival at the terminal of the means of transport would be a recourse variable, subject to the variability of the travel time ([Birge and Louveaux, 2011](#)).

Appendix A. Performances of the proposed heuristic and CPLEX

See [Table 15](#).

Table 15

Computational statistics. BI stands for “Best Integer” (Upper Bound solution found by CPLEX). BN stands for “Best Node” (Lower Bound solution found by CPLEX). BS stands for “Best Solution” (Best solution found by the heuristic). CPLEX computational limit set to 10.800 s. or 4 GB of memory.

Shipping Line	CPLEX performance		Heuristic			
	Avg Gap (BI-BN)/BI	AVG end time (sec)	AVG (BS-BI)/BS	AVG (BS-BN)/BS	AVG Std. Dev.	AVG time
Nyk Line	5.4%	2975	−3%	2.9%	0	105
CSAV	5.3%	3665	−3.3%	2.8%	20	120
Yang Ming	6.4%	2560	−3.0%	4.0%	0	150
CMA CGM	3.5%	2145	−0.9%	2.7%	0	125
COSCO	4.5%	2450	−1.8%	2.8%	15	85
Hamburg Süd	4.3%	1790	−1.4%	3.1%	0	90
Maersk	10.9%	4260	−4.3%	8%	20	105
Hapag Lloyd	7.1%	2820	−4.9%	3.1%	0	95
Evergreen	4.4%	2370	−1.8%	2.9%	0	90
APL	5.5%	2135	−3.6%	2.7%	5	85
CSCL	2.3%	1500	−0.6%	1.8%	0	50
MOL	7.9%	3105	−3.4%	5.5%	15	145
OOCL	7.4%	2695	−2.3%	5.7%	10	100
MSC	4.3%	2200	−2.3%	2.7%	0	60
No D&D	1.1%	1575	−0.1%	1.0%	0	5

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