Multi-stage approach for the transshipment of import containers at maritime container terminals

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Abstract: The management of container flows is one of the most challenging tasks for terminal managers. In this regard, the freights inside the containers have to be transported towards their requesting companies. This delivery is subject to many factors such as the vessel berthing time, yard assignment, time windows of the companies, availability of internal vehicles etc. Therefore, the time a given company waits for its requested containers is highly dependent on the management of the technical resources at the container terminal. To appropriately address the coordination of involved operations, a multi-stage approach is proposed. It is aimed at providing a complete schedule of all the involved processes and supporting the operational decisions related to the technical terminal resources in an integrated way, from the berth to the delivery of the freights inside containers to the requiring companies. The computational results indicate that this solution approach provides a suitable solution in all cases and is appropriate for supporting terminal managers when addressing strategic decisions involving the technical equipment.

Nomenclature

Parameters

V	set of incoming container vessels
nV	number of incoming container vessels
B	set of berths
nB	number of berths
$qc(b)$	number of quay cranes at berth $b \in B$
$\rho(b)$	productivity of each quay crane at berth $b \in B$
C	set of containers
nC	number of containers
C_v	set of containers of vessel $v \in V$
Y	set of yard blocks
nY	number of yard blocks
E	set of companies
nE	number of companies
t_e	opening time of company $e \in E$
t'_e	closing time of company $e \in E$
$C(e)$	set of containers requested by company $e \in E$
K^{in}	set of internal vehicles at the terminal
nK_{in}	number of internal vehicles at the terminal
K^{out}	set of external delivery vehicles at the terminal
nK_{out}	number of external delivery vehicles at the terminal
$\max_{K^{\text{out}}}$	number of external delivery vehicles that can be simultaneously at the terminal
δ	maximum waiting time of a container in its berth
$\text{index}(c)$	order in which container $c \in C_v$ is unloaded from vessel $v \in V$
$t_{\text{in}}(b, y)$	time required by an internal vehicle to move a container from berth $b \in B$ to yard block $y \in Y$
$t_{\text{out}}(b, e)$	time required by an external vehicle to move a container from berth $b \in B$ to company $e \in E$
$t_{\text{out}}(y, e)$	time required by an external vehicle to move a container from yard block $y \in Y$ to company $e \in E$
$d(e)$	time required by an external vehicle to unload a container at company $e \in E$
t_b	opening time of the time window of the berth $b \in B$

t'_b	closing time of the time window of the berth $b \in B$
a_v	arrival time of the container vessel $v \in V$
b_v	maximum departure time of the container vessel $v \in V$
p_v	service priority of the container vessel $v \in V$
s_{vb}	time required to serve a container vessel $v \in V$ in berth $b \in B$
S	set of stacks in each yard block
nS	number of stacks in each yard block
T	set of tiers in the stacks in each yard block
nT	number of tiers in the stacks in each yard block
$d(c)$	delivery time of container c
$r(c)$	retrieval time of container c
H_{SP}	planning horizon of the stacking problem

Variables:

$\text{wt}(e)$	waiting time of company $e \in E$
$\text{dt}(c)$	delivery time of container $c \in C$
$\text{bt}(v)$	berthing time of vessel $v \in V$
x_{vb}	binary variable that takes value one if vessel $v \in V$ is berthed at berth $b \in B$. Zero, otherwise.
$\text{ut}(c)$	unloading time of container $c \in C$
$\text{wt}(c, b)$	waiting time of container $c \in C$ at berth $b \in B$
$p(c, y)$	waiting time of container $c \in C$ until it is picked up by the yard crane of block $y \in Y$
$s(c, y)$	storage time of container $c \in C$ in the yard block $y \in Y$
$r(c, y)$	retrieval time of container $c \in C$ in the yard block $y \in Y$
ϕ_c	one if and only if container $c \in C$ is stored in the yard. Zero, otherwise
$\bar{\phi}_c$	one if and only if container $c \in C$ is directly delivered to its destination company. Zero, otherwise
C^b	set of containers unloaded at berth $b \in B$
$\text{wt}_{k_{\text{in}}}(c, b)$	waiting time of container $c \in C$ in berth $b \in B$ for internal delivery vehicle $k_{\text{in}} \in K^{\text{in}}$
$\text{wt}_{k_{\text{out}}}(c, b)$	waiting time of container $c \in C$ in berth $b \in B$ for external delivery vehicle $k_{\text{out}} \in K^{\text{out}}$

$wt_{k_{out}}(c, y)$ waiting time of container $c \in C$ in yard block $y \in Y$
for external delivery vehicle $k_{out} \in K^{out}$

1 Introduction

Maritime container terminals are the most highlighted infrastructures within global supply chains. The reason is found that nowadays they are handling, according to the Review of Maritime Transport 2016 published by the United Nations Conference on Trade And Development (UNCTAD) (<http://unctad.org>), more than 10 billion tons of the freights moved around the world.

A maritime container terminal is usually split into three main functional areas[1]:

- i. *Seaside*. It is the part of the terminal dedicated to providing service to incoming container vessels. Meisel [2] provides a comprehensive analysis of the main seaside operations. He highlights that one of the main problems on this side of the terminal is the berth allocation problem (BAP), which aims at allocating and scheduling vessels to berthing positions.
- ii. *Yard*. It is a temporal storage for the containers until their later retrieval. Carlo *et al.* [3] review the literature concerning those operations related to container storage management. The operations aimed at handling the storage and retrieval of containers are considered in the stacking problem (SP).
- iii. *Landside*. It is the part of the terminal dedicated to serving external trucks and trains. One important issue arising at this side is the management of vehicles related to collecting and delivering incoming containers at the terminal. See the work by Carlo *et al.* [4] for more details.

One most widespread indicator concerning the maritime container terminal competitiveness is the time required to serve those container vessels arrived at the terminal [5]. The seaside operations are those directly related to the service of container vessels. The operational decisions stemming from serving container vessels can be modelled through a well-defined sequence of steps. Once a certain vessel arrives at the terminal, a berthing position along the quay is assigned to it on the basis of its particular characteristics (dimensions, draft, cargo etc.). A subset of the available quay cranes at the terminal is allocated to the vessel. These quay cranes conduct the loading and unloading operations associated with the containers of the container vessel. In-depth surveys on the seaside operations are presented by Carlo *et al.* [6] and Bierwirth and Meisel [7].

Once the seaside operations have been managed, two general scenarios related to stored containers arise. Firstly, they can be loaded into container vessels with a later departure time in order to be moved to another port while satisfying a given shipping route [8]. Secondly, they can be moved towards a certain infrastructure of a known private company located outside the terminal. In this latter case, freights required by the companies must be efficiently delivered with the goal of fulfilling their time and contractual requests. In this context, Tongzon and Heng [9] indicated that a key determinant of port competitiveness passes through a service differentiation, landside accessibility, integration of door-to-door transport, and reliable schedules. In this context, Min *et al.* [10] interviewed terminal operators and experts and reported that one of the main key performance indicators is users (i.e. carrier and shipper) satisfaction. This is directly related to the proper management of the above-mentioned scenarios. If a terminal causes delays or long waiting times, this can entail the risk that the seaside and landside operators rearrange their service network to another container terminal. In this context, as indicated by Notteboom [11], trucking companies might also consider charging their clients demurrage. This can affect the shippers' perception of schedule reliability and terminal reliability, leading to a change of terminal or route. Moreover, Ng and Mak [12], Giuliano and O'Brien [13], Schulte *et al.* [14] and Heilig *et al.* [15] showed that scheduling truck delivery routes contributes reducing emissions. This impels the necessity of scheduling the different involved operations in an integrative way while pursuing a competitive goal

for maritime terminals such as reducing the total time to deliver containers to landside operators, increasing their satisfaction.

Due to the large amount and high complexity of the processes brought together and the intrinsic dynamism and uncertainty within maritime container terminals, it is not easy in real-world applications to determine the elapse of time a certain company is going to wait for all its freights. In this work, time is estimated by carefully analysing the flow of containers from their arrivals to port up to their deliveries to their destination companies. This requires properly solving and integrating the terminal operations at each functional area. Many operational problems inside the above-mentioned functional areas of maritime ports have been addressed in the literature [16]. Efficiently solving them has relevant importance in decision support and terminal operating systems (TOS) as they are involved in the synchronisation and coordination of different operations and resources. Murty *et al.* [17] study the daily terminal operations and their interrelation at the port of Hong Kong, where terminal operators remarked the necessity of having intelligent decision support tools. The authors design a computer-aided decision support system to jointly manage the storage space, dispatching policy at terminal gates, berthing space, and routing of trucks. Singgih and Hong [18] consider an automated container terminal and propose a TOS design. Their design includes managing components that encapsulate different functions held at the terminal, e.g. quay cranes, yard, or hinterland managers. In their design explanation, the authors point out the importance of considering and coordinating the different equipment along managing components through an integrated scheduling function. Dotoli *et al.* [19] point out the need for decision support tools for solving in an integrated way interdependent problems appearing at railroad container terminals. They also highlight that even though the addressed problems may have different objectives, adopting integrated solutions contribute to the overall terminal's profitability. In their specific case, once containers arrive, they can be either immediately loaded onto a train heading to their destination or temporarily stored on the yard. Min *et al.* [10] studied the current situation of seaport terminal operators at the Inner Harbour of the Incheon Port in Korea. They indicate, by also considering TOS related literature, the necessity of systematic measurement tools for assessing the integration of terminal operations. The authors listed various integration options, where joint berth operations and yard operations through coordination of inbound and outbound containers were listed in first and second positions, respectively. From that viewpoint, our work seeks to enhance the management of import container flow by considering interrelated operations. Those operations can be delimited by the three main steps that containers have to carry out, namely: (i) arrival to the terminal from the seaside, (ii) storage in the yard if necessary, and (iii) departure to the destination in the landside. Therefore, we have focused on the three main problems that stand out and most directly influence delivery times: the BAP in the seaside, the SP in the yard, and the management of vehicles to deliver containers to the landside.

Based on the previous discussions and greatly extending the work of Lalla *et al.* [20], the main contributions of this study are described hereafter:

- i. Introducing an analysis of the main flows of containers in a maritime container terminal, from their arrival positions in container vessels to their delivery to companies. The analysis allows obtaining a complete tracking of the movements of each container around the terminal. This tracking is useful for terminal managers to identify potential improvements in the integral management of the terminal. This consideration of the whole flow of import containers inside a maritime terminal constitutes a novelty. Other approaches in the literature focus on the flow and optimisation of activities in one or a few isolated problems inside the terminal [21–24]. Thus, many other external factors are not taken into account, which may lead to less realistic decisions in the maritime terminal. For this reason, we consider the whole flow and propose a decision-making framework.

- ii. Proposing a multi-stage approach that seeks to be a decision-making support tool. It provides a feasible schedule of the technical equipment involved in the handling of container flows as well as an accurate estimation of the arrival of freights to the destination companies. We propose a framework devoted to integrate different solution methods for individual problems bundled and connected in such a way that larger and interrelated operations can be addressed. Therefore, this multi-stage approach contributes to the state-of-the-art integration approaches. It allows practitioners and interested researchers to include their isolated methods within the proposed multi-stage framework, leading to more realistic solutions.
- iii. Moreover, although it is true that there are studies on the flows of containers, schedules of equipment and algorithms, they are limited by what their point of view encompasses. Our proposal is a holistic approach that allows analysis to identify potential improvements in the integral management of the terminal.
- iv. Providing a scenario generator aimed at obtaining realistic environments to analyse the import container flows and the performance of algorithmic techniques designed to optimise it.
- v. The remainder of this paper is structured as follows. Section 2 proposes an optimisation problem to analyse suitable flows of freights from the incoming container vessels towards their destination companies. Afterwards, Section 3 introduces a multi-stage approach and related problems to optimise the flow of containers within and across a maritime container terminal. Section 4 presents a set of computational experiments to check the suitability of the multi-stage approach in realistic scenarios. Finally, Section 5 extracts the main conclusions from the paper and suggests several lines for further research.

2 Problem description

2.1 Scenario under analysis

The freights are packed into containers that arrive at the terminal within container vessels. Once a vessel is berthed, its containers must be unloaded and later transported to their requesting companies by means of delivery trucks. The time a given company waits for its containers depends on the type and amount of available technical resources as well as their management, among other factors.

Fig. 1 depicts the general scheme of a conventional maritime container terminal, which constitutes the scenario under analysis in this study. It is given a set of incoming container vessels that arrive at port carrying the containers with the freights requested by the companies. A suitable berth and berthing time must be assigned to each container vessel. For instance, the scheme shown in Fig. 1 considers a quay physically divided into five berths. In this case, the two illustrated vessels are berthed at the first and third berth. Then, the containers inside the vessels are unloaded using the available quay cranes at each berth. Depending on the container's time windows, it can be either stored for its later retrieval or directly delivered to its destination company. This delivery is possible whenever the destination company of a container is open to receive it and the terminal capacity enables it. For the sake of simplicity, a company is here represented by a single point. The direct delivery of a container is only possible whenever there is at least one available delivery truck to move the container from its berth towards its company. If this is the case, the available truck is directly used to load the container and deliver it to the company. Once it arrives at the company, the container is unloaded. The corresponding times required to perform these movements are considered. Otherwise, it is temporarily stored in one of the yard blocks of the terminal to be later delivered. The target position of each container in the assigned yard block is at the top of a stack with at least one empty slot. Due to the fact that multiple alternatives are usually available in a given yard block, the target position is determined as that in which the total number of relocation movements is minimised by using the algorithmic technique described in Section 3.2. A yard block is a storage place composed of bays arranged in parallel, whereas a bay is a two-dimensional set of stacks with a maximum stacking height (nT , see

Section 3.2). In this case, Fig. 1 shows five yard blocks composed of ten bays with five stacks each one.

The scenario under analysis considers a set of assumptions derived from an assessment of the most relevant maritime container terminals and which are consistent with the literature review in this field. These assumptions are described in the following:

- The destination company of each container is single and known in advance. This implies that the incoming containers can be allocated in advance to be stored on the yard on the basis of their characteristics, retrieval time, or pricing policy [25]. As discussed by Chen and Lu [26], additional challenges derived from the storage space allocation and location assignment appear when the destination company and departure time is unknown. The interested reader is referred to the work by Sauri and Martin [27] to obtain an exhaustive analysis of location assignment problems of containers with uncertain information.
- Each company requests freights included in one or several containers. In this regard, those containers requested by a given company arrive at a port inside one or several container vessels. In addition, destination companies usually delegate container transportation to third party logistics companies, which have a limited fleet of trucks aimed at collecting containers and transporting them to their destinations. Patterson *et al.* [28] provide a comprehensive analysis of the role of these companies in supply chains. However, multiple vehicle routing problems can be tackled in future works to model those scenarios in which the destination companies have their own fleets [29].
- There is a single yard block associated with each berth in the terminal to minimise transfer times. It should be noted that the number of blocks and their arrangement on the yard in a particular maritime terminal are highly dependent on the storage layout, their dimensions, handling machinery, and the containerised trade volumes. The interested reader is referred to the works by Petering and Murty [30] and Li [31]. In addition, such as considered in this study, Han *et al.* [32] discuss the impact of a static assignment of a block to each berth with the aim of reducing the berthing time of the incoming vessels. A similar approach is also considered by Nishimura *et al.* [33]. When storage is required, those containers unloaded from the vessels berthed in the relevant berth are temporarily stored in it.
- Each yard block is served by a unique yard crane (e.g. rubber-tyred gantry crane, rail-mounted gantry crane or overhead bridge crane), which performs the storage and retrieval of containers. In spite of being the most prevalent approach in existing terminals, cooperative strategies that combine multiple cranes are used by a few terminals. As discussed by Vis and Carlo [34], this latter approach improves the overall performance at the expense of increasing the complexity of the container operations. For this reason, it has been ruled out in this work and opens to further research.
- The movement of containers among the different functional areas of the maritime container terminal is carried out through specialised vehicles. Two types of vehicles are identified: internal vehicles (e.g. automated guided vehicles, yard trucks etc.), which are entrusted with the transshipment between the quay and the yard, and external vehicles (i.e. delivery trucks), which are dedicated to transporting containers from the quay towards their destination companies.
- The maximum capacity of the maritime container terminal in terms of simultaneous external vehicles depends on its technical characteristics: dimensions, availability of gates, efficiency of scanner-based inspections, existence of vehicle tracking systems etc. This fact could give rise to potential delays on the container transport among the functional areas due to the shortage of vehicles. Indeed, it is required that an analysis of access policies is integrated into the multi-stage approach in future work with the aim of overcoming potential long delays in terminal gates as well as optimising the container arrangement.

Finally, it is worth mentioning that, as described in the next section, the independent optimisation problems occurring at each

Fig. 1 Overview of the optimisation problem in the environment of a maritime container terminal

functional area of the maritime container terminal under analysis are already known to be $\mathcal{NP}$ -hard (see [35–37]) and, consequently, the resulting integrated problem is also $\mathcal{NP}$ -hard.

2.2 Estimating the waiting time of the companies

Let $V = \{v_1, v_2, \dots, v_{nV}\}$ be the set of incoming container vessels in the whole planning horizon and $B = \{b_1, b_2, \dots, b_{nB}\}$ the set of available berths at the terminal. Each berth $b \in B$ has a fixed number of similar quay cranes, denoted as $qc(b)$ and dedicated to perform the container handling operations. Each quay crane has a certain productivity, denoted as $\rho(b)$, i.e. expressed in terms of containers to load/unload into/from a container vessel per time unit (i.e. per hour) and given by the technical characteristics of the quay crane, ability, experience of the crane operator etc. In addition, $C = \{c_1, c_2, \dots, c_{nC}\}$ is the set of homogeneous containers to unload at the terminal from the incoming vessels. Also, let C_v be the set of containers to unload from the container vessel $v \in V$, where $C = \cup_{v \in V} C_v$, $\cap_{v \in V} C_v = \emptyset$, and $C_v \neq \emptyset, \forall v \in V$. Furthermore, the yard of the terminal contains a set of yard blocks, denoted as $Y = \{y_1, y_2, \dots, y_{nY}\}$.

Moreover, $E = \{e_1, e_2, \dots, e_{nE}\}$ is the set of companies to serve. Each company $e \in E$ has a known time window, denoted as $[t_e, t'_e]$ (where $t'_e > t_e$). The set of containers requested by company $e \in E$ is denoted as $C(e)$, where $C = \cup_{e \in E} C(e)$, $\cap_{e \in E} C(e) = \emptyset$, and $C(e) \neq \emptyset, \forall e \in E$.

Lastly, the movement of containers between the terminal and the companies is carried out by means of a known set of homogeneous external vehicles, denoted as $K^{\text{out}} = \{k_1^{\text{out}}, k_2^{\text{out}}, \dots, k_{nK^{\text{out}}}^{\text{out}}\}$, with capacity for only one container at once. The maximum capacity of the terminal in terms of simultaneous external vehicles is denoted as $\max_{K^{\text{out}}}$. Furthermore, the containers are transported from the berths towards the yard by means of a set of internal vehicles, denoted as

$K^{\text{in}} = \{k_1^{\text{in}}, k_2^{\text{in}}, \dots, k_{nK^{\text{in}}}^{\text{in}}\}$. In order to facilitate the follow-up of this study, the notations used are listed in Nomenclature.

The time the company $e \in E$ waits for the containers (i.e. $C(e)$) in which its requested freights are contained is termed *waiting time* and denoted as $wt(e)$. This time is elapsed from the beginning of the planning horizon until all its corresponding containers have been already delivered. It is assumed that all the freights are exactly requested at the beginning of the planning horizon. Therefore, the waiting time of company $e \in E$ is computed as follows:

$$wt(e) = \max \{dt(c) | c \in C(e)\}, \quad (1)$$

where $dt(c)$ is the time in which the container $c \in C(e)$ is delivered to company $e \in E$.

The objective of the optimisation problem under analysis is to minimise the waiting times of the companies in order to ensure the quality of service since the waiting time is one of the foremost criteria used to assess the performance of a given planning while supporting the fluidity of the companies' subsequent linked operations (e.g. delivering the goods to final customers). This is formally expressed as follows:

$$\min \sum_{e \in E} wt(e). \quad (2)$$

According to (1) and (2), the main decision here is to determine how to deliver the containers to their destination companies in the most efficient manner.

As shown in Fig. 2, the time in which a certain container is delivered to its destination company can be broken down into various time periods:

- i. *Berthing time*. A certain requested freight arrives at the terminal within a container, which, in turn, is inside a known

incoming container vessel. The time elapsed from the beginning of the planning horizon until the berthing time of the container vessel $v \in V$, denoted as $bt(v)$, constitutes the first time period to wait. This berthing time is established by the terminal manager on the basis of the characteristics of the container vessels, availability of the berths, productivity of the quay cranes etc. This issue gives rise to the definition of the BAP that is widely discussed in Section 3.1.

- ii. *Container unloading.* Once a given container vessel is berthed at the terminal, its containers must be unloaded according to its stowage plan [38]. The stowage plan of a container vessel determines the set of containers to be loaded and unloaded in each maritime container terminal along the shipping route. This means that those containers to unload can be sorted according to their unloading times.

In the following, an estimation of the time in which each container is unloaded from its container vessel is provided. For this purpose, let $index(c)$ be the order in which container $c \in C_v$ must be unloaded from container vessel $v \in V$, where $index(c) \in \{1, 2, \dots, |C_v|\}$. The unloading time of container c once v has berthed depends on the number and productivity of the quay cranes at the assigned berth $b \in B$ and the unloading order of c . This time is initially estimated as follows:

$$ut(c) = \frac{index(c)}{qc(b) \cdot \rho(b)}. \quad (3)$$

As discussed in Section 3.3, the estimated unloading time of a container is satisfied whenever the container vessel carrying it berths on time and there are enough vehicles to move it towards its destination. Otherwise, the whole unloading process is delayed until they can perform the transfer.

Finally, it is worth mentioning that alternative estimations of the container unloading time could be proposed in further research by taking into account other factors not yet considered here. For instance, Schonfeld and Sharafeldien [39] consider an interference exponent derived from quay crane interferences.

- iii. *Wait for a vehicle.* The unloaded containers must be picked up in an ideal scenario by delivery trucks with the aim of being transported from their berths towards their destination companies outside the terminal. However, in those cases in

which there is no delivery truck available, the containers must wait for their pick up. The waiting time of a container $c \in C$ at berth $b \in B$ is denoted as $wt(c, b)$.

These waiting times impair the performance of the quay cranes due to the fact that they delay the unloading of the subsequent containers, and then the berthing time of further vessels. In this study, it is assumed that, in general terms, a given container cannot wait longer than δ time units to be transported to its destination company, where δ is a prefixed value set by the decision-maker. This means that if no delivery truck can pick up a container when unloaded in a maximum of δ time units, it is stored on the yard until its later retrieval.

- iv. *Storage on yard.* Some containers arriving at the terminal must be stored on the yard. This is the case of those that cannot be directly delivered to their destination companies due to the fact that either there are not available delivery trucks or the companies are not ready to receive them (e.g. time windows constraints). Consequently, it should be noted that the container storage is an optional stage.

The storage of a certain container can be split into the following steps:

(a) *Transport to yard block.* The container is transported from its berth towards the nearest yard block with at least one empty slot. It is worth mentioning that the filling rate of the blocks is usually below 70% in most of container terminals [40]. For this reason, the probability of not finding an empty slot to store the containers is negligible in practice. This attempt to minimise the transport time around the terminal and maximise the usage of the internal vehicles. In this regard, the time an internal vehicle $k_{in} \in K^{in}$ requires to move a container from the berth $b \in B$ to the yard block $y \in Y$ is denoted as $t_{in}(b, y)$.

(b) *Pick-up by yard crane.* Once the internal vehicle carrying the container to store arrives at its destination yard block, it must wait until the yard crane is available to pick it up and store it. Specifically, once the vehicle arrives at its block, it follows its handover lane to the destination bay. The vehicle waits there for discharging by the corresponding crane [41]. In this regard, the time a container $c \in C$ must wait for the internal vehicle until being picked up by the yard crane of block $y \in Y$ is denoted as $p(c, y)$. It should be noted that when the container is removed from the internal vehicle, this is ready to move another container.

Fig. 2 Breakdown of the delivery time of container $c \in C(e)$ to company $e \in E$. It is assumed that c is unloaded from vessel $v \in V$ at berth $b \in B$. Note that optionally instead of deliver c directly, it can be stored in yard block $y \in Y$

(c) *Storage time in yard block*. The container is stored in the yard block until it can be transported to its destination company by means of a delivery truck. The storage time of container $c \in C$ in the yard block $y \in Y$ is denoted as $s(c, y)$.

(d) *Retrieval time by yard crane*. When a container is about to be moved towards its destination company, the yard crane retrieves it from its current location in the yard block. The time required to retrieve container $c \in C$ from yard block $y \in Y$ is denoted as $r(c, y)$.

- v. *Transport to company*. The containers are transported towards their destination companies by delivery trucks that depart from either (i) the berth in which the vessel containing them berths or (ii) the yard block in which they are temporarily stored. The time a delivery truck $k_{out} \in K^{out}$ requires to move a container towards its destination company $e \in E$ is $t_{out}(b, e)$ or $t_{out}(y, e)$ when it is directly moved from either the berth $b \in B$ or the yard block $y \in Y$.
- vi. *Unloading at company*. The technical characteristics of the destination company of a container (e.g. number of operators, manoeuvrability of the delivery trucks etc.) determine the time required to unload it.

The time required by a delivery truck to unload a container at company $e \in E$ is denoted as $d(e)$. It is worth pointing out that once the container is unloaded at the company, the delivery truck is ready to move another container.

The time in which a certain container $c \in C$ is delivered to its destination company $e \in E$ can be formally expressed on the basis of the previous time periods, i.e.

$$\begin{aligned} dt(c) = & bt(v) + \frac{\text{index}(c)}{qc(b) \cdot \rho(b)} + wt(c, b) \\ & + \phi_c \cdot (t_{in}(b, y) + p(c, y) + s(c, y) + r(c, y) + t_{out}(y, e)) \quad (4) \\ & + \bar{\phi}_c \cdot t_{out}(b, e) + d(e), \end{aligned}$$

where ϕ_c is a binary decision variable that takes a value of one if and only if the container c is temporarily stored in a yard block. Similarly, $\bar{\phi}_c$ is a binary decision variable that takes a value of one if and only if the container c is directly transported from its berth towards its destination company. As can be seen, Fig. 2 illustrates this delivery time.

3 Multi-stage approach

In this section, a multi-stage approach dedicated to address the transport of containers around a maritime container terminal and the delivery of freights to the requesting companies is introduced. This approach considers different solution stages, i.e. one stage represents the solution for a given problem. Thus, our approach starts with the stage corresponding to the berthing operations, continues with the stage related to the storage of containers, and finalises with the delivery of containers to companies. Its pursued objective is to minimise the waiting times of the companies, as expressed by (2). Along this section, the stages considered as well as their algorithmic connections are described.

Algorithm 1 (Fig. 3) depicts an illustrative scheme of this approach. As can be seen, it is split into several stages concerning the successive logistic problems appearing from the container arrival to their delivery to companies. The main stages of this approach are described as follows:

- At the first stage, the incoming vessels carrying the containers have to be berthed along the quay (lines 1 and 2). Hence, the BAP must be solved to determine the berthing positions and berthing times of the vessels. This process is discussed in Section 3.1.
- The goal of this stage is to provide a feasible berthing schedule in such a way that the time required to serve the vessels is minimised and, consequently, their containers are available to be delivered as soon as possible. The solution of the BAP also

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1: Allocate incoming container vessels,  $V$ , to available berths,  $B$ 
2: Schedule the container vessels in berths
3: for (each  $b \in B$ ) do
4:    $C^b \leftarrow$  Set of containers to be unloaded at berth  $b$ 
5:   Determine the unloading time of each container  $c \in C^b$ 
6:   for (each  $c \in C^b$ ) do
7:      $e \leftarrow$  Destination company of  $c$ 
8:     if ( $c$  cannot be moved towards  $e$  before its closing time)
9:       then
10:         $y \leftarrow$  Assign block to  $c$ 
11:        Move  $c$  towards its yard block,  $y$ 
12:        Store  $c$  in a stack of  $y$ 
13:        for ( $t \leftarrow 1$  to  $\max\{r(c) \mid c \in C^b\}$ ) do
14:           $C^b(t) = \{c \in C^b \mid r(c) = t\}$ 
15:          for (each  $c \in C^b(t)$ ) do
16:            Relocate those containers placed above  $c$  in other stacks
17:            Retrieve  $c$  from its current stack
18:          end for
19:        end for
20:        Move  $c$  towards its destination company,  $e$ 
21:      end if
22:    end for

```

Fig. 3 Algorithm 1: pseudo-code of the proposed multi-stage approach

establishes the unloading time of the containers (line 5), and therefore the starting point of the container flows.

- In the second stage, the container storage is addressed, i.e. once the containers are unloaded from the vessels, they can be either directly delivered to the respective destination companies or, otherwise, stored on the yard (lines 8–19). For doing this, the SP detailed in Section 3.2 is tackled. In this case, yard blocks must be first selected adequately (line 9). Afterward, the container storage has to be carried out (line 11) in such a way that they are available at their retrieval times (lines 12–18). With this objective in mind, those containers placed above the next to retrieve must be suitably relocated in other stacks of the block (line 15).
- The final stage aims to collect the outgoing containers from the terminal by the respective companies. Moving containers among the functional areas of the terminal and the recipient companies require a suitable management of the available delivery vehicles at the terminal. In this regard, when a container is unloaded, the set of external delivery vehicles is checked in order to evaluate if it can be directly delivered while satisfying the vehicle capacity of the terminal. This occurs when an external delivery vehicle can pick up the container and deliver it within the time window of its destination company (line 20). Otherwise, the container is moved to a yard block by the next available internal delivery vehicle (lines 9–18). In both cases, it should be noted that delays in the container pick up give rise to unforeseen stops of the quay cranes and, then, considerable deviations in the departure times of the container vessels.

Algorithmic techniques used in the first and second stages are based on previous works in these fields, while the algorithm for the final stage is a new proposal. However, it is worth mentioning that proposing algorithmic techniques dedicated to addressing the individual optimisation problems embedded in the multi-stage approach described here (i.e. BAP, SP etc.) is not an objective of this study, but the integration of each stage to consider the whole process. This means that the approach is totally independent of the particular algorithmic techniques used. In this case, those presented in the remainder of this section are highly competitive in comparison with proposals already found in the related literature, but alternative techniques can be considered in further research.

In spite of the fact that several highlighted decisions are made by the proposed multi-stage approach when managing the incoming containers, some others have been ruled out because they have a narrow application field or a reduced impact on the goals of the study. However, integrating them in the proposal would enrich it and allow modelling a container terminal rigorously in future

Fig. 4 Example of a solution of the BAP composed of $nV = 6$ container vessels and $nB = 3$ berths

works. In this regard, providing a precise estimate of container delivery is a challenge that managers have to deal with by considering simultaneously design problems, operational planning problems, and real-time control problems [42]. Additional decisions found in the seaside are determining the suitable set of quay cranes to assign to each individual container vessel [43] and establishing the schedule to unload its containers [7]. Also, assigning the containers to slots within the vessels gives rises to substantial operative fluctuations that ultimately impact the deliveries. For this reason, it is advisable to also take this decision into account [44]. Furthermore, we have focused our attention on selecting the storage locations and rehandling containers on the yard. The uses of policies aimed at reserving yard capacity are beneficial to improve the service to incoming vessels while also optimising the existing resources [45]. At the same time and as indicated in the previous section, it is required to integrate traffic control strategies to improve the access to the terminal while maintaining security measures [46]. The interested reader is referred to the work by Gharehgozli *et al.* [47] to obtain a recent analysis of complementary operations in the field.

3.1 Berth allocation problem

One of the most widespread indicators for assessing the competitiveness of a maritime container terminal is the time required to serve the container vessels arriving to port [5]. In this regard, inefficient utilisation of some key resources, such as berths, could produce delays on the yard and landside operations, giving rise to poor overall productivity of the container terminal.

The aforementioned issue leads to the definition of an $\mathcal{NP}$ -hard optimisation problem called BAP. Its main goal is to allocate and schedule incoming vessels to berthing positions in order to optimise a certain cost function. The BAP has been extensively studied in the literature. In this regard, due to the large variety of maritime terminal layouts around the world, research has given rise to a multitude of variants for this problem. Depending on how the quay is modelled, the BAP can be referred to as discrete (the quay is divided into segments called berths) or continuous (the quay is not divided, thus the vessels can berth at any position along the quay). Moreover, in some related works (e.g. Cordeau *et al.* [35] and Umang *et al.* [48]), there is also a hybrid consideration of the quay (i.e. it is divided into a set of berths and a vessel can occupy more than one berth at a time or share its assigned berth with other container vessels). Depending on the arrival time, the BAP can be classified into static (the vessels are already in port when the berths

become available) or dynamic (the vessels arrive during the planning horizon). For detailed descriptions, the reader is referred to the works by Bierwirth and Meisel [49] and Christiansen *et al.* [50].

The BAP primarily aims to assign a berth to each incoming container vessel. Its main constraint is that each berth can serve at most one vessel at once. In this regard, each berth $b \in B$ has a time window $[t_b, t'_b]$ and can serve the container vessels. Each container vessel $v \in V$ has a certain service priority, p_v . The time a given container vessel is at the terminal depends on multiple factors, such as its cargo, the number and productivity of the quay cranes allocated to it etc. In this case, the time required to serve a container vessel $v \in V$ in berth $b \in B$ is denoted as s_{vb} . In addition, each container vessel $v \in V$ has a known time window $[a_v, b_v]$, which must be served.

The objective function aims to minimise the total (weighted) service time of all the incoming container vessels, defined as the time elapsed between their arrival to the port and the completion of their handling operations, i.e.

$$\min \sum_{v \in V} p_v \cdot (bt(v) + s_{vb} \cdot x_{vb}), \quad (5)$$

where $bt(v)$ is the berthing time of vessel $v \in V$ and $b(v)$ is the berth assigned to v , and x_{vb} is a binary variable that takes a value of one if vessel $v \in V$ is berthed at berth $b \in B$, zero otherwise.

In order to improve the understanding of the BAP, Fig. 4 shows an example of a berthing schedule composed of $nV = 6$ container vessels and $nB = 3$ berths. The rectangles represent the vessels and, inside each rectangle, its corresponding service priority is shown. The time windows of the vessels are represented by the lines at the bottom of the figure. In this case, for instance, vessel 1 arrives at time step 4 and it must be served before time step 14. Moreover, the time window of each berth is limited by the non-hatched areas. Table 1 reports the handling time of each vessel on the basis of its assigned berth. For example, if vessel 1 is assigned to berth 1, its handling time would be equal to 6, which is shorter than the handling time of 8 that it would have at berth 2. As can be seen in Fig. 4, vessels 5 and 6 would have to wait for berthing in their respective assigned berths. In this regard, since their service priorities are 1, their waiting times will have less impact on the objective function value than delaying other vessels, such as vessels 3 and 4, for which the service priorities are $p_3 = 6$ and $p_4 = 4$, respectively, i.e. if their berthing times are delayed, the

The BAP solved within our proposed multi-stage approach introduced along this section corresponds to the discrete and dynamic variant. Furthermore, the solution method used to provide a berthing plan for this problem is a tabu search with path-relinking restarting strategy proposed by Lalla *et al.* [51]. As indicated in that work, the best exact approach for this problem has been proposed by Christensen and Holst [52], but unfortunately requires large amounts of computational memory when addressing realistic scenarios. Therefore, as indicated by Lalla *et al.* [51], the tabu search provides a suitable balance between the quality of the achieved solutions and the computational times. Lastly, it is worth mentioning that alternative approaches can be found in the related literature (e.g. [53–57]) and can be transparently used by the multi-stage approach. For instance, Mauri *et al.* [55] proposed a large neighbourhood search to solve this problem. It is the best metaheuristic algorithm in terms of best solutions provided so far but it requires higher amounts of computational time than other metaheuristic approaches. In this sense, as reported in that work, the approach provided in [51] reports shorter computational times and competitive solutions. Thus, considering the importance of having fast algorithms required in this type of environment and that all decisions have to be made in a real-time fashion (see [18]), in this work we used the approach provided in [51]. For a more detailed review of the BAP, the reader is referred to the work of Bierwirth and Meisel [7].

Certain containers unloaded from the incoming container vessels must be stored in the yard due to the fact that, as discussed previously, they cannot be directly moved towards their destination companies. The containers unloaded in a given berth are usually stored in the nearest yard block in order to minimise the transport time around the terminal and maximise the productivity of the internal delivery vehicles [58].

The yard cranes are highly expensive technical equipment and their suitable management is a cross-cutting goal for terminal managers [30]. The yard cranes are aimed at responding to the container storage and retrieval requests. In an ideal scenario, each yard crane movement gives rise to the storage or retrieval of a given container. However, the container stacking on the yard precludes all the containers can be accessed directly. In this regard, the main shortcoming associated with the stacking arises from the last in first out policy [3], i.e. only one movement is required

The container relocation movements are unproductive and consequently give rise to low performance in container terminals. With the goal of minimising the waiting time of the containers during a given time horizon, appropriate planning strategies must be designed [60]. These planning strategies place the incoming containers in storage locations in which they will be accessible for their future retrieval. This discussion draws forth the lack of efficient approaches to determine the sequence of movements carried out by the yard cranes when storing and retrieving containers. With this objective in mind, in the following, the SP is firstly described and afterwards a planning strategy for solving it is introduced.

The SP aims to determine the sequence of movements carried out by a yard crane to store and retrieve a set of containers, $C = \{1, 2, \dots, nC\}$, in a yard block during a well-defined time horizon, denoted as H_{SP} (e.g. a working shift), in such a way that the number of relocation movements is minimised. It is worth mentioning that only one movement is required to store and retrieve containers, but one additional relocation movement is required for each container placed above the next to retrieve. Determining the target position of the containers to store and relocate are the main decisions of the problem. The block consists of $S = \{1, 2, \dots, nS\}$ stacks and $T = \{1, 2, \dots, nT\}$ tiers. Each container $c \in C$ must be stored during its delivery time, $d(c) > 0$ and retrieved during its retrieval time, $0 < r(c) \leq H_{SP}$, where $r(c) > d(c)$. Finally, it is worth mentioning that, as demonstrated by Rei and Pedroso [37], the SP is known to be $\mathcal{NP}$ -hard.

Fig. 5 depicts an example for the SP in which there are $nS = 8$ stacks and $nT = 5$ tiers in time period $t = 17$ (i.e. those containers with retrieval time before $t = 17$ have been already removed). Each container contains its due time. In this case, the next incoming container is released in time period 18 and must be retrieved from the block in time period 89.

The SP is solved within the framework of the multi-stage approach using the heuristic algorithm proposed by Expósito-Izquierdo *et al.* [61]. It is an algorithmic technique with high performance in comparison with previous proposals found in the related literature, reporting high-quality solutions in short computational times. This heuristic determines the target of each incoming container and those placed above the next to retrieve. Additionally, it exploits those time periods in which the yard crane is idle to arrange the containers within the yard block. For a comprehensive literature survey on the SP, the interested reader is referred to a recent review by Lin and Chiang [62], where authors also proposed a decision rule-based heuristic implemented at the Port of Kaohsiung, Taiwan. Although this was found to be effective, their approach relies heavily on information prior to container arrival. Finally, a later and very recent approach by Gharehgozli and Zaerpour [63] introduces an alternative stacking policy allowing different container types to share the same pile. However, the approach focuses on outbound containers in a deep-sea container terminal.

Vessel	Berth 1	Berth 2	Berth 3
1	6	8	5
2	2	3	4
3	5	5	4
4	4	6	5
5	5	8	7
6	4	4	5

Fig. 5 Example of the SP with $nS = 8$ stacks and $nT = 5$ tiers

```

1: for (each  $c \in C$ ) do
2:    $v \leftarrow$  Vessel that arrives  $c$  to the terminal
3:    $b \leftarrow$  Berth in which  $c$  is unloaded
4:    $e \leftarrow$  Destination company of  $c$ 
5:    $k_{out} \leftarrow$  Select external delivery vehicle from  $K^{out}$  for  $c$ 
6:    $wt_{k_{out}}(c, b) \leftarrow$  Compute waiting time of  $c$  in  $b$  for  $k_{out}$ 
7:   if  $((wt_{k_{out}}(c, b) \leq \delta)$  and  $(bt(v) + ut(c) + wt_{k_{out}}(c, b) +$ 
    $t_{out}(b, e) + d(e) \in [t_e, t'_e]))$  then
8:     Carry  $c$  from  $b$  to  $e$  by means of  $k_{out}$ 
9:     Update availability of  $k_{out}$ 
10:    Delay unloading process during  $wt_{k_{out}}(c, b)$  time units
11:  else
12:     $k_{in} \leftarrow$  Select internal vehicle from  $K^{in}$  for  $c$ 
13:     $wt_{k_{in}}(c, b) \leftarrow$  Compute waiting time of  $c$  in  $b$  for  $k_{in}$ 
14:    if  $((wt_{k_{in}}(c, b) \leq \delta)$  and  $(wt_{k_{in}}(c, b) < wt_{k_{out}}(c, b)))$ 
      or  $(bt(v) + ut(c) + wt_{k_{out}}(c, b) + t_{out}(b, e) + d(e) \notin$ 
       $[t_e, t'_e])$  then
15:      Carry  $c$  to its yard block by means of  $k_{in}$ 
16:      Update availability of  $k_{in}$ 
17:      Delay unloading process during  $wt_{k_{in}}(c, b)$  time units
18:    else
19:      Carry  $c$  from  $b$  to  $e$  by means of  $k_{out}$ 
20:      Update availability of  $k_{out}$ 
21:      Delay unloading process for  $wt_{k_{out}}(c, b)$  time units
22:    end if
23:  end if
24: end for

```

Fig. 6 Algorithm 2: transport of containers towards their destination companies

```

1:  $y \leftarrow$  Yard block in which  $c$  is stored
2:  $e \leftarrow$  Destination company of  $c$ 
3:  $k_{out} \leftarrow$  Select external delivery vehicle from  $K^{out}$  for  $c$ 
4:  $wt_{k_{out}}(c, b) \leftarrow$  Compute waiting time of  $c$ 
5: if  $(et(c) + wt_{k_{out}} + t_{out}(y, e) < t_e)$  then
6:    $wt_{k_{out}} \leftarrow wt_{k_{out}} + (t_e - (et(c) + wt_{k_{out}} + t_{out}(y, e)))$ 
7: end if
8: Carry  $c$  from  $y$  to  $e$  by means  $k_{out}$ 
9:  $\Gamma \leftarrow \{c' \in C \mid et(c) + wt_{k_{out}} > et(c')\}$ 
10: Delay containers in  $\Gamma$  during  $wt_{k_{out}}$  time units

```

Fig. 7 Algorithm 3: Picking up process of a container c from its yard block

3.3 Management of delivery vehicles

Once container vessels arrive at the port, their corresponding containers are unloaded at the berths on the basis of their stowage plans using the available quay cranes at the terminal. Each unloaded container must be delivered to a known destination company. However, the availability of delivery vehicles, time constraints, and traffic congestion are factors that prevent optimal delivery.

To the best of our knowledge, there are no approaches in the literature integrating the management of internal and external delivery vehicles in a container terminal. Thus, we propose the heuristic in Algorithm 2 (Fig. 6), which depicts the process of delivering containers to their destination companies. In this regard, the following scenarios can happen:

1. *Direct delivery.* In an ideal scenario, once a container $c \in C$ is unloaded at a berth $b \in B$ (line 3), it is directly delivered to its destination company, $e \in E$ (line 4). This avoids the effort derived from storing it on the yard, minimise its delivery time, and maximise the productivity of the external delivery vehicles by avoiding their waiting times. With this objective in mind, the next available external delivery vehicle, $k_{out} \in K^{out}$, is selected (line 5) taking into account the number of external delivery vehicles that can be simultaneously at the terminal, $\max_{K^{out}}$. At this point, the waiting time of c in its berth b for vehicle k_{out} can be easily computed on the basis of its unloading time (i.e. $ut(c)$) and the arrival of k_{out} . This waiting time is denoted as $wt_{k_{out}}(c, b)$ (line 6).

As illustrated in lines 7–10, a container c arrived at the terminal inside a vessel $v \in V$ (line 2) can be directly delivered to its destination company $e \in E$ by the vehicle $k_{out} \in K^{out}$ whenever the following constraints are fulfilled:

$$wt_{k_{out}}(c, b) \leq \delta, \quad (6)$$

$$bt(v) + ut(c) + wt_{k_{out}}(c, b) + t_{out}(b, e) + d(e) \in [t_e, t'_e]. \quad (7)$$

Equation (6) indicates that the waiting time of c has to be no longer than the pre-specified maximum waiting time of a container in its berth (i.e. δ), whereas (7) checks if c can be delivered to e within its corresponding time window (i.e. $[t_e, t'_e]$). It should be noted that (7) is closely related to (4) when setting $\phi_c = 0$, $\bar{\phi}_c = 1$, and $wt(c, b) = wt_{k_{out}}(c, b)$.

Whenever (6) and (7) are satisfied, c is moved from berth b towards its destination company e by means of the delivery vehicle k_{out} (line 8). In this case, the availability of k_{out} is updated according to the delivery time of c (line 9) and the unloading time of every container at berth b is delayed during $wt_{k_{out}}(c, b)$ time units (line 10).

2. *Storage.* In those scenarios in which the unloaded container $c \in C$ cannot be directly delivered to its destination company, it must be stored in a yard block. For this purpose, the next available internal vehicle, $k_{in} \in K^{in}$, is selected (line 12). As is done in the previous case, the waiting time of c at berth b for k_{in} is computed and denoted as $wt_{k_{in}}(c, b)$ (line 13). Then, it is considered that c must be stored in the yard whenever it cannot be directly delivered under time windows constraints (i.e. (7) is not satisfied) or the following constraints are fulfilled:

$$wt_{k_{in}}(c, b) \leq \delta, \quad (8)$$

$$wt_{k_{in}}(c, b) < wt_{k_{out}}(c, b). \quad (9)$$

Equation (8) indicates that the waiting time of c has to be no longer than the pre-specified maximum waiting time of a container in its berth (i.e. δ), whereas (9) checks c has to wait a lesser time for k_{in} than for k_{out} . In these cases, c is carried to the corresponding yard block by k_{in} . It should be noted that it is necessary to update the availability of k_{in} (line 16) and delay the unloading time of every container at berth b during $wt_{k_{in}}(c, b)$ time units (line 17).

Lastly, once a container $c \in C$ is carried to the yard, it is necessary to determine when it can depart to its destination company. An estimated retrieval time for c , denoted as $et(c)$, is obtained by solving the underlying SP (Section 3.2). However, this estimated retrieval time can be modified according to the availability of external delivery vehicles. Algorithm 3 (Fig. 7) depicts this process. Firstly, the next available external delivery vehicle, $k_{out} \in K^{out}$ (line 3), is selected in order to pick up c from its yard block, denoted as $y \in Y$ (line 2). The waiting time of c in y , $wt_{k_{out}}(c, y)$, is computed. Sometimes, taking into account this waiting time, c arrives at its destination company e too late, i.e. the time window of e is already closed. In this case, c is delayed for the next day, increasing its waiting time $wt_{k_{out}}(c, y)$ (line 4). Having calculated $wt_{k_{out}}(c, y)$, it must be checked if c arrives at e before this is open (lines 5–7), in this case c must be delayed (line 6). Finally, c is carried to company e by k_{out} with a delay of $wt_{k_{out}}(c, y)$ time units from its estimated retrieval time (line 8). Also, those containers in the yard block y whose estimated retrieval time is lesser than the estimated retrieval time of c are delayed appropriately (lines 9–10).

3. *Delayed direct delivery.* There are some scenarios in which, due to unavailability of vehicles, congestion in the terminal etc., an unloaded container $c \in C$ has to wait for more than δ time units to be picked up. In this regard, it is more advisable to be directly delivered to its destination company than to be stored in the yard in order to minimise the delivery time. With this objective in mind, an

Table 2 Parameter values used for generating the scenarios

Parameter	Values
nC	{250, 500, 750, 1000}
nE	{0.2, 0.25, 0.33, 0.5, 1} · nC
nB	{5}
nV	{25}

Table 3 Parameter values used for executions

Parameter	Values
δ	{5, 10, 15, 20}
$qc(b)$	{1, 2, 3, 4} · nB
nK_{in}	{1, 2, 3, 4} · $qc(b)$
nK_{out}	{0.25, 0.5, 0.75, 1} · nE
$max_{K^{out}}$	{0.1, 0.2, 0.3, ..., 1} · nK_{out}

external delivery vehicle, $k_{out} \in K^{out}$, is selected. However, it should be noted that the company can be closed when k_{out} arrives with c (line 19). In these cases and in contrast to the above-described first scenario (i.e. *direct delivery*), the vehicle has to wait until the company opens. Once the delivery has been carried out, the availability of k_{out} is updated according to the delivery time of c (line 20) and the unloading time of every container at berth b is delayed during $wt_{k_{out}}(c, b)$ time units (line 10).

4 Computational experiments

This section is dedicated to assessing the performance of the multi-stage approach proposed in this study. This approach has been implemented using the programming language Java Standard Edition 7.0. All the computational experiments have been carried out on a PC equipped with Ubuntu 13.10, a processor Intel Core 2 Duo 3.16 GHz, and 4 GB of RAM.

The objectives pursued in the remainder of this section are:

- Describing a domain-specific scenario generator aimed at obtaining realistic scenarios in which import container flows are modelled. These scenarios are subsequently used in the computational experiments.
- Assessing the influence of the different elements of the maritime container terminal in the companies waiting time, and checking the correct behaviour of our approach.

4.1 Scenario generation

In order to overcome the lack of reference benchmark suites in the literature, a domain-specific scenario generator has been developed in this work. Its main objectives are to provide a set of scenarios with realistic characteristics dedicated to checking the suitability of the multi-stage approach introduced in this work and either be used in further works with comparative purposes or as a basis to consider additional features not studied yet.

The scenario generator aims to assign a certain value to each parameter that defines the optimisation problem under analysis in this work, for instance, the number of incoming container vessels, the productivity of the quay cranes, the time windows of the companies, and so forth. The complete list of parameters is presented in Nomenclature.

The value of each parameter, termed hereafter α , is selected at random according to a uniform distribution within the interval $[\min(\alpha), \max(\alpha)]$, where $\min(\alpha)$ and $\max(\alpha)$ are the known minimum and maximum values allowed for the parameter α . In this method, the user has to set the minimum and maximum values of the range in which the value of each parameter has to be defined. It should be noted that when the value of a certain parameter is pre-established in the environment (i.e. number of berths, blocks etc.), the minimum and maximum values of its range must be equal.

In this work, 250 scenarios with realistic characteristics have been obtained using the scenario generator here described. These are available for the interested reader in the website (<https://sites.google.com/site/gciports/container-transshipment>).

Table 2 presents the summary of the main parameter values set in the scenarios. For instance, the number of containers in the scenarios ranges from 250 up to 1000 units, whereas the number of companies ranges from 0.2 up to 1 per number of containers. Without loss of generality, these values have been adequately selected in order to study the performance of the proposed multi-stage approach over one week in an international maritime container terminal. It is worth mentioning that the generated scenarios include features not considered in the problem under analysis but that they can be used in further research. This is the case of, for instance, the weight of the incoming containers or the draft of the berths.

4.2 Results analysis

In order to assess the performance of the multi-stage approach proposed in this study, the scenarios described in the previous subsection have been executed with different parameter values.

Table 3 details the range of parameter values used. In this case, the value of the parameter δ is expressed in minutes. Moreover, the number of quay cranes per berth has been selected in order to capture different real-world container terminals ranging from small terminals to large ones such as those located in Singapore or China.

The aim of this first experiment is to check the influence of the number of external vehicles simultaneously allowed inside the terminal ($max_{K^{out}}$) over the companies waiting time. Fig. 8 shows four graphics corresponding to a different number of companies under the scenarios with the following fixed parameters values: maximum waiting time $\delta = 10$, number of containers handled $nC = 500$, number of internal vehicles $nK_{in} = 10$, and number of quay cranes $qc(b) = 1, \forall b \in B$. Each line within each graphic corresponds to a different number of external vehicles nK_{out} and they represent the behaviour of the companies waiting time when the percentage of external vehicles allowed inside the terminal $max_{K^{out}}$ increases. For each graphic, the higher the percentage, the smaller the companies have to wait. Moreover, there is certain stability in terms of companies waiting time obtained when a percentage is reached. In this regard, this stability is achieved earlier when the number of external vehicles increases, since the percentage of allowed vehicles in the terminal is calculated on the basis of the total number of external vehicles. Hence, the higher the total number of external vehicles, the larger the number of external vehicles allowed inside terminal, and therefore, the better the results in terms of the companies waiting time. This way, when the total number of external vehicles is very high there is no difference between allowing 10 or 100% of them inside a terminal.

This kind of graphics can be useful to determine which is the limited number of external vehicles allowed inside the terminal for which no significant improvement occurs in terminal performance according to the particular characteristics of the studied terminal. In those cases where the number of external vehicles is below 0.5 per company, allowing more than $max_{K^{out}} = 30\%$ external vehicles simultaneously inside the terminal does not provide a meaningful change on the companies' waiting time. On the other hand, when the ratio of vehicles and companies is equal or higher than 0.5, it can be checked that having $max_{K^{out}}$ over 10% would be a reasonable strategy.

In the subsequent experiment, for analysing the impact of the number of companies over the objective function value, the total number of external vehicles has been fixed to the $0.25 \cdot nE$ and the number of companies varies from 100 up to 500. This analysis is summarised in Fig. 9. In the figure, the lines represent the number of companies considered. As can be seen, the rank of the waiting time is different based on the number of companies, to which containers belong, going from 4 days to 2 days. It should be noted that the case of 500 companies is the best case in terms of waiting time, which are rationale since in real scenarios the companies are the ones that provide the external vehicles. Hence, the more

Fig. 8 Average waiting time of companies along a range of percentage over the maximum number of external vehicles ($max_{K^{out}}$)
 (a) 100 companies, (b) 125 companies, (c) 166 companies, (d) 250 companies

Fig. 9 Summary of average companies waiting time according to a percentage over a maximum number of external vehicles ($max_{K^{out}}$). The parameter of external vehicles nK_{out} is set to $0.25 \cdot nE$

companies, the more external vehicles for the same total workload of containers, which in this case is 500 containers.

Once the influence of the number of external vehicles inside the terminal has been analysed, the influence of the number of required containers in companies waiting time is assessed. In doing so, based on the previous result (see Fig. 9) the parameter $max_{K^{out}}$ is fixed to 30. Moreover, some other parameter values have been fixed for this experiment, namely, $nK_{in} = 10$, $qc(b) = 1$, $\forall b \in B$, $nK_{out} = \{0.25..1\} \cdot nE$. This way, Fig. 10 presents the increment of companies waiting time when the number of required containers increases. In the figure, each line corresponds to a number of companies, where the total number of companies depends on the containers handled in the scenario.

As can be checked in the figure, the companies' waiting time increases with the number of containers. This increment is quasi-linear which makes sense taking into account the increase of containers within a terminal with the same characteristics. Moreover, in those cases where the number of companies is small (which is based on the number of containers), the companies waiting time is higher since the total number of external vehicles depends on the number of companies, and with fewer vehicles the transportation of containers is slower.

Furthermore, the other important factor in maritime container terminals is the number of available internal vehicles. For this reason, in the subsequent experiment the effect of this parameter in the waiting time of companies is evaluated. Fig. 11 and Table 4

Fig. 10 Average waiting time of companies according to the number of containers (nC)

report the waiting time of companies regarding the number of internal vehicles. For this aim, the following parameters values have been fixed: $\delta = 10$, $nC = 500$, $qc(b) = 1$, $\forall b \in B$, $\max K_{out} = 30$, $nK_{in} = \{5, 10, 15, 20\}$, and $nK_{out} = \{0.25, 0.5, 0.75, 1\} \cdot nE$. Each line in the figure and each column in the table represent the different number of companies considered. The higher the number of vehicles, the lower the waiting time. In this regard, the reduction is more relevant in terms of the objective function value when the number of companies increases, i.e. when the number of companies is high, the number of external vehicles is also high, so it is more probable that an external vehicle may carry a container directly to a company without requiring the use of any internal vehicle. Hence, one conclusion drawn from this experiment may be that the number of internal vehicles has less importance in the overall performance of the terminal.

On the other hand, since the quay cranes are the elements responsible for the loading/unloading of containers to/from vessels, it is expected to affect a number of cranes in the companies waiting time. Thus, in order to evaluate this presumption, some experiments have been performed with the parameter values fixed to $\delta = 10$, $\max K_{out} = 30$, $nE = \{0.2, 0.25, 0.33, 0.5, 1\} \cdot nC$, and $nK_{out} = \{0.25, 0.5, 0.75, 1\} \cdot nE$. Table 5 reports the average companies waiting time according to the number of quay cranes, number of internal vehicles per crane, and number of containers. As can be seen, the companies waiting time decreases when the number of quay cranes increases, this makes sense since the more quay cranes the higher unloading speed. This fact indicates the logic and appropriate performance of our approach.

Finally, the parameter δ (i.e. maximum waiting time of a container in its berth), which is not a physical element of the maritime container terminal, but a strategic one, has been analysed in order to determine how this parameter impacts when deciding whether to carry a container to the yard or not, i.e. the bigger the value of δ , the more probable the container can be picked up by an external vehicle to be directed delivered to the terminal. The subsequent experiment has been done with the following parameter values fixed: $nC = 250$, $\max K_{out} = 30$, $nE = 50$, $qc(b) = 1$, and $\forall b \in B$. Table 6 shows the percentage of containers carried to the yard according to δ for different scenarios where the number of external vehicles and the number of internal vehicles varies. When the number of external vehicles is small, practically every container is carried to the yard. Nevertheless, the higher the number of external vehicles, the lower the percentage of containers carried to the yard, since more containers can be directly delivered to their corresponding company. It should be noted that the detailed results follow a tendency in terms of percentage but they are not directly connected in the sense that our proposed algorithm is a non-deterministic approach and it is completely re-executed for the

Fig. 11 Average waiting time of companies according to the number of internal vehicles (nK_{in})

different values of δ each time. Thus, the results from the same scenario with a specific value of δ may not have to be considered as a bound when the δ is increased. This can be seen in the scenario with the parameter values $K_{out} = 13$ and $K_{in} = 5$ where, for $\delta = 5$, the containers sent to the yard are lesser than for $\delta = 10$. The rationale behind this behaviour is found in that, e.g. when solving the BAP the berth scheduling may vary at each execution, and hence from there, all the management of the containers. Nevertheless, taking into account the average percentages, the influence of the parameter δ is not very relevant, but the percentages have a certain tendency to decrease when the value of the parameter δ increases due to the longer time that containers can wait for the external vehicle in order to be directly carried out to their corresponding companies.

5 Conclusions and further research

In this study, the optimisation problem for planning the freight delivery from their arrival within containers at the terminal to their corresponding delivery to requesting companies is addressed. For providing a complete management of the technical equipment involved in all those processes, a multi-stage approach is proposed. Through this approach the berth allocation, yard allocation, and vehicle scheduling are tackled by means of a well-defined number of stages. Thus, it provides an overall schedule of the decisions to

Table 4 Average waiting time of companies according to the number of internal vehicles (nK_{in}) and number of companies (nE)

nK_{in}	nE				
	100	125	166	250	500
5	393,152.39	324,464.09	263,756.70	221,071.60	167,157.47
10	366,842.52	315,150.17	262,793.58	214,457.18	166,005.43
15	361,079.06	307,337.74	262,560.16	215,206.25	165,432.28
20	360,385.22	304,778.57	261,785.20	215,020.96	164,726.63

Table 5 Average waiting time of companies

$nK_{in}/qc(b)$	$qc(b)$	nC			
		250	500	750	1000
1	1	138,705.72	240,420.09	349,389.97	455,286.33
	2	102,121.57	141,036.70	192,218.16	242,094.47
	3	84,827.96	118,339.97	145,562.27	179,015.05
	4	85,040.45	105,508.74	127,114.16	150,955.34
2	1	137,047.46	235,699.64	342,858.00	442,039.44
	2	101,277.34	138,531.23	184,787.91	235,068.31
	3	85,743.61	116,844.16	140,016.15	171,588.80
	4	83,986.17	104,927.53	123,598.85	143,283.21
3	1	137,917.80	235,800.31	342,410.02	441,145.34
	2	102,217.03	137,916.84	184,906.71	233,010.22
	3	85,944.14	115,263.25	139,125.38	169,703.94
	4	84,288.83	104,204.79	123,310.92	140,690.10
4	1	137,732.51	236,784.44	342,532.83	441,449.83
	2	101,350.49	137,957.09	184,127.40	232,418.92
	3	86,285.96	117,387.00	137,755.36	171,266.39
	4	82,857.12	105,147.04	123,039.05	140,561.11

Table 6 Percentage of containers that are stored in the yard

nK_{out}	nK_{in}	δ			
		5	10	15	20
13	5	100.0	99.9	100.0	99.9
	10	100.0	100.0	100.0	100.0
	15	100.0	100.0	100.0	100.0
	20	99.9	100.0	99.9	99.9
	Avg.	99.9	99.9	99.9	99.9
25	5	82.5	81.2	82.7	79.9
	10	82.0	80.0	78.2	79.2
	15	82.6	80.1	80.1	78.3
	20	83.3	82.4	81.4	80.1
	Avg.	82.6	80.9	80.6	79.4
38	5	55.3	54.9	56.3	56.9
	10	55.8	54.2	53.8	53.5
	15	55.4	55.7	57.0	53.5
	20	59.7	55.4	53.3	54.8
	Avg.	56.5	55.0	55.1	54.7
50	5	49.7	49.5	49.1	48.1
	10	49.8	49.0	48.8	48.9
	15	49.7	47.4	47.6	49.2
	20	48.1	48.4	48.9	47.9
	Avg.	49.3	48.6	48.6	48.5

be made to deliver arriving containers. Due to the fact that each stage is independent, different methods can be used. This flexibility in the choice of the method for solving the isolated problem is a relevant characteristic of our approach since it provides a fast and easy update. It is important to highlight that this solution scheme adds the possibility to assess the performance of isolated algorithms when integrated with others. In this regard, if specific methods according to the user preferences for the isolated problems tackled at each stage are developed, they can be easily adapted and assessed over the overall scheme.

In the computational results, the multi-stage approach is tested over realistic scenarios for different handling equipment configurations. The results indicate, on the one hand, that the proposed solution approach provides a holistic schedule by considering interrelated operations (i.e. berth allocation, internal/external vehicle scheduling, and yard management). This allows managers to analyse all the incoming container flows and perform a proper planning of the integrated processes. Also, as indicated in the related literature (see [19]), the application of this type of functional scheme is worthwhile as it enables users and

stakeholders evaluating alternative plans. On the other hand, it also provides terminal managers a suitable tool for addressing strategic decisions related to the handling equipment used to transfer the containers along the terminal such as the number of vehicles, number of quay cranes etc. Furthermore, the benefits of this approach permit to solve and combine the isolated problems by means of specific methods in an integrative way, and thus, assess their impact over the other problems. Decision support and TOS can benefit from that capability as one of the largest concerns in terminal operations is the lack of integration and uncoordinated functionalities [10]. In this regard, numerical results are also competitive and aligned to key performance indicators considered by terminal operators, i.e. users (i.e. carrier, shipper etc.) satisfaction. Therefore, this is a step towards a more defined knowledge about the interaction and performance of the processes involved when tackling flows.

On the basis of the contributions presented in this study, the subsequent stage of the research will be focused on the development of a tool for monitoring and tracing all the import and export containers. Moreover, a deeper integration with the vehicle routing problem to include the diverse companies' situation and perspectives including the consideration of multiple objectives will also be a topic for future works.

6 References

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