PhD Thesis

STRATEGIES FOR IMPROVING IMPORT YARD PERFORMANCE AT CONTAINER MARINE TERMINALS

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To my parents, Enrique and Aurora
and to my brothers, Alberto and Carlos

(…) In 1956, China was not the world's workshop. It was not routine for shoppers to find Brazilian shoes and Mexican vacuum cleaners in stores in the middle of Kansas. Japanese families did not eat beef from cattle raised in Wyoming, and French clothing designers did not have their exclusive apparel cut and sewn in Turkey or Vietnam. Before the container, transporting goods was expensive, so expensive that it did no pay to ship many things halfway across the country, much less halfway around the world.

The Box: how the shipping container made the world smaller and the world economy bigger.
Marc Levinson (2006). Princeton University Press, New Jersey.

STRATEGIES FOR IMPROVING IMPORT YARD PERFORMANCE AT CONTAINER MARINE TERMINALS

Enrique Martín Alcalde

Abstract

The process of containerization and its continuous development involves changes and technological innovations in containerships and maritime container terminals. In the current era of "gigantism", despite existing fleet overcapacity, shipping companies are booking larger and fuel-efficient vessels to benefit from economies of scale and to reduce operating costs. Consequently, port terminals have to cope with unprecedented container volumes and increasing demands, as a result, handling operations are likely to be subject to delay.

In this context, container terminals are dealing with the huge challenge of readjusting themselves in order to, on one hand, improve productivity and level of service offered to the customers (minimize turnaround time) and, on the other hand, to manage terminal handling operations efficiently with the aim of reducing operating costs and becoming more competitive.

Moreover, considering that adapting facilities and terminal infrastructures involves large investment and given the lack of space in many urban ports for expanding the operational area, the improvement of handling operations efficiency is more important than ever. Thus, many efforts are required to improve the productivity of container terminals by introducing efficient solutions and optimization techniques to decision-making processes and, on the other side, introducing technological improvements such as the automation of handling equipment.

In light of this, this thesis is focused on the optimization of handling operations in the storage yard, which is considered to be the most complex terminal subsystem since terminal performance depends on its efficiency.

In particular, it attempts to: (1) determine optimal storage space utilization by considering the yard inventory and congestion effects on terminal performance; (2) introduce new allocating storage strategies with the aim of minimizing the amount of rehandling moves, which are considered to be the most important cause of inefficiency in container yard terminals, and; (3) develop a generic storage pricing schedule to encourage customers to pick up their containers promptly and, as a consequence, reduce the average duration of stay, avoiding yard congestion.

In order to tackle these issues, two different analytical models are introduced in this thesis. The first one aims to forecast storage yard inventory by dealing explicitly with stochastic behavior, yard inventory peaks and seasonal fluctuations. The second one, which is based on probabilistic and statistical functions, is derived to estimate the average number of rehandles when containers with different departure probabilities are mixed in the same stack.

Finally, the numerical experiments presented in this thesis prove the usefulness of the different analytical models, yard design methods, cost models and operative and tactical strategies developed herein. These can be applied by other researchers, planners and terminal operators to optimize the yard handling processes, to improve their efficiency rates and to increase terminal throughput without incurring large investment. By being technically efficient, the terminal will be more cost-efficient as well, resulting in the overall optimization of terminal performance.

Keywords: container terminals, yard inventory planning, storage capacity, allocating strategies, storage pricing schedule, stochastic analysis, rehandling moves, terminal performance.

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Barcelona, 5 de mayo de 2014

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Chapter 1

Introduction, objectives and contributions

1.1 Background and objectives

The globalization of production and consumption and the use of shipping containers have revolutionized the way that cargo is handled and transported, improving the efficiency and cost-effectiveness of the transportation systems that link global supply chains. It is likely, that globalization would not have been possible without containerization. More than 80% of global merchandise trade is currently carried by sea and handled by ports worldwide. In 2008, the highest seaborne trade volume was recorded with 8.2 billion tons of cargo (UNCTAD, 2013).

Although the international maritime transport of containers is a relatively recent activity, having begun barely fifty years ago, its growth rate has been stunning. Over the past two decades, container traffic has grown at an average annual rate of around 10%, with six years of consecutive double-digit growth between 2002 and 2007 (UNCTAD, 2013). In such a context, the supremacy of Asian ports is reflected in port container rankings: 14 of the 20 busiest container ports are Asian, with the port of Shanghai the busiest one in 2012, with 32 million twenty-foot equivalent units (TEU).

This steady growth is explained by several factors, such as reduced transit time, reduced shipping costs, increased reliability and security, and multi-modality. However, the global financial crisis and subsequent economic recession halted this growth in 2009, when container trade volumes fell sharply (9%) to an overall volume of 124 million TEUs. However, a relative recovery was witnessed for a wide range of trades in 2010, leading to a global growth recovery of 12% to reach a total container trade of about 140 million TEUs.

Nevertheless, the rhythm of containerization might be immersed in the maturity phase throughout the following years (Rodrigue and Notteboom, 2008) assuming that the process of globalization slows and most comparative advantages in manufacturing are exploited.

In view of the complex environment that maritime transport and container ports are facing (periods of continuous twists and turns), ship and terminal operators are making efforts to meet their minimum operating costs by introducing technological innovations, increasing vessel size and improving the efficiency of container terminal processes.

With regard to container ship size, the trend is increasing size to profit from economies of scale, designing fuel-efficient vessels in order to get environmental improvements and reducing operating costs. For example, the delivery to Maersk of the first “Triple E” container ship with a declared capacity of 18,000 full TEUs was realized in 2013.

However, one of the consequences of increasing vessel size is that inefficiencies are simply moved elsewhere in the logistics chain and advanced solutions and progresses are required not only for policies of port infrastructure, but also for the methods of management (Steenken et al., 2004).

Thus, in the era of mega-vessels and shipping line alliances, the competition between seaports has strengthened and port container terminals are facing a big challenge: offering a good enough service at competitive prices and increasing productivity in container handling. The competitiveness of container terminals will be noticed by different key elements such as vessel turnaround time in port, the optimum cooperation between different types of handling equipment and the cost of the transshipment process between modes of transportation.

These issues can be overcome by introducing efficient solutions and optimization techniques that do not require significant investment in physical facilities or by introducing technological improvements such as the automation of handling processes.

In view of the previous statements and taking into account the hierarchical approach adopted to analyze complex terminal operations, this thesis is focused on the storage yard subsystem which is considered to be the most complex resource since storage yard operations involve the main resources (Chen et al., 2003; Jiang et al., 2012).

Moreover, according to previous practical and research analysis (i.e. Vis and de Koster, 2003; Steenken et al., 2004; Günther and Kim, 2006; Ku et al., 2010), the efficiency of yard operations is considered to be a measure of a terminal’s competitive strength which confirms the importance of analyzing this subsystem.

The major **objective** of this thesis is to provide efficient solutions and techniques to optimize storage yard operations and, as a consequence, improve productivity and terminal performance.

In particular, the following singular goals will be achieved in this thesis:

1) To determine the optimal storage space utilization by considering the yard inventory and congestion effects on terminal performance.
2) To improve the efficiency of yard handling processes by minimizing the incidence of rehandling movements during retrieval processes. This will be achieved by introducing new allocating storage strategies.
3) To avoid yard congestion and increase the profitability of the storage space by reducing, through pricing storage strategies, the average length of stay at the container yard.

   Thus, operating variable costs will be minimized and a smooth container transshipment process between modes of transportation would be guaranteed.

1.2 Terminal operations and port container terminals

1.2.1 Container terminal operations

Containers are nowadays the main type of equipment used in intermodal transport: any container has a standardized load unit that is suitable for ships, trucks and trains and can be transferred quickly from one transport mode to another. In this context, container terminals are key connections between different transportation modes and cargo handling represents a critical point in the transportation chain.

Generally, container terminals are described as open systems of cargo flow with two external interfaces: the quayside, with the loading and unloading of containerships, and the landside, where containers are loaded and unloaded on/off external trucks and trains. Containers are stored in stacks, thus facilitating the decoupling of quayside and landside operations, because the moment of loading and unloading a vessel does not always correspond to the moment of loading onto the hinterland mode.

From an operational perspective, the port terminal itself can also be considered to be a chain consisting of consecutive links (e.g. ship unloading, storage transport, storage, loading transport and hinterland loading) (Zondag et al., 2010) or, as commented in the introduction, as a group of independent processes or subsystems (ship to shore, transfer, storage, and delivery/reception), as depicted in Figure 1.1.

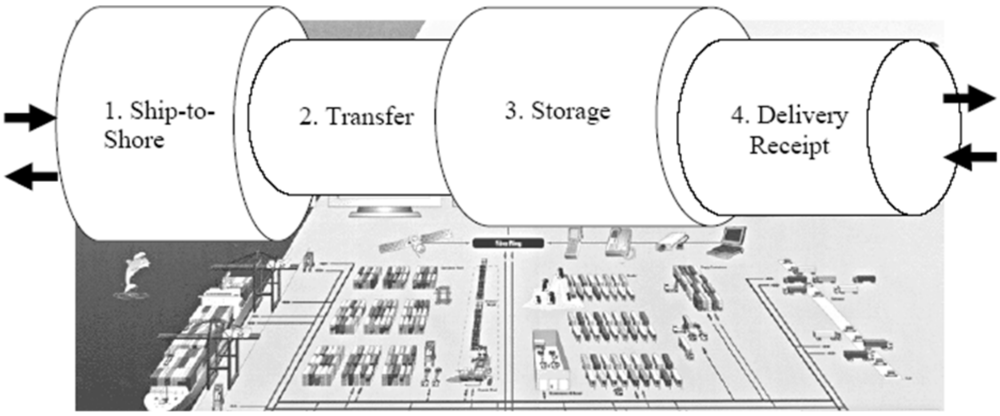


Figure 1.1: Container terminal divided into the main subsystems. Source: Henesey, 2004.

Although port container terminals greatly differ by the type of handling equipment employed and geometric size and layout, processes and terminal operations have several aspects in common among container terminals, which are briefly described as follows:

- **Ship to shore subsystem** (quayside operations): When a containership arrives at the port, it has to moor at the quay, which is made up of berthing positions alongside. The loading and unloading of containerships is carried out by quay cranes (QCs) which take the containers off the containerships or off the deck. QCs are used both in automated and in manned terminals and are manned because the automation of this process encounters practical problems, such as the exact positioning of containers.

The process of loading or unloading containers to/from the container ship is conducted according to a stowage plan previously analyzed by the terminal operator and shipping company.

- **Transfer subsystem** (transport operations): Once the inbound containers are taken off the containership, they are transferred from the QCs to vehicles that travel between the ship and the storage yard. Depending on the characteristics of the terminal (manned or (semi)automatic), containers can be transferred to the yard by multi-trailer systems with manned trucks, automated guided vehicles (AGVs), automated lifting vehicles (ALVs) which are capable of lifting a container from the ground by themselves or by using straddle carriers (SC). Transportation equipment is also used to move containers from the yard to the gate and, when needed, to relocate containers within the storage area. This process can also be executed in reverse order, namely loading export containers onto a ship or loading and unloading transshipment containers.
- **Storage subsystem** (storage and stacking operations): Because the moment of loading and unloading a vessel does not always correspond to the moment of loading the hinterland mode, containers need to be stored in the terminal. Thus, the storage yard serves as a buffer for loading, unloading and transshipping containers. Two ways of storing containers can be distinguished: storing on a chassis and stacking on the ground. With stacking on the ground containers can be piled up, which means that not every container is directly accessible, unlike under the chassis system.

  Usually, the container yard is served by several yard cranes (YCs) such as rubber-tired or rail-mounted gantry cranes (RTG/RMG), SC or automated stacking cranes (ASC) in the case of an automated container terminal. The equipment used to operate the yard depends on the level of utilization: intensive yard terminals require a high storage capacity and these are mainly operated by RMGs or RTGs; by contrast, extensive yard terminals require lower storage capacity and are these are typically operated by SC. Consequently, the organization of the storage space and layout of the terminal will differ.

  The process of storing (or retrieving) a container includes the time for adjusting the RTG, picking up the container, moving toward the allocation place and downloading the container. Since a container must be allocated to (or picked up from) a certain place at the block, it may be necessary to relocate one or more other containers to access that container. This means a higher operating time and cost for RTGs.
- **Delivery and receipt subsystem** (hinterland operations): Finally, inbound containers have to be transported from the storage yard to other modes of transportation, such as barges, rail and road in an area called the gate, where containers are received and delivered. When a driver of an external truck (train or barge) requests an inbound container, an inter-terminal vehicle has to transport the target container from the storage yard. This process differs according to the layout of the terminal. Usually, it takes too much time because YCs must remove the containers on top of the target container (rehandling moves), increasing operational cost and the turnaround time of truckers.

In the reverse order, when an outbound container arrives at the terminal by truck or train, the container is identified and registered at the land gates. Then, depending on the layout and terminal organization, the container will be picked-up by internal transportation equipment or by a YC from block lanes or transfer points within designated the blocks.

1.2.2 Layout of container terminals

In general terms, two different types of yard layout are defined according to the position in which storage blocks are laid out regarding the quay line: parallel and perpendicular yards. The layout of container terminals varies according to the region where the terminal is situated, container throughput, morphological layout, demands of transportation companies, and type of terminal with regard to handling and transportation equipment (automated, semi-automated or conventional terminals).

For example, many automated and semi-automated container terminals in Northern Europe, such as the ECT Delta Terminal and Euromax Terminals in Rotterdam, the Container Terminal Altenwerder (CTA) in the port of Hamburg and the Barcelona Europe South Terminal use the perpendicular layout because of its simple traffic control. However, the majority of container terminals in Eastern Asia utilize the parallel layout such as the Newport in Busan (South Korea) and several container terminals at the port of Hong Kong. Complementarily, many medium-sized terminals commonly use the all-SC system option, such as the Container Terminal of Barcelona (TCB).

The main characteristics of each type of terminal layout are summarized as follows:

1) The **parallel yard layout** is characterized by the following aspects:
   - Storage blocks are laid out parallel to the quay.
   - YCs can move from one block to another.
   - The traffic areas for receiving or delivering containers are placed alongside blocks; therefore internal and external trucks go through aisles to pick-up or drop-off the target container.
   - Storage blocks are dedicated to either inbound or outbound containers (no mixed blocks).
2) The main attributes of the **perpendicular yard layout** are:
   - Storage blocks are laid out perpendicular to the quay.
   - The number of YCs is fixed for each storage block.
   - Internal and external trucks cannot enter the storage area and delivery and receipt operations take place at the edge of each block (transfer point areas).
   - Inbound and outbound containers are mixed in the same block. Generally, the bays close to the waterside are devoted to outbound containers, while inbound containers will be placed close to the landside.

For both terminal layouts, the container yard is divided into areas called blocks. A block can be considered to be the basic unit of storage space (Lee and Kim, 2010b). Usually terminals divide their available storage yard into import container blocks and, on the other side, export and transshipment blocks. Each block is organized in bays (length) and rows (width). The number of bays is equivalent to the number of slots and each bay has several stacks in which containers can be placed one over another. In this thesis, the term sub-block will be used to refer to a group of bays.

Figure 1.2 depicts how a typical container yard with a perpendicular layout is distributed. Petering (2009) stated in his study that the optimal block width ranges from 6 to 12 rows, depending on the amount of equipment deployed in the yard, but the common actual value is within the range 6 to 9 and a typical block is about 40 slots long. In each stack, containers are stacked from 3 to 6 tiers high depending on the span of the YC.

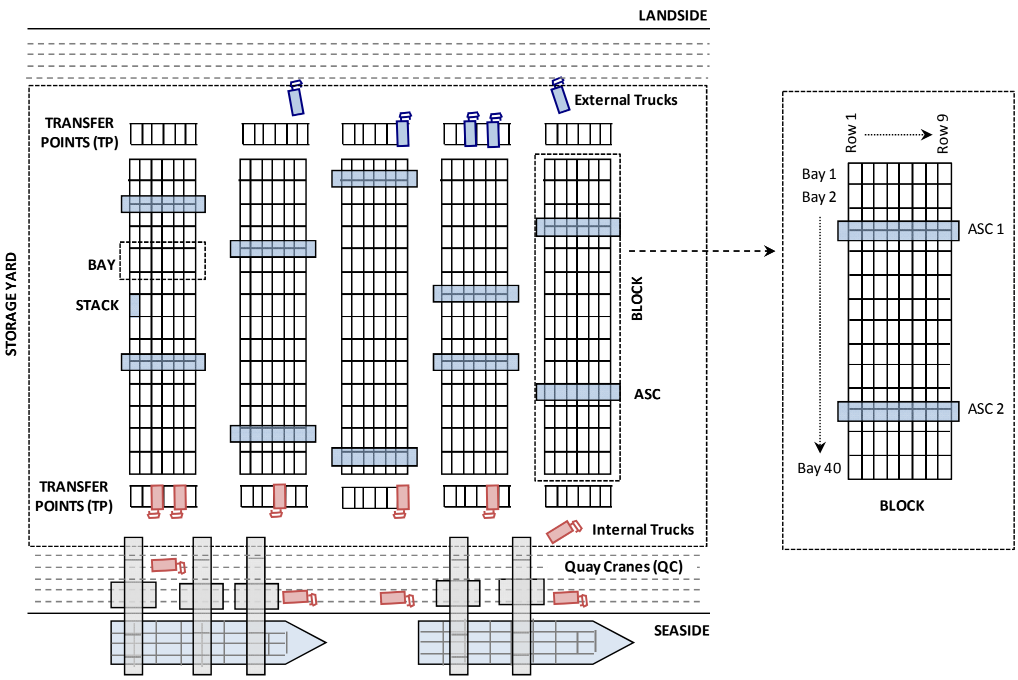


Figure 1.2: An illustration of a container terminal with a perpendicular layout and block detail.

1.2.3 Planning problems and decision making levels in container terminals

As introduced in the previous section, a container terminal represents a complex system with highly dynamic interactions between all the different types of transportation, handling equipment, storage units and uncertain information about future events.

Hence, many decision problems arise. There are three different decision-making levels based on the time horizon involved: namely strategic (long-term), tactical (mid-term) and operational (short-term). This classification has been considered by several researchers such as Meersmans and Dekker (2001) and Vis and De Koster (2003) for different container handling terminal operations.

They established that at the strategic level the terminal layout and material handling equipment selection (design of the terminal) should be defined, where the time horizon involved covers several years, whereas the tactical and operational levels cover a day to months and daily decisions, respectively. In addition, Meersmans and Dekker (2001) suggested considering another decision level related to real-time operations such as the schedule for QCs along with resources and drivers.

In such a context, Murty et al. (2005) mentioned that operative decisions planned in advanced by terminal operators (a few weeks before the vessel arrival time) may be modified by real-time decisions, since current information about terminal activities cannot be defined in advance due to the uncertainty that characterizes terminal operations.

Similar to the abovementioned decision-making levels, Günther and Kim (2006) divided the planning and control levels in container terminals into three categories (terminal design, operative planning and real-time planning). In general terms and according to those expository update papers of operation research methods in containers terminals (Steenken et al., 2004; Günther and Kim, 2006; Stahlbock and Voβ, 2008), each category may include the following issues:

- **Terminal design** problems take place in the initial planning stage of the terminal and these are analyzed from an economic and technical feasibility and performance point of view. The main issues and topics related to this level are: terminal layout, handling and transportation equipment choice, berthing and storage capacity, assisting and IT systems and multi-modal interfaces.
- **Operative planning** problems comprises planning procedures for performing the different logistics processes. Because of the complexity of operations, the entire logistics control system is subdivided into various modules for the different types of subsystems or resources: allocation problems (ship planning process), crane split and assignment, stowage planning and sequencing, storage and stacking logistics problems and workforce scheduling.
- Finally, **real-time planning** decisions are related to those logistics activities that must be solved within a very short time span such as the assignment of transportation orders to vehicles or vehicle routing and scheduling, the assignment of storage slots to individual containers and the determination of detailed sequences for QCs and stacking cranes.

In conclusion, a terminal operator faces many decisions to run terminal operations and processes efficiently. To satisfy its customers and to maximize profit, the operator has to strive for decisions that lead to a maximum customer satisfaction level at minimum costs. However, those two objectives are conflicting and the operator has to find the best way to achieve both.

1.3 Research scope of the thesis

This thesis is focused on the optimization of the storage yard subsystem which is a complex resource considered to be the key point of container terminals since it allows synchronizing handling and transport operations for import and export flow working as a buffer.

As is well known, storage operations in container terminals involve various resources such as QCs, YCs, transport vehicles, storage space and driving lanes and their performance directly affects other terminal processes such as vessel, external trucks and train operations. Hence, it can be stated that the efficiency of the whole terminal is mainly ruled by the efficiency of storage yard performance, which is considered to be a measure of a terminal's competitive strength (Chen et al., 2003).

For instance, the highest priority objective in port container terminals is the minimization of vessel turnaround time. This indicator directly depends on the productivity of QCs involved in the operations, but it also depends on the performance of YCs and then on the synchronization of QCs and YCs with the transport handling equipment. For this reason it is greatly important to guarantee that yard operations are processed efficiently and this will be achieved by optimizing the storage yard management

In particular, the following decision-making problems shown in Table 1.1 are analyzed in depth in the present thesis. Some comments are described below.

Table 1.1: Decision-making problems analyzed in the thesis

Decision making problem	Level	Category
Determination of the optimal storage space capacity	Strategic	Terminal design
Allocating storage strategies for import containers	Tactical and operational	Operative planning
Storage pricing policies for import containers	Strategic and tactical	Operative planning

- The first problem consists of determining the optimal storage capacity. This kind of decision is highly important because the productivity and efficiency of handling operations depends on it, but unfortunately, it is made with inaccurate information. Therefore the workflow forecasting dealing with stochastic effects becomes one of the main important issues in this stage.
- The second and third issues belong to the storage and stacking logistics problem. The objective of allocating storage strategies is to decide where to stack containers, bearing in mind the amount of rehandling movements generated. These policies take into consideration all the available information with regard to the arrival and departure time and average length of stay; however, for import containers, this information is uncertain which makes the process more difficult.
- Finally, the storage pricing problem consists of introducing a pricing scheme for temporary storage in order to reduce the average length of stay and thus, reducing yard congestion. It is recognized that customers respond to pricing changes by reducing storage time, which is the final target of terminal operators.

1.4 Main contributions of the thesis

The major contributions of the present thesis to the literature are introduced below:

1) First, this thesis introduces an analytical model, based on a probabilistic and statistical approach, to **forecast the yard inventory** of a container terminal.

   Differently from previous approaches and simulation models, it deals explicitly through a mathematical formulation with the stochastic effects and seasonal fluctuations in yard inventory and assumes that multiple vessels arrive randomly and separately at the terminal with an uncertain amount of unloaded containers.

   Practical equations are provided, which will allow planners and terminal operators to estimate yard inventory fluctuations and to predict yard inventory peaks without requiring detailed simulation models.

   In addition, this thesis also makes use of the potential of extreme value theory to improve the knowledge of yard inventory behavior and estimate the likelihood of yard inventory peaks over a period, which is interesting in stochastic analysis and future predictions, for instance, to determine the optimal storage yard capacity.

2) Regarding **storage yard planning and design**, this thesis proposes an optimization model to determine how much space should be provided, separately, for the import area and export and transshipment storage area, considering the effect of space utilization on terminal performance. The objective is to minimize the total integrated cost. In addition, a mixed strategy is considered in the cost model in which private and rental storage space are combined.

   It should be mentioned that this issue has not been addressed by previous studies, since most of them have merely focused on equipment selection and layout design.

   From the results, it was found that:

   - Optimal storage space utilization for the export and transshipment area is higher than that for the import area. In addition, the optimal space utilization for the parallel layout is higher than that for the perpendicular layout because YC operating costs are higher for perpendicular layout.
   - Thus, the highest optimal storage space utilization is achieved for the export and transshipment area in the parallel layout. According to the numerical experiments it was about 65% of total capacity.
   - With regard to the comparison between the parallel and perpendicular layouts it was found that the space required for the perpendicular layout was 10% higher than that for the parallel layout although the total cost was 6% lower than that for the parallel layout.

3) The contributions of this thesis to the literature review related to the **storage allocation problem** for import containers are as follows:

   - An analytical model to determine the expected amount of rehandles when containers with different leaving probabilities are mixed in the same stack is developed. Previous methodologies consider that the probability is the same for all containers within the stack, which is not true in current container terminals.
   - Three new storage and stacking strategies are defined for inbound containers, allowing operations to be analyzed more in depth than the strategies developed in previous contributions (segregation and non-segregation). These strategies go one step further than the strategies defined by De Castilho and Daganzo (1993) since these utilize rehandling moves more intelligently by combining static and dynamic strategies. As can be seen in this thesis, by implementing dynamic allocating strategies the profitability of storage space will be much higher.
   - From the results, some policy actions and general rules are derived about how to organize the import storage yard with regard to the minimization of rehandling movements and operating costs. Depending on the average stacking height, vessel headway-to-container dwell time ratio and occupancy rate of the storage yard the optimal implementation of each new strategy is suggested.

4) Finally, the contributions of this thesis to the **pricing storage problem** for import containers are the following:

   - This thesis considers a generic schedule for the pricing storage problem which is characterized by a flat rate and afterwards a charge proportional to storage time. The generic case includes the practical storage charges used in terminals and those considered by other researchers.
   - The demand of the terminal yard is estimated by considering the main stochastic properties of the storage yard, as mentioned in the first contribution of this thesis. Nonetheless, in such a case, the formulation introduced also considers the migration to a remote warehouse when the storage charge is applied, which suppose an additional contribution.
   - Lastly, some recommendations for terminal operators are introduced about how to define the storage pricing schedule depending on the yard occupancy rate. Thus, different solutions are provided according to the congestion rate of the storage yard.

1.5 Publications from this thesis

The results and main contributions of this thesis have been published or accepted for publication in international journals and at international conferences of great interest to the research community related to port and container terminals.

1) Papers published in international SCI journals:

   - Saurí, S. and Martín, E. (2011) Space Allocating Strategies for Improving Import Yard Performance at Marine Terminals. Transportation Research E, 47: 1038–1057. ISSN: 1366-5545.
   - Saurí, S., Serra, J. and Martin, E. (2011) Evaluating Storage Pricing Strategies for Import Container in Terminals. Transportation Research Record, 2238: 1-7. ISSN: 0361-1981.
   - Martín, E., Salvador, J. and Saurí, S. (2014) Pricing strategies for storage at import container terminals with stochastic container arrivals. Transportation Research E, 68: 118–137. ISSN: 1366-5545.

2) Papers submitted and under reviewing process at international SCI journals:

   - Martín, E., Kim, K.H. and Saurí, S. (2014) Forecasting container inventory in container terminals. Proceedings of the 5th International Conference in Information Systems, Logistics and Supply Chain, Breda, The Netherlands.
   - Martín, E., Kim, K.H. and Saurí, S. Optimal space for storage yard considering inventory fluctuations and terminal performance. (expected to be submitted to a SCI journal in logistics and maritime transport)

1.6 Outline of the thesis

Once the main background of container terminals has been introduced and the objectives and contributions of the thesis are described, the remainder of this thesis is structured according to Figure 1.3.

In particular, chapter 2 summarizes the literature review and presents the major contributions from previous studies regarding each of the decision-making problems that are analyzed in this thesis. Special emphasis is given to the storage allocation problem, storage pricing problem and design of the storage yard which includes the terminal planning processes used to calculate the capacity of the storage yard by determining the potential workflow of the terminal. In chapter 3 an analytical model based on probabilistic and statistical functions is introduced to forecast the number of containers in the storage yard. Then, in chapter 4, the results from this model are used to determine the optimal storage space by considering space utilization regarding terminal performance.

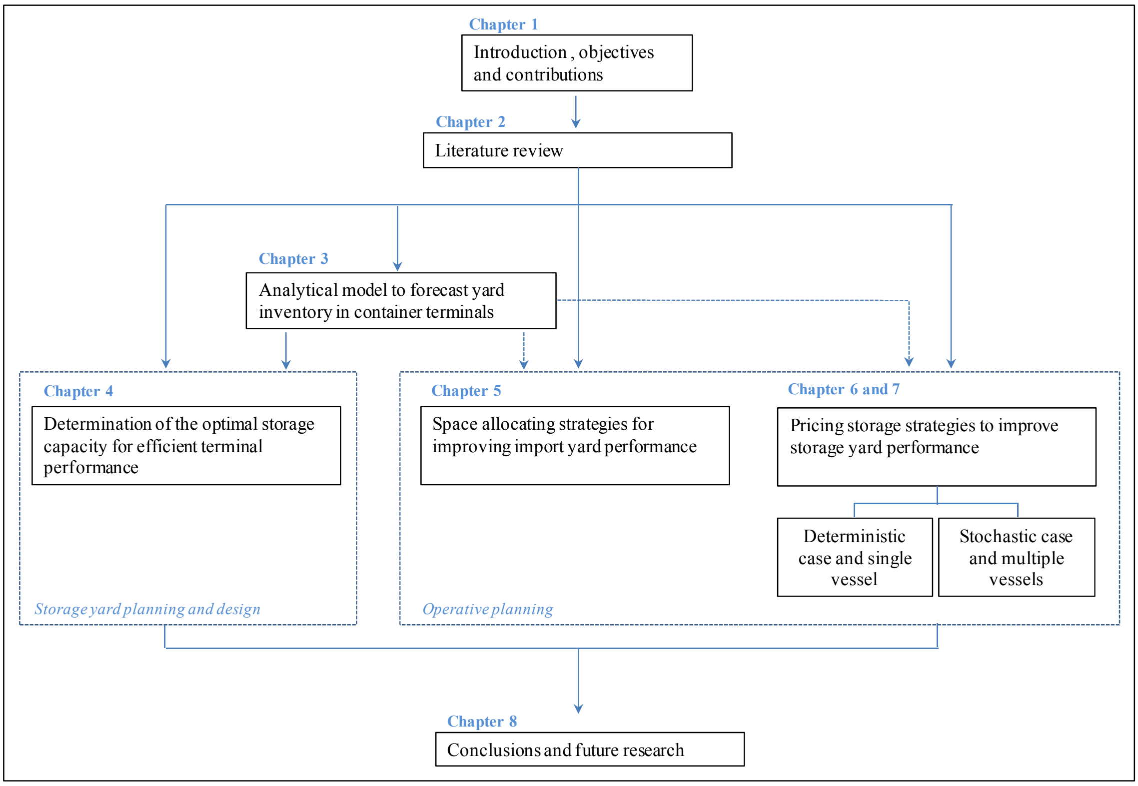


Figure 1.3: General overview of the thesis contents

Next, chapter 5 focuses on the inbound yard area and discusses how to allocate import containers in order to reduce the expected amount of rehandling movements during pick up operations. Moreover, three new storage strategies are introduced in order to improve the efficiency of handling processes and to guarantee an optimal profitability of storage space.

The final part of the research is related to the storage pricing problem which is analyzed from by considering two different approaches: chapter 6 analyzes the problem under the assumption that the container arrival process is deterministic and constant, while chapter 7 goes one step further, by considering the number of import containers arriving in the terminal as stochastic. A comparison between both approaches is included in the final part of chapter 7. Finally, overall conclusions and issues for future research are provided in chapter 8.

Chapter 2

Literature review

2.1 Overview

The goal of this chapter is to present a general summary of the state-of-the-art models, methodologies, strategies and contributions of previous studies with regard to the optimization of the storage yard. Those are the basis and starting points of the proposed solutions in this thesis.

According to the classification shown in Table 1.1, this literature review is organized into three blocks which are detailed as follows:

2.2 Storage yard planning and design

In container terminals, one factor affecting handling operations and their productivity is the layout and design of the storage yard, which is affected by previous decisions regarding terminal capacity and the type of equipment used for stacking operations, which are decisions that belong to the storage yard planning stage (Wiese et al., 2011).

Decisions with regard to yard planning take place in the initial stages when the size and capacity of the storage area are determined by considering primarily the trade-offs between the set-up and operational efficiency (Zhang et al., 2003). At that time, the amount of information available is small (low level of detail) and planners have to think about the annual workflow of the terminal dealing explicitly with stochastic effects regarding seasonal variations, peak factors or dwell time, which are usually surrounded with some uncertainty (Saanen, 2009; Schütt, 2011). Further, for yard planning, once the capacity of the main resources has been defined, the availabilities of the resources need to be checked in advance and allocated efficiently (Won et al., 2012).

According to current trends, the terminal planning process is mainly supported by advanced simulation-based modelling approaches as stated in Vis and de Koster (2003), Steenken et al. (2004), Stahlbock and Voβ (2008) and mainly in Angeloudis and Bell (2011). Saanen (2011) stated that a model is a simplified representation of reality that enables a designer or planner to investigate the subject in a cost-efficient way and allows for the consideration of the dynamics in the system.

In fact, several simulation and emulation models have been developed to be used during the planning stage of container yard. In particular, with regard to the calculation of yard capacity, Boll (2004) developed a simulation tool to determine the capacity of the container stacking area and quay, while Sgouridis et al. (2003) developed a simulation model of inbound container handling processes to optimize yard parameters (number of cranes, yard layout, stacking techniques and working shifts). Nonetheless, the disadvantage of simulation models is that the amount of input data is too large to represent the real situation of a container terminal and this makes the process complex.

Complementarily, Brinkmann (2005) developed a study in which the required storage capacity was approximately calculated for each type of equipment by considering the annual container turnover, average dwell time and a peak factor. Similarly, Chu and Huang (2005) derived a general equation to calculate the total number of container ground slots for different yard sizes with different handling systems (SC, RMG and overhead bridge cranes (OHBC)) based on different equipment dimensions, the transshipment ratio and average container dwell times.

Once the main decisions related to yard planning have been made, such as storage capacity and equipment choice, as analyzed by many authors such as Nam and Ha (2001), Liu et al. (2002), Vis and Harika (2004), Yang et al. (2004), Vis (2006) and Duinkerken et al. (2006), the next step for planners refers to yard layout design.

According to the literature review by Carlo et al. (2013), layout design studies can be divided into two streams: (1) overall yard layout design, including determining the number of blocks, and (2) block yard layout design.

In such a context, several studies of container terminal design can be found in the literature. Some compare the parallel and the perpendicular yard layouts by means of simulation such as Liu et al. (2004), who focused on automated transshipment container terminals and concluded that the perpendicular layout was better regarding QC moves and amount of horizontal transport equipment required.

By contrast, Petering (2008), who also analyzed both layouts in a transshipment terminal, stated that the parallel layout is preferable to the perpendicular layout, although in some cases a perpendicular layout outperforms a parallel one considering the QC rate. Further, Wiese et al. (2009) showed that in about 90% of cases where RTGs are used for stacking a parallel layout with transfer lanes is used and in 85% of these cases, a perpendicular layout is used for A-RMG systems.

Kim et al. (2008) also analyzed the optimal layout of container yards and presented a method for layout design where transfer cranes and yard trucks were used. To evaluate the yard layouts (parallel and perpendicular), truck travel cost and the relocation cost of transfer cranes were considered to be objective factors. The results of that paper showed that a parallel layout reduces expected travel distance and costs compared with a perpendicular layout.

Later, Lee and Kim (2013) determined the optimal layout of an entire container yard, which was specified by the dimensions of a block and the number of aisles (this yard parameter was also analyzed by Kim et al., 2008 and Wiese et al., 2011). They employed an optimization model to minimize the total cost of the terminal operator under certain constraints related to road truck turnaround time and transporter cycle time. The results of that paper showed that the performance of a parallel layout is superior to that of a perpendicular layout in terms of total cost. Further, for both layouts, block width needs to be increased for a better performance and a lower total cost in the yard.

Other interesting papers are those related to the design of the storage block, since YC cycle times as well as the travel distance of road trucks and transport vehicles depend on it. In such a context, Petering (2009) and Petering and Murty (2009) analyzed the influence of the width and length (number of bays) on the terminal performance (long-run average QC rate) in case of a parallel layout, respectively. In both studies a simulation model was used for the analysis of a transshipment container terminal. The results showed that the optimal block width ranges from 6 to 12 rows and block length between 56 and 72 since these values guarantee the highest QC work rate and greater YC mobility.

Lee and Kim (2010b) attempted to determine the optimal size of a single block (number of bays, rows and tiers) by considering the throughput requirement of YCs and block storage requirements. Two different objective functions were defined: maximizing the throughput capacity subject to the minimum block storage capacity and maximizing the storage capacity subject to a maximum truck waiting time. This paper also provided detailed formulas for the expected cycle times and variances of all YC operations, which depend on the block layout. However, in Lee and Kim (2010a) a much more detailed expression of the expectancies of YC cycle time can be found for the parallel and perpendicular layouts and for different block layouts, which are useful for estimating YC operating costs.

Finally, the paper of Kim and Kim (2002), in which the optimal size of storage space and number of transfer cranes to serve outside trucks for import containers were determined, must be highlighted. In this paper, the authors considered that the number of slots to be allocated to import containers remains constant (storage capacity) and that the required number of slots depends on the inventory profile of inventory containers. In order to get the optimal number of slots in a bay (decision variable) and the number of transfer cranes a cost model was developed in which space cost, the investment cost of handling equipment, the operating cost required to pick up and deliver import containers and customer's cost in terms of waiting cost are included in the objective functions. The numerical examples showed that the optimal number of slots per bay was 22 and 17 for minimizing terminal operator cost and integrated total cost, respectively.

As can be concluded from the literature review, many studies have focused on the storage yard design problem, with some addressing the yard planning problem. In such a context, authors and researchers have addressed this problem through simulation or optimization models but none of them has attempted to determine how much space should be provided for the storage area. Generally, researches assume a predetermined storage space utilization, which is estimated from historical data on other terminals already in operation.

2.3 Storage space allocation problem

The storage space allocation problem deals with those decisions about the best allocation of containers to storage spaces. This problem, according to Murty (1997), can be divided into two stages: (1) block assignment; and (2) storage position assignment. It aims to determine the optimal available position for each container arriving in the block in order to minimize the incidence of reshuffling that may arise while retrieving them later.

However, it should be mentioned that few studies have analyzed the problem as a whole, such as Chen and Lu (2012). The authors focused on the two decision making problems (allocating yard block and determining the exact location of containers) by developing a mixed integer programming model and a hybrid sequence stacking algorithm, whose performance was compared with random and vertical stacking algorithms.

Kim et al. (2000) analyzed the block assignment problem in the first stage by considering weight information. Dynamic programming was then used to solve the problem. Zhang et al. (2003) developed a rolling-horizon approach and formulated a mathematical programming model in order to determine the number of containers to be placed in each storage block in each time period (balance of workloads among blocks). Later, Bazzazi et al. (2009) extended previous works on different types of import containers by proposing a meta-heuristic approach (genetic algorithm) to solve the programming model. Nishimura et al. (2009) also analyzed this problem by using a heuristic based on the Lagrangian relaxation technique but this focused on transshipment flow.

By contrasting the abovementioned studies and the ones by Kim and Park (2003), Lee et al. (2006) and Lim and Xu (2006), the study of Woo and Kim (2011) assumed that the amount of space allocations was not given. They thus proposed methods based on four principles to determine space reservation, which was being used in practice, for locating outbound containers considering the fluctuation in container inventory level.

The location assignment problem is characterized by a combinatorial and dynamic nature, which makes the problem hard, even for its static version. The special case of the dynamic problem has to consider the processes of emptying stacks and the placement decisions of reshuffled containers combined with the original placement issue. As shown in the literature, the storage location assignment differs from import and export flows as well as for conventional and automated container terminals; therefore, several types of stacking strategies are analyzed separately as follows.

2.3.1 Space allocation problem for inbound containers

The space allocation problem for inbound containers, particularly the study of the rehandling problem for import containers, was first analyzed by De Castilho and Daganzo (1993), although Sculli and Hui (1988) developed the first relation between stacking height and reshuffles by using a simulation model.

De Castilho and Daganzo (1993) examined two different strategies for imports: non-segregation and segregation strategies, in which containers from different ships are separated. The non-segregation strategy allows inbound containers to be stacked on top of the containers already stacked whereas stacking inbound containers on top of containers that are already stacked is not allowed under the segregation strategy. The former strategy entails extra moves because the containers most likely to be retrieved are beneath inbound containers; while the latter reduces the number of extra moves but does require additional moves before the ships arrive in order to clear space for inbound containers. The authors concluded that the segregation strategy presents better solutions for less busy terminals, whereas the non-segregation strategy reduces the operating cost in terminals with massive arrivals of vessels and, therefore, containers. One of the objectives of this thesis is to identify when such segregation would be useful.

Regarding the calculation of rehandling moves, few methodologies and algorithms are available to evaluate the number of unproductive moves. Kim (1997) proposed a methodology, based on an exact procedure and a regression analysis to calculate the expected number of unproductive moves to retrieve a container and the total number of rehandles required to pick up all import containers in a random way. The main variables of the formulation were the number of containers, number of rows and distribution of stacking heights in the bay; these all applied only to a given initial stacking configuration. This paper showed that the total number of unproductive moves directly depends on the stacking height and number of rows; hence, it can be concluded that higher stacks increase handling effort because the number of unproductive moves increases proportionally.

Similar to that developed by Kim (1997), a more conventional method has been used to quantify the overall amount of replacements (Index of Selectivity, IOS) (Watanabe, 1991). Later, Ashar (1991) opposed Watanabe's idea by stating that such an index must take into account factors such as storage density and handling convenience, which are decisive factors for quantifying efficiency in the storage subsystem. Therefore, such an accessibility index takes into account the amount of replacements based on the optimum relation between storage area density and unproductive movements.

For the segregation strategy, a new procedure for estimating the expected number of rehandles was applied by Kim and Kim (1999). This procedure tried to minimize rehandling moves by determining the optimum height of stacks. The formulation developed relates the optimum stacking height to the amount of rehandling moves. Both studies based their formulations on probabilistic methods and expected values and they both coincided in directly relating the average height of the stacks to the expected replacements.

Chen (1999) and afterwards Chen et al. (2000) tried to find the major causes of unproductive movements, and focused their study on import storage management. They found a trade-off between the available storage capacity and stacking height, which was directly related to the operation's efficiency. If import containers are stacked higher, the delivery operations carried out will entail several unproductive moves.

Aydin and Ünlüyurt (2007) tried to minimize the number of container relocations and total crane runs by using a branch and bound algorithm and heuristic rules. Alternatively, Imai et al. (2002, 2006) introduced the idea of probability and developed a mathematical programming model to estimate the number of rehandles, assuming the loading sequence had previously been defined.

Huynh (2008) introduced methods to evaluate the effects of storage policies and container dwell time on import throughput and rehandling productivity. The storage strategies studied were mixed and non-mixed. The main difference lies in the possibility of stacking inbound import containers on top of already stored containers. This paper showed the effect of dwell time on rehandling productivity by comparing the amount of import deliveries with the amount of import moves. A Monte Carlo simulation method was used to estimate the expected amount of rehandles.

2.3.2 Space allocation problem for outbound and transshipment containers

For outbound containers, Taleb-Ibrahimi et al. (1993) described two different handling and storage strategies: the static space allocation strategy and dynamic strategy. From this study, it was found that the efficiency of each strategy depended on the container arrival pattern and that one of the main problems of the static strategy was the inefficient use of the storage yard; this can be virtually eliminated by moving containers within the storage yard by means of a dynamic strategy.

Dynamic strategies increase the handling effort but help make the most of the space available. Taleb-Ibrahimi et al. (1993) also presented procedures to calculate the maximum and average container accumulation, as well as the number of container slots that must be reserved for storing inbound containers. Complementarily, and with the aim of minimizing the number of rehandlings for outbound containers, Kang et al. (2006) proposed a method for deriving a good stacking strategy based on uncertain weight information. They applied a simulated annealing algorithm to find a good strategy for stacking export containers and developed a methodology to calculate the expected number of container rehandlings.

Wan et al. (2009) also studied the allocation problem, but their approach can handle the location problem for blocks, as well as for stacks. They gave the first integer program formulation of the static version of the location assignment problem analyzed by Kim and Hong (2006). Both studies proposed heuristic rules for relocating blocks during emptying processes. In addition to the static problem, Wan et al. (2009) extended their IP-based heuristic to the dynamic problem.

Following the same research line, Park et al. (2011) proposed an online search algorithm that dynamically adjusts the stacking policy represented as a vector of weight values for automated container terminals. They support the fact that online search is a good option in dynamic settings where there is not enough time for computation before taking actions. The proposed stacking policy is decided in two steps: block and slot determination. Finally, they introduced an evaluation function characterized by a weighted sum of four decision criteria in order to determinate the slot for an incoming container.

In addition, several studies have analyzed the location assignment problem for large terminals with marshaling areas. Stowage planning defines the containership loading process, and some terminals with low workloads prefer to pre-marshal export containers in order to minimize vessel loading times. In such a context, Kim and Bae (1998), Imai et al. (2002), Hirashima et al. (2006), Lee and Hsu (2007), Lee and Chao (2009), Han et al (2008) and Fan et al. (2010) deserve special attention.

Lastly, special mention should be given to the stacking strategies for automated container terminals investigated by Duinkerken et al. (2001) and Dekker et al. (2006).

They compared random and category stacking by using a simulation program and stacking algorithms. Containers within the same category (weight class, destination and type of container) according to the classification by Steenken et al. (2004) were stacked together, but exchange was also possible. The term exchangeable in this paper means that a container with a different category may be substituted when a container is requested. They concluded that a stacking algorithm is mainly influenced by the information available at the moment of stacking. Later, Borgman et al. (2010) investigated two concepts to increase efficiency and compared several stacking algorithms to allocate incoming containers to a stacking position by using a discrete-event simulation tool. These concepts (considered in online stacking rules) were related to the use of container departure time information, the trade-off between traveling and finding a position that limits the probability of reshuffles.

To close this section, Table 2.1 presents the most important contributions of existing papers on this issue.

Table 2.1: Summary of main studies related to the space allocating problem for inbound containers and contributions

References	Contributions			
	Storage strategy	**Objective**	**Rehandles calculation**	**Storage strategy applicability**
Castilho and Daganzo (1993)	Segregation strategy Non-segregation strategy	It presents methods for measuring the amount of handling effort required for each strategy proposed. The authors suggested the availability of both strategies regarding stacking height and arrival rate of inbound containers to the yard.	A method was developed to calculate the expected number of rehandles to retrieve a single container from the bay and secondly, to retrieve a several containers from a group of stacks. A probabilistic approach based on expected values and variability was considered. Expected rehandling and clearing movements were calculated	The segregation strategy seems to perform better when the arrival rate of inbound containers is small or when land is scarce and containers have to be stacked high as then the impact of clearing moves should be relatively smaller. The non-segregation strategy reduces handling effort for higher arrival rates and it favors in shorter stacks. For intermediate values of inbound arrival rates they said that the "best strategy" depends on average stack height.
Kim and Kim (1999)	Segregation strategy	Reducing the number of rehandles through efficient space allocation for static and dynamic space requirement. For each study case they found the optimal stacking height (which guarantee the minimum number of expected rehandles)	They derived a formula which describes the relationship between the height of stacks and the number of rehandles.	The advantages of the segregation strategy are the easy traffic control for the external trucks during the retrieval operation and the reduced number of rehandling operations, by preventing that old containers which are more likely to be picked up in the near future from being buried under the new ones.

References	Contributions			
	Storage strategy	Objective	Rehandles calculation	Storage strategy applicability
Huynh (2008)	Non-mixed storage policy Mixed storage policy	This paper analyzed the effect of container dwell time on rehandling productivity for each policy	A Monte Carlo simulation method is used to calculate the expected number of rehandles in order to consider the variances of expected values as a function of height, different probabilities and storage strategies.	The non-mixed storage policy was suggested to be applied when dwell time is high due to as dwell time increases rehandling productivity is better (lower throughputs) The mixed storage policy is suggested for low dwell times because as dwell time increases rehandling productivity becomes lower for this strategy (higher throughput).
Taleb-Ibrahimi et al., (1993)*	Static strategy Dynamic strategy	This paper quantifies the performance of storage strategies for outbound containers according to the amount of space and number of handling moves they require.		Dynamic strategies can virtually eliminate the wasted space by moving containers between storage areas in the yard (clearing moves, for example).

2.4 Storage pricing strategies

As shown in previous sections, some literature is available on storage and stacking logistics, while few researchers have addressed price scheduling for yard storage and the demand analysis.

Of the limited work in this field, the first example is the report produced by UNCTAD in 1975, which analyzed port pricing in the context of developing countries and laid the foundation for port pricing, together with the book written by Bennathan and Walters for the World Bank in 1979. They identified two basic approaches to port pricing aimed at promoting economic growth and seeking the maximization of port profit, at least, balanced budgets. In addition, they found that marginal cost pricing seems to be particularly appropriate for establishing the storage charges in transit sheds, although they did not analyze container storage.

Later, in a study more focused on storage pricing, De Castilho and Daganzo (1991) demonstrated that efficient pricing schemes can be helpful to avoid the abusive use of terminal storage areas, and showed that optimal shed pricing policies are affected by the capacity of sheds, user characteristics and availability of auxiliary warehouses.

The model developed by De Castilho and Daganzo (1991) assumed that flow and length of stay are independent of storage prices. Moreover, shippers' behavior and costs were examined when storage rent price functions changed, and a savings function was defined. Given a storage price function, the shipper was assumed to choose the duration of stay that would maximize their savings. Both non-discriminatory and variable price functions were applied. The total savings and costs were evaluated in two scenarios: with and without off-dock warehouses. It should be highlighted that transit sheds were first used by UNCTAD (1975) as an illustration of how pricing can contribute to the better utilization of port assets.

Holguín-Veras and Jara-Díaz (1999) analyzed the consistency of optimal pricing policies with space allocation constraints: space allocation and the pricing scheme were taken as a joint problem subject to the capacity constraint (determined by the space in the yard). Holguín-Veras and Jara-Díaz (2006) generalized this model by making the arrival rates dependent on the terminal storage charge (elastic arrivals). They demonstrated that optimal prices generally have three components that capture the different facets of storage pricing for intermodal terminals: the combined effect of willingness to pay and marginal cost (Ramsey's solution), capacity constraint and role of elastic arrivals, which is the last contribution of the authors. They showed that the relative rate of changes in arrival and dwelling times had a direct impact upon prices.

Kim and Kim (2007) proposed optimal storage pricing for import containers. The charge is based on the free-time limit (during which a container can be stored without charge) and the variable storage charge (depending on the time spent in the terminal). Customers face two storage-and-delivery schedules. One is stacking in the container yard and then direct delivery to the consignee. The other is for storage at the container yard only for the period of free storage, then moving to an off-dock warehouse and stacking for another period of time before delivery. The optimal prices for three schemes of administration are considered: (i) profit maximization for the terminal, (ii) profit maximization subject to a minimum service level and (iii) minimization of the total public cost. In these three different schemes, the optimal free period limit was found to be zero.

Finally, the contribution of Lee and Yu (2012) should also be noted. They suggested that earlier papers should not have taken the price for the external site as given and should not have ignored the price competition between the terminal and remote container terminal. Thus, they considered the competition between storage prices by developing a game-theory duopoly model of the Bertrand type, a non-cooperative game theory. In this study, two cases were considered: price-independent and price-dependent container dwell time. The latter case is particularly interesting for our study, as it considers the situation in which the customer tends to treat the container yard and remote container yard as long-term storage places, analyzing both price schemes and assuming that the customer make a random tolerance payment for every container (the container's dwell time is sensitive to storage prices). The objective in all cases is to decide on an appropriate price for the inbound container storage service, which maximizes the profits of the terminal yard and the remote container yard.

Overall, the main characteristics and particularities of the most relevant studies of the storage pricing problem are presented in Table 2.2.

Table 2.2: Summary of main studies related to pricing strategies for storage and contributions

References	Contributions			
	Demand function	**Cost and revenues functions**	**Yard tariff scheme**	**Objective function**
Castilho and Daganzo (1991)	The model assumes that the flow and length of stay are independent of storage prices			Maximization of system benefit Maximization of shed revenue
Holguín-Veras and Jara-Díaz (2006)	The number of containers arriving at the terminal are elastic to price (price-dependent)			
Kim and Kim (2007)	The model assumes that the length of stay follows a probability distribution function. Price-independent (customers minimize their own cost based on the price structure of the storage fee).	The operating cost in the limit capacity of the container terminal yard is mainly determined by the rehandle operations. Unlike previous studies, this study is based on a detailed cost model of handling activities in container yards.	Price schedule introduced has a zero flat rate (during the free-time limit, F) and then a time dependent rate	Maximization profit of the terminal operator and the same but subjected to a container service constraint. Minimization total public cost. Optimum value of time free-limit (F)
Lee and Yu (2012)	There are two different situations: • Dwell time is random and follows a probability distribution function (price-independent) • Inbound container's dwell time is sensitive to storage space (price-dependent) Other authors ignore price competition.	Container operation cost is a quadratic function of the dwell time. This paper consider the cost function used in Luo et al., (2010) and Kim and Kim (2007)	Price schedule introduced has a zero flat rate (during the free-time limit, F) and then a time dependent rate	Maximization profits of container yard and remote container yard (existence and uniqueness of the price equation) Storage prices with a competition environment (non cooperative game theory).

2.5 Summary and contributions

To sum up, this section introduced the main contributions and characteristics from the most important studies of the different issues and topics that belong to the research scope of this thesis. This is useful to indicate the basis of the thesis and to describe the contributions to the research community.

2.5.1 Storage yard planning and design

As can be derived from the literature review, previous studies of storage yard planning and design have merely focused on yard layout and equipment selection.

Nonetheless, the determination of storage capacity has been analyzed in a few studies through simulation models, in order to treat the stochastic effects, seasonal variations and peak factors that characterize yard inventory. However, this requires a large amount of detailed data involving tough development.

Moreover, the decision about how much space is provided to the import area and export and transshipment area has not yet been addressed. Thus, in such a context, the contributions to the literature review of this thesis are as follows:

1) Firstly, an analytical model based on a statistical and probabilistic approach is developed. This model considers the stochastic behavior of the storage yard by assuming that container arrival and departure processes are random.
2) Secondly, this thesis provides explicit and simple formulations for researchers, planners and terminal designers in order to forecast yard inventory over a certain period of time.
3) Thirdly, extreme value theory is adapted in order to estimate the likelihood that a particular extreme yard inventory value will occur in a given and representative period of time.

   This issue is especially important because one of the potential utilities of this thesis is determining the optimal storage capacity of the yard regarding storage space requirement.
4) Finally, a cost model for determining optimal storage space utilization is introduced. This cost model considers terminal performance, namely the effect of storage yard congestion on other terminal operations.

2.5.2 Storage space allocation for inbound containers

In general terms, two storage strategies are used for inbound containers: segregation and non-segregation. The applicability of both strategies was analyzed by de Castilho and Daganzo (1993), Kim and Kim (1999) and Huynh (2008) but these studies did not provide an accurate analysis of intermediate situations regarding traffic and dwell time. In addition, the strategies are static, and thus the profitability of storage space is not guaranteed.

In such a context, this thesis provides new allocating storage strategies in order to offer solutions for those cases that have not yet been analyzed in depth. These new strategies aim to utilize rehandling moves more efficiently by taking advantage of dynamic strategies that were firstly used for export containers by Taleb-Ibrahimi et al. (1993).

In particular, the following contributions regarding the space allocation problem are made in this thesis:

- First, three dynamic strategies are presented for import containers in order to cover those intermediate for which previous strategies are unsuitable (S1, S2 and S3).

  The objective of these strategies is to manage the storage yard efficiently by reducing the inefficiencies related to rehandling moves and by increasing the profitability of storage space.

- Second, an analytical model based on a probabilistic approach is proposed to calculate the expected number of rehandles when containers with different leaving probabilities are mixed in the same stack. Previous methodologies consider that all containers have the same chance of leaving the terminal.

Complementary to the usefulness of these generic strategies, the applicability of the new strategy is as follows:

- S1 and S2 are recommended for terminals with a short average stacking height and a ship headway-to-container dwell time ratio less than 0.5, or when container dwell is high.

- S3 becomes more preferable for terminals with a small storage area and high traffic volume (when storage capacity must increase by way of higher container stacking). In such a context, clearing moves are lower which demonstrates the advantage of dynamic strategies.

2.5.3 Storage pricing strategies for the storage of containers

As previously stated, the main contributions of this thesis to the storage pricing problem are as follows:

- A generic schedule with a flat rate and a charge proportional to storage time is developed. The flat rate can be zero or higher than zero, according to the objective function and occupancy rate of the yard. This pricing schedule includes the previous theoretic schedule and those currently used in container terminals.

  Differently from previous papers related to this issue (see Table 2.2), this thesis considers that:

- Two different assumptions are taken separately regarding the demand function. The first considers that demand is inelastic and thus independent of the storage charge, whereas the second one assumes that demand is reduced when a tariff is introduced, but not drastically since the terminal operator has some market power (in this case, a deterministic number of containers is considered).

- The analytical model introduced to estimate the demand of the storage yard considers the stochastic behavior of the yard by defining the input and output container flow as random variables. Furthermore, this model assumes multiple vessels (short-sea and deep-sea) that arrive randomly and separately with uncertain amounts of unloaded containers.
- In this thesis, regarding the cost and revenue functions, it is assumed that the operating and variable costs increase according to the occupancy rate of the storage yard in two different ways: linear for low occupations and afterwards exponentially for higher occupations (capacity shortages).
- Finally, in order to obtain the optimal value for the pricing parameters, two objective functions are defined: the profit maximization of the terminal operator and the minimization of the total integrated cost of the system (terminal operator and customers).

Chapter 3

An analytical model to forecast yard inventory in container terminals

3.1 Introduction

In container terminals, the storage yard is perceived as the most complex element. Storage operations involve various resources such as QCs, YCs, transport vehicles, storage space and driving lanes. Exactly for that reason, the efficiency of yard operations sometimes can be considered to be a measure of a terminal's competitive strength because it affects the rest of terminal performance.

One factor affecting handling operations and its productivity is the design and layout of the storage yard which, at the same time, is affected by previous decisions regarding terminal capacity and the type of equipment used for stacking operations (Wiese et al., 2011).

However, the size and capacity of the storage yard are determined in the initial planning stages when the available information and level of detail are too small. Moreover, planners have to think about the annual workflow of the terminal dealing explicitly with stochastic effects regarding seasonal variations, peaks factors or dwell time which usually are surrounded with some uncertainty.

If it is also taken into account that the size of containerships is becoming larger and that container terminals currently have to cope with unprecedented container volumes and increasing demand, the forecasting of yard inventory and its fluctuations over a period are really important to assure the efficient use of the main yard and terminal resources.

Simulation models enable planners to investigate a determinate problem in a cost-efficient way and allow for consideration the dynamics in the system, but it requires collecting large amount of data in order to reproduce real terminal processes.

Thus, the goal of this chapter is to forecast the yard inventory of a container terminal by using a mathematical formulation based on a probabilistic and stochastic approach. The formulation developed in this thesis will allow to planners and terminal operators to estimate yard inventory fluctuations and to predict extreme inventory values without requiring detailed simulation models. Thereby, an analysis of extreme inventory values is presented for improving the knowledge of extreme yard inventory behavior and to estimate the likelihood of peaks over a period.

The rest of the chapter is structured as follows: section 3.2 provides the mathematical formulation to estimate the number of containers stored in the yard at any time (yard inventory). In Section 3.3, extreme value theory is applied to yard inventory data in order to analyzed peaks behavior and in Section 3.4, a numerical case is illustrated. Finally, Section 3.5 discusses the main contributions and potential future applications.

3.2 Estimation of the container yard inventory

In this section, a formulation based on a statistical approach to estimate the inventory yard, in terms of number of containers, is presented. Additionally, the extreme value theory will be used to analyze the inventory peaks behavior of the storage yard.

3.2.1 Assumptions and notation

Because different types of containers are stored in the yard different patterns of accumulation (outbound) and dissipation (inbound and transshipment) will be considered for calculating storage space requirement (see Figure 3.1).

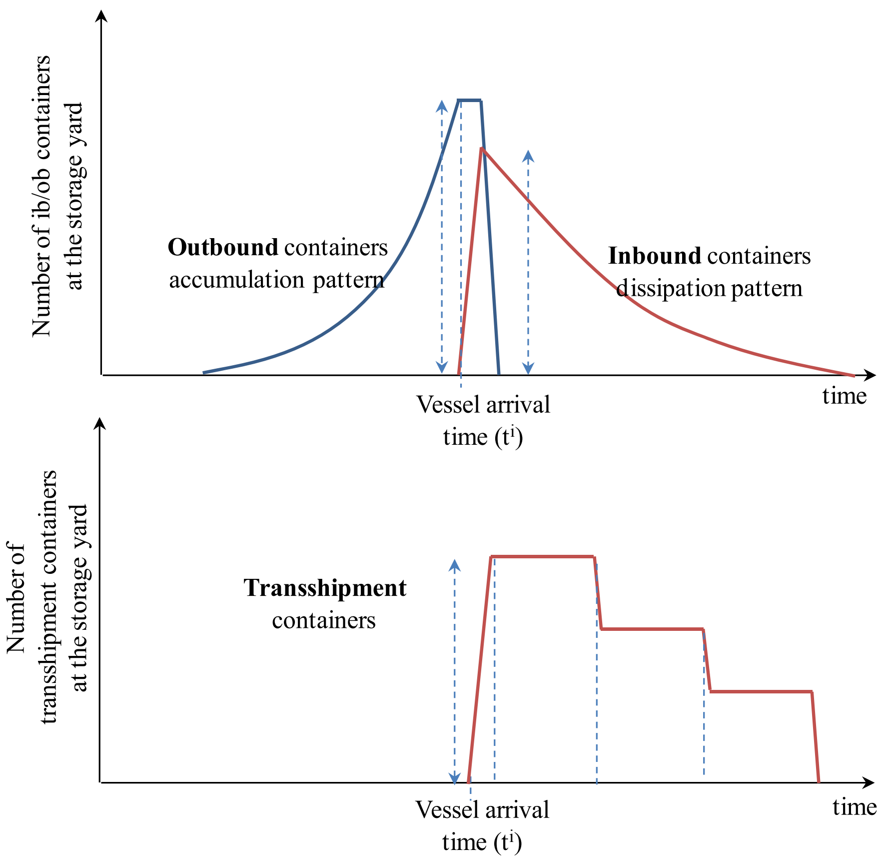


Figure 3.1: Container accumulation and dissipation patterns from the storage yard related to a single vessel

Therefore some assumptions are required, that is:

1) The vessel inter-arrival time is constant.
2) Inbound, outbound and transshipment container dwell time is considered as a random variable which, in this chapter, is approximated to a Weibull distribution function in which the Exponential distribution is considered as a particular case. The distributions can be derived from historical data.
3) The number of loading (outbound) and unloading (inbound and transshipment) containers per vessel is also considered as a random variable which follows a Weibull distribution function according to historical data. In addition, the amount of loaded/unloaded container per vessel will depend on the type of vessel, that is: deep-sea and short-sea.

   Assumptions (2) and (3) characterize the stochastic properties of the storage space requirement.

Then the notation for data and variables within the formulation is presented below:

v:	overall number of vessels arriving at the terminal during the forecasting period
i:	index of a vessel, which is covered by $[1, v]$ (i^{th} arrival position).
z:	index for the type of vessel: deep-sea or short-sea.
$\mathrm{N}^{\mathrm{I}}_{\mathrm{i(z)}}, \mathrm{N}^{\mathrm{O}}_{\mathrm{i(z)}}, \mathrm{N}^{\mathrm{T}}_{\mathrm{i(z)}}$:	random variables which represents the amount of inbound (I), outbound (O) and transshipment (T) containers (un)loaded from/to the i^{th} vessel of type *z*. λ_z , k_z are the distribution parameters.
$\mathrm{T}^{\mathrm{I}}, \mathrm{T}^{\mathrm{O}}, \mathrm{T}^{\mathrm{T}}$:	random variables which represent the inbound, outbound and transshipment container dwell time, respectively (length of time that a container remains at the storage yard after/before being unloaded /loaded from/to a vessel).
t^i:	arrival time of the i^{th} vessel at the terminal.

3.3 Space requirement associated to a single vessel

This part focuses on the calculation of the expected number of containers related to a single vessel in the yard. The development of the formulation is divided according to the three different kinds of containers:

3.3.1 Inbound containers

The amount of containers in the storage yard depends on the container dwell time. Therefore, assuming that the time a container remains at the storage yard (dwell time) is typically considered to be a non-negative continuous random variable whose probability distribution function ($F^{\mathrm{I}}(t) = Pr(T^{\mathrm{I}} \leq t)$) is approximated to a Weibull distribution, the probability that an inbound container has not left the terminal by time t (that is, a container is still stored in the yard), can be obtained by the survivor function ($Pr\left(T^{\mathrm{I}} > t\right) = 1 - F^{\mathrm{I}}(t)$=$S^{\mathrm{I}}(t)$).

Next, bearing in mind both probabilistic functions ($F^{I}(t)$ and $S^{I}(t)$) and its conceptual meanings, we proceed to calculate the probability that x_I, $x_I \in [0, n^{\mathrm{I}}_{\mathrm{i(z)}}]$, inbound containers are still stored at the yard at time t (assuming that the amount of unloaded containers from the *i*th vessel is the stochastic variable $N^{\mathrm{I}}_{\mathrm{i(z)}}$). This probability can be obtained as follows:

$$P^{x_I}_{i(z)}(t) = \sum_{n^{\mathrm{I}}_{\mathrm{i(z)}}} \left(\left(\binom{n^{\mathrm{I}}_{\mathrm{i(z)}}}{n^{\mathrm{I}}_{\mathrm{i(z)}} - x_I} [F^{I}(t - t^{i})]^{\left(n^{\mathrm{I}}_{\mathrm{i(z)}} - x_I\right)} [S^{I}(t - t^{i})]^{x_I} \right) Pr\left[n^{\mathrm{I}}_{\mathrm{i(z)}}\right] \right) \qquad t > t^{i} \qquad [3.1]$$

where the term $\left[F^{I}\left(t - t^{i}\right)\right]^{\left(n^{\mathrm{I}}_{\mathrm{i(z)}} - x_I\right)}$ represents the probability that $(n^{\mathrm{I}}_{\mathrm{i(z)}} - x_I)$ inbound containers have left the container terminal yard at time t (being picked-up from an external truck in independent successes); and the term $\left[S^{I}\left(t - t^{i}\right)\right]^{x_I}$ represents the probability that x_I inbound containers are still stored in the yard at time t. The combinatorial number at the beginning of expression [3.1] indicates all those different cases in which s_{ib} containers could be stored in the yard regarding the amount of unloaded containers from the i^{th} vessel ($n^{\mathrm{I}}_{\mathrm{i(z)}}$).

Because of the number of unloaded containers is considered a stochastic variable, it is required to consider the probability that $n^{\mathrm{I}}_{\mathrm{i(z)}}$ containers are unloaded. This is why the term $Pr\left[n^{\mathrm{I}}_{\mathrm{i(z)}}\right]$, which shows that chance ($Pr\left[N^{\mathrm{I}}_{\mathrm{i(z)}} = n^{\mathrm{I}}_{\mathrm{i(z)}}\right]$), is included in expression [3.1].

Moreover, as this variable is approximate to a continuous distribution function, it is required to make a correction for continuity because of the amount of containers is a discrete variable. For such a reason, the following calculation will be carried out:

$$\begin{aligned} Pr\left[N^{\mathrm{I}}_{\mathrm{i(z)}} = n^{\mathrm{I}}_{\mathrm{i(z)}}\right] &= Pr\left[\left(\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}} - 0.5\right) < \mathrm{N}^{\mathrm{I}}_{\mathrm{i(z)}} < \left(\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}} + 0.5\right)\right] \\ &= G^{\mathrm{I}}\left(\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}} + 0.5\right) - G^{\mathrm{I}}\left(\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}} - 0.5\right) \end{aligned} \qquad [3.2]$$

where $G(\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}})$ is the probability that the i^{th} vessel will unload $\mathrm{n}^{\mathrm{I}}_{\mathrm{i(z)}}$ containers or less.

Lastly, the expected number of inbound containers at time t in the storage yard unloaded from the i^{th} vessel of type *z* (deep-sea or feeder) is:

$$E\left[C^{\mathrm{I}}_{i(z)}(t)\right] = \begin{cases} \displaystyle\sum_{x_I=0}^{n^{\mathrm{I}}_{\mathrm{i(z)}}} x_I \cdot P^{x_{\mathrm{I}}}_{i(z)}(t) & t > t^{i} \\ 0 & t \leq t^{i} \end{cases} \qquad [3.3]$$

However, expression [3.3] could be formulated in a different way in order to make calculations easier. Because we are interested in the total expected number of inbound containers at any time t, expression [3.1], which is really useful to estimate the probability that an exact amount of containers is stored in the yard but difficult to calculate due to the combinatory approach, can be avoided. In such context, by considering inbound container dwell time, the new expression to estimate the amount of inbound containers at the yard is:

$$E\left[C_{i(z)}^{\mathrm{I}}(t)\right]=\begin{cases}\sum_{n_{\mathrm{i(z)}}^{\mathrm{I}}}\left(n_{\mathrm{i(z)}}^{\mathrm{I}}\cdot Pr\left[n_{\mathrm{i(z)}}^{\mathrm{I}}\right]\right)\left[S^{\mathrm{I}}(t-t^{i})\right] & t>t^{i}\\ 0 & t\leq t^{i}\end{cases} \quad [3.4]$$

where $\sum_{n_{\mathrm{i(z)}}^{\mathrm{I}}}\left(n_{\mathrm{i(z)}}^{\mathrm{I}}\cdot Pr\left[n_{\mathrm{i(z)}}^{\mathrm{I}}\right]\right)$ is equivalent to $E\left[n_{\mathrm{i(z)}}^{\mathrm{I}}\right]$.

Finally, by considering the problem assumptions, expression [3.4] can be rewritten as:

$$E\left[C_{i(z)}^{\mathrm{I}}(t)\right]=$$

$$=\begin{cases}\sum_{n_{\mathrm{i(z)}}^{\mathrm{I}}}\left(n_{\mathrm{i(z)}}^{\mathrm{I}}\cdot\left(e^{-\left(\frac{n_{\mathrm{i(z)}}^{\mathrm{I}}-0.5}{\lambda_z^{\mathrm{I}}}\right)^{k_z^{\mathrm{I}}}}-e^{-\left(\frac{n_{\mathrm{i(z)}}^{\mathrm{I}}+0.5}{\lambda_z^{\mathrm{I}}}\right)^{k_z^{\mathrm{I}}}}\right)\right)\left(e^{-\left(\frac{t-t^{i}}{\lambda_T^{I}}\right)^{k_T^{I}}}\right) & t>t^{i}\\ 0 & t\leq t^{i}\end{cases} \quad [3.5]$$

where k_z^I and λ_z^I are the shape and scale parameter of the distribution function which fits the number of unloaded containers per vessel and k_T^I and λ_T^I are the parameters of the dwell time distribution.

3.3.2 Outbound containers

Differently from inbound containers which arrive in a bunch and are dissipated one by one from the vessel arrival time onwards, outbound containers arrive individually and are being accumulated in the yard until the vessel loading time. Then, the dwell time of outbound container runs from vessel arrival time (t^i) backwards (i.e. if an outbound container dwell time is one day, it means that it just arrived to the terminal one day before being loaded to vessel).

Similarly to the formulation introduced for inbound containers but taking into account previous differences between dwell time patterns, the probability that x_O, $x_O\in[0,n_{\mathrm{i(z)}}^{\mathrm{O}}]$, outbound containers are already stored in the yard at time t from the i^{th} vessel is:

$$P_{i(z)}^{x_O}(t)=\sum_{n_{\mathrm{i(z)}}^{O}}\left(\left(\binom{n_{\mathrm{i(z)}}^{O}}{n_{\mathrm{i(z)}}^{O}-x_O}\left[F^{O}(t^{i}-t)\right]^{\left(n_{\mathrm{i(z)}}^{O}-x_O\right)}\left[S^{O}(t^{i}-t)\right]^{x_O}\right)Pr\left[n_{\mathrm{i(z)}}^{O}\right]\right) \quad t>0 \quad [3.6]$$

where $\left[F^{O}\left(t^{i}-t\right)\right]^{\left(n_{\mathrm{i(z)}}^{O}-x_O\right)}$ is the probability that $\left(n_{\mathrm{i(z)}}^{O}-x_O\right)$ outbound containers have not arrived yet at the terminal because its length of stay at the terminal is lower than $\left(t^{i}-t\right)$, that is $Pr\left(T^{O}\leq\left(t^{i}-t\right)\right)$. Next, the term $\left[S^{O}\left(t^{i}-t\right)\right]^{x_O}$ represents the probability that x_O containers are already stored in the yard and finally, the term $Pr\left[n_{\mathrm{i(z)}}^{O}\right]$ indicates the probability that $n_{\mathrm{i(z)}}^{O}$ outbound containers could be loaded to the i^{th} vessel of type z at time t^i. In the same way as in case of inbound containers, this probability is calculated according to:

$$Pr\left[N_{\mathrm{i(z)}}^{O} = \mathrm{n}_{\mathrm{i(z)}}^{O}\right] = Pr\left[\left(\mathrm{n}_{\mathrm{i(z)}}^{O} - 0.5\right) < \mathrm{N}_{\mathrm{i(z)}}^{O} < \left(\mathrm{n}_{\mathrm{i(z)}}^{O} + 0.5\right)\right] \\ = G^{ob}\left(\mathrm{n}_{\mathrm{i(z)}}^{O} + 0.5\right) - G^{O}\left(\mathrm{n}_{\mathrm{i(z)}}^{O} - 0.5\right) \quad [3.7]$$

where $\mathrm{G}^{O}\left(\mathrm{n}_{\mathrm{i(z)}}^{O}\right)$ is the cumulative distribution function (Weibull distribution in this chapter) evaluated at $\mathrm{n}_{\mathrm{i(z)}}^{O}$.

Finally, the expected number of outbound containers that will be loaded to the i^{th} vessel of type z at time t is:

$$E\left[C_{i(z)}^{O}(t)\right] = \begin{cases} \sum_{x_O=0}^{\mathrm{n}_{\mathrm{i(z)}}^{O}} x_O \, P_{i(z)}^{x_O}(t) & 0 < t \le t^i \\ 0 & t > t^i \end{cases} \quad [3.8]$$

Similarly to the formulation for inbound containers, expression [3.8] can be rewritten as [3.9] in order to simplify calculations:

$$E\left[C_{i(z)}^{O}(t)\right] = \begin{cases} E\left[n_{\mathrm{i(z)}}^{O}\right]\left[S^{O}(t^i - t)\right] & 0 < t \le t^i \\ 0 & t > t^i \end{cases} \quad [3.9]$$

where $n_{\mathrm{i(z)}}^{O}$ are all those values that the random variable $N_{\mathrm{i(z)}}^{O}$ include and $S^{O}\left(t^i - t\right)$ is the survival function related to outbound dwell time (T^{O}).

Finally, by considering the problem assumptions expression [3.9] can be redefined as:

$$E\left[C_{i(z)}^{O}(t)\right] = \\ = \begin{cases} \sum_{n_{\mathrm{i(z)}}^{O}} \left(n_{\mathrm{i(z)}}^{O} \cdot \left(e^{-\left(\frac{n_{\mathrm{i(z)}}^{O} - 0.5}{\lambda_z^{O}}\right)^{k_z^{O}}} - e^{-\left(\frac{n_{\mathrm{i(z)}}^{O} + 0.5}{\lambda_z^{O}}\right)^{k_z^{O}}} \right) \right) \left(e^{-\left(\frac{t^i - t}{\lambda_T^{O}}\right)^{k_T^{O}}} \right) & 0 < t \le t^i \\ 0 & t > t^i \end{cases} \quad [3.10]$$

where k_z^{O} and λ_z^{O} are the shape and scale parameter of the distribution function which fits the number of loaded containers per vessel and k_T^{O} and λ_T^{O} are the parameters of the outbound container dwell time distribution.

3.3.3 Transshipment containers

Transshipment containers flow into the terminal in different ways: from the deep-sea vessels to the feeder service vessels and/or in the opposite way but also between deep-sea or feeder vessels consolidating cargo from different maritime routes (for instance from eastern-western routes to northern-southern ones).

Then, this kind of containers does follow neither individual dissipation nor accumulation pattern because their arrival and departure process takes place by group at seaside. Nonetheless, these containers are required to be stored in the yard for a certain length of time due to time differences between vessel arrivals or vessel stowing plans.

Because it is unknown into which vessels a specific transshipment container will be loaded, it is reasonable to assume that the expected length of time at the terminal follows a probabilistic distribution function for transshipment containers ($F^T(t)$). The main characteristic of this probability function is that its tail shape is light and enclosed in comparison with inbound containers whose tail is heavy and long (see Figure 3.1).

Following the same procedure as that for inbound containers, the probability that x_T, $x_T \in [0, n_{\mathrm{i(z)}}^T]$, transshipment containers are still stored at the yard at time t (assuming that the amount of unloaded containers from the *i*^th vessel is the stochastic variable $N_{\mathrm{i(z)}}^T$) is:

$$P_{i(z)}^{x_T}(t) = \sum_{n_{\mathrm{i(z)}}^{\mathrm{tr}}} \left(\left(\binom{n_{\mathrm{i(z)}}^T}{n_{\mathrm{i(z)}}^T - x_T} \left[F^T(t-t^i)\right]^{\left(n_{\mathrm{i(z)}}^T - x_T\right)} \left[S^T(t-t^i)\right]^{s_T} \right) Pr\left[n_{\mathrm{i(z)}}^T\right] \right) \quad t > t^i \qquad [3.11]$$

where:

$$\begin{aligned} Pr\left[N_{\mathrm{i(z)}}^T = n_{\mathrm{i(z)}}^T\right] &= Pr\left[\left(\mathrm{n}_{\mathrm{i(z)}}^T - 0.5\right) < \mathrm{N}_{\mathrm{i(z)}}^T < \left(\mathrm{n}_{\mathrm{i(z)}}^T + 0.5\right)\right] \\ &= G^T\left(\mathrm{n}_{\mathrm{i(z)}}^T + 0.5\right) - G^T\left(\mathrm{n}_{\mathrm{i(z)}}^T - 0.5\right) \end{aligned} \qquad [3.12]$$

and $G(\mathrm{n}_{\mathrm{i(z)}}^T)$ is the probability that the *i*^th vessel will unload $\mathrm{n}_{\mathrm{i(z)}}^T$ containers or less according to the probability distribution chosen for approximate this variable.

Hence, for the *i*^th calling vessel at the terminal and taking into account that the amount of unloaded transshipment containers per vessel is a random variable, the expected number of transshipment containers associated to vessel of type z at time t is:

$$E\left[C_{i(z)}^T(t)\right] = \begin{Bmatrix} \sum_{x_T=0}^{n_{\mathrm{i(z)}}^T} x_T\, P_{i(z)}^{x_T}(t) & t > t^i \\ 0 & t \le t^i \end{Bmatrix} \qquad [3.13]$$

Then, expression [3.14] is a simplified version of expression [3.13] because only the expected value for the inventory yard is used.

$$E\left[C_{i(z)}^T(t)\right] = \begin{Bmatrix} E\left[n_{\mathrm{i(z)}}^T\right]\left[S^T(t-t^i)\right] & t > t^i \\ 0 & t \le t^i \end{Bmatrix} \qquad [3.14]$$

where $n_{\mathrm{i(z)}}^T$ are all those values that the random variable $N_{\mathrm{i(z)}}^T$ include and $S^T(t-t^i)$ is the survival function related to inbound dwell time (T^T). Finally, by taking into account the problem assumptions, expression [3.14] can be redefined as:

$$E\left[C_{i(z)}^{T}(t)\right] = \\ = \begin{cases} \sum_{n_{i(z)}^{T}} \left(n_{i(z)}^{T} \cdot \left(e^{-\left(\frac{n_{i(z)}^{T}-0.5}{\lambda_z^T}\right)^{k_z^T}} - e^{-\left(\frac{n_{i(z)}^{T}+0.5}{\lambda_z^T}\right)^{k_z^T}} \right) \right) \left(e^{-\left(\frac{t-t^i}{\lambda_T^T}\right)^{k_T^T}} \right) & t > t^i \\ 0 & t \leq t^i \end{cases} \quad [3.15]$$

3.3.4 Total amount of containers related to a single vessel

The total amount of containers associated to a single vessel (i.e. the i^{th} vessel calling at the terminal) of type z will be the sum up of the amount of each type of containers at time t, that is:

$$E\left[C_{i(z)}(t)\right] = \begin{cases} E\left[C_{i(z)}^{O}(t)\right] & 0 < t \leq t^i \\ E\left[C_{i(z)}^{I}(t)\right] + E\left[C_{i(z)}^{T}(t)\right] & t > t^i \end{cases} \quad [3.16]$$

where the different components from equation [3.16] correspond to expressions [3.4], [3.9] and [3.14], respectively.

3.4 Total storage space requirement

The target of this part is to extent the formulation developed for a single vessel to the overall arrival process for multiple vessels during a certain length of time.

Assuming that v vessels (considering deep-sea and short-sea vessels) call the terminal over a period of time in which time between consecutive arrivals is considered as a constant in this chapter, it is required to adjust the formulation developed in the previous section to a vector problem in order to consider the variable time (t).

Hence, the vector V represents the vessel arrival sequence at the terminal. The dimensions of the vector V are: v rows (due to v vessels call the terminal separated by the inter-arrival time) and 1 column ($V_{[vx1]}$) and is calculated as follows:

$$V_{[vx1]} = V_{ds_{[vx1]}} + V_{fs_{[vx1]}} \quad [3.17]$$

where $V_{ds_{[vx1]}}$ and $V_{fs_{[vx1]}}$ are the vectors associated to deep-sea and feeder vessels, respectively, which components are:

$$V_{ds_{[vx1]}} = \left(v_{ds_1}, \;\cdots\; , v_{ds_i}, \;\cdots\; , v_{ds_v}\right)^T \quad [3.18]$$

$$V_{fs_{[vx1]}} = \left(v_{fs_1}, \;\cdots\; , v_{fs_i}, \;\cdots\; , v_{fs_v}\right)^T \quad [3.19]$$

in which:

$$v_{ds_i} = \begin{cases} 1 & \text{for a deep} - \text{sea vessel in the i}^{\text{th}} \text{ position} \\ 0 & \text{for a feeder vessel in the i}^{\text{th}} \text{ position} \end{cases} \quad [3.20]$$

$$v_{fs_i} = \begin{cases} 1 & \text{for a feeder vessel in the i}^{\text{th}} \text{ position} \\ 0 & \text{for a deep} - \text{sea vessel in the i}^{\text{th}} \text{ position} \end{cases} \quad [3.21]$$

The vector components indicate whether the i^{th} calling vessel is a deep-sea or feeder-service vessel, depending on whether there is a 0 or 1 in the corresponding position. If the vector component is equal to 1, then it indicates that a vessel of that kind is arriving at the terminal and if it is equal to 0, it means that any vessel of this type is not calling the terminal for that period of time. For the particular case that two types of vessel are considered (deep-sea and fedder) and under the assumption that just one vessel calls the terminal per period of time (for instance, one per day) the vector $V_{[vx1]}$ will be equal to the unit vector ($I_{[vx1]}$).

Then the expected total amount of containers stored in the yard per type of container is:

3.4.1 Inbound containers

In order to obtain the expected total amount of inbound containers at the storage yard for any time t, it is firstly required to define the vector that specifies the expected amount of inbound containers per each vessel at time t. This vector has the following structure:

$$E\left[C^{I}_{(z)}(t)\right]_{[1xv]} = \left(E\left[C^{I}_{1(z)}(t)\right], \quad \cdots \quad , E\left[C^{I}_{i(z)}(t)\right], \quad \cdots \quad , E\left[C^{I}_{v(z)}(t)\right]\right) \quad [3.22]$$

in which each component is defined according to expression [3.4] for $i \in [1, v]$ and concerning main characteristics of each type of vessel (z) (deep-sea and feeder).

Hence, the expected number of inbound containers at the yard unloaded from i vessels ($i \in [1, v]$) will be the result of the following scalar product between both vectors defined in [3.17] and [3.22] (characterized according to the type of containership and its stowage plans), that is:

$$E[C^{I}(t)] = E\left[C^{I}_{(ds)}(t)\right]_{[1xv]} \cdot V_{ds_{[vx1]}} + E\left[C^{I}_{(fs)}(t)\right]_{[1xv]} \cdot V_{fs_{[vx1]}} \quad [3.23]$$

And finally, considering those remaining inbound containers from previous time before first vessel ($i = 1$) was served in the terminal ($\mathrm{E}[\mathrm{C}^{\mathrm{I}}(\mathrm{t}_0)]$), the total expected amount of inbound containers is:

$$E_T[C^{I}(t)] = E[C^{I}(t)] + E[C^{I}(t_0)]. \quad [3.24]$$

3.4.2 Outbound containers

For outbound containers, the calculation process is exactly the same as that for inbound containers. The vector that contains the expected amount of outbound containers per each vessel at time t for any kind of vessel is defined as follows:

$$E[C_z^O(t)]_{[1xv]} = \left(E\left[C_{1(z)}^O(t)\right], \quad \cdots \quad, E\left[C_{i(z)}^O(t)\right], \quad \cdots \quad, E\left[C_{v(z)}^O(t)\right]\right) \quad [3.25]$$

where $E\left[C_{i(z)}^{ob}(t)\right]$ corresponds to expression [3.8].

Next, the scalar product of vector [3.17] and [3.25] give the expected amount of outbound containers that will be loaded to i vessels at each period of time t.

$$E[C^O(t)] = E[C_{ds}^O(t)]_{[1xv]} \cdot V_{ds_{[vx1]}} + E\left[C_{fs}^O(t)\right]_{[1xv]} \cdot V_{fs_{[vx1]}} \quad [3.26]$$

Finally, considering those remaining outbound containers ($\mathrm{E}[\mathrm{C}^O(\mathrm{t}_0)]$), the total expected amount of outbound containers is:

$$E_T[C^O(t)] = E[C^O(t)] + E[C^O(t_0)] \quad [3.27]$$

3.4.3 Transshipment containers

Lastly, the vector associated to the expected amount of transshipment containers per vessel at time t is:

$$E[C_z^T(t)]_{[1xv]} = \left(E\left[C_{1(z)}^T(t)\right], \quad \cdots \quad, E\left[C_{i(z)}^T(t)\right], \quad \cdots \quad, E\left[C_{v(z)}^T(t)\right]\right) \quad [3.28]$$

where $E\left[C_{i(z)}^{tr}(t)\right]$ corresponds to expression [3.13].

Then, the mathematical expression of the expected amount of transshipment containers at the storage yard can be represented by the same form to [3.17] and [3.28], that is:

$$E[C^T(t)] = E[C_{ds}^T(t)]_{[1xv]} \cdot V_{ds_{[vx1]}} + E\left[C_{fs}^T(t)\right]_{[1xv]} \cdot V_{fs_{[vx1]}} \quad [3.29]$$

Finally, considering those remaining transshipment containers from a previous stage of the storage yard ($\mathrm{E}[\mathrm{C}^T(\mathrm{t}_0)]$), the total expected amount of transshipment containers is:

$$E_T[C^T(t)] = E[C^T(t)] + E[C^T(t_0)]. \quad [3.30]$$

3.4.4 Total amount of containers

To sum up, the total amount of containers stored in the yard at time t ($E_T[C(t)]$) will be the summation of total stored units of all different types of containers, that is:

$$E_T[C(t)] = E_T[C^I(t)] + E_T[C^O(t)] + E_T[C^T(t)]. \quad [3.31])$$

3.5 Numerical experiments

A numerical experiment is conducted to illustrate how the above formulation works and to realize about the inventory yard fluctuations alongside time. It is assumed that a short-sea vessel and a deep-sea vessel call intermittently and randomly the terminal in such way that just one vessel call the container terminal per day.

The number of loaded and unloaded containers per vessel follows a Weibull distribution which main distribution parameters are: $\left(k_{ds}^{I}=4,\lambda_{ds}^{I}=1{,}400\right)$, $\left(k_{ds}^{O}=2,\lambda_{ds}^{O}=1{,}400\right)$, and $\left(k_{ds}^{T}=3,\lambda_{ds}^{T}=1{,}200\right)$ for a deep-sea vessel which means that the average number of unloaded containers is 2,340 and the average number of loaded containers is 1,240 in which transshipment containers represents as an average the 45% of unloaded containers.

On the other hand, for feeder vessels the following parameters are used: $\left(k_{fs}^{I}=2,\lambda_{fs}^{I}=600\right)$,$\left(k_{fs}^{O}=2,\lambda_{fs}^{O}=700\right)$, and $\left(k_{fs}^{T}=2,\lambda_{fs}^{T}=300\right)$, which means that the average number of unloaded containers is 797 and the average number of loaded containers is 620 in which transshipment containers represents as an average the 34% of unloaded containers.

Inbound and outbound container dwell time distribution functions have been calibrated in such way that the average length of stay for inbounds is around 4.5 days $(k_{T}^{I}=1,\lambda_{T}^{I}=4.3)$ and for outbounds an average period of 2.5 days $\left(k_{T}^{O}=1,\lambda_{T}^{O}=2.5\right)$. For transshipment containers, the average period of time at the storage yard is 3 days with a tail length shorter than previous type of containers. Therefore, the parameters of the distribution are: $(k_{T}^{T}=2,\lambda_{T}^{T}=3.2)$.

Finally, the components of the vector $V_{fs_{[vx1]}}$, which indicates in which position feeder vessels call the terminal, is generated randomly. Thus, $V_{ds_{[vx1]}}$ will be the complementary one in order to satisfy the assumption taken for this sample (every day a vessel of either of two types arrives at the terminal), therefore $V_{[vx1]}$ will be the identity vector.

Once all input data is defined and by implementing expressions developed in previous section, the total storage space requirement time by time is depicted in Figure 3.2.

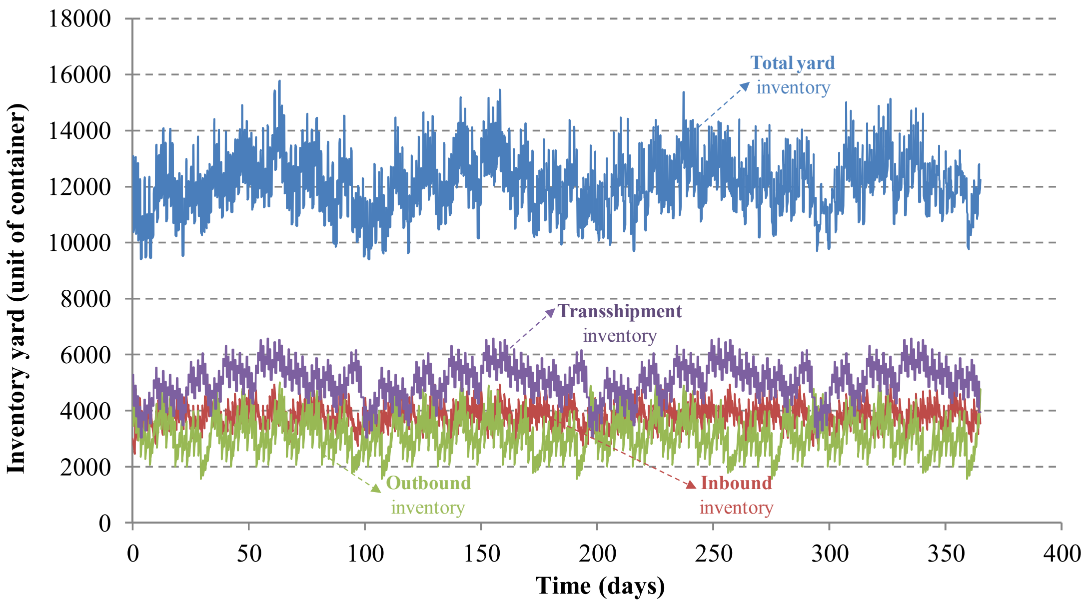


Figure 3.2: Storage space requirement and inventory yard fluctuations during an operating year

As an alternative, the requirements for storage capacity over a period of time can be depicted as it is shown in Figure 3.3.

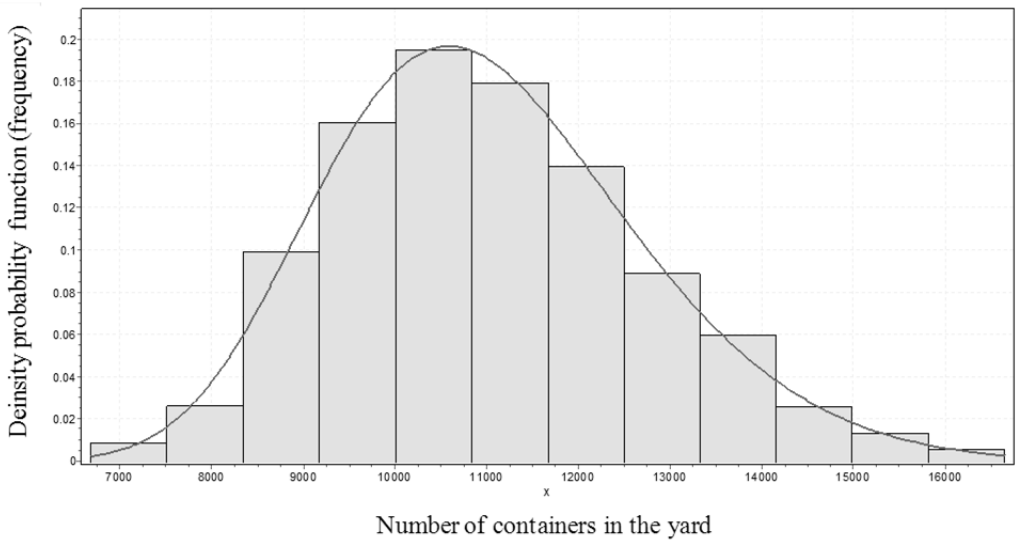


Figure 3.3: Storage space requirement over an operating year (histogram)

In Figure 3.3, the frequency of different yard inventory ranges and the probability distribution curve are illustrated. After fitting the yard inventory data to a theoretical distribution function by using the commercial software, *EasyFit*, the equation that characterizes the curve depicted in Figure 3.3 is:

$$f(z) = \frac{1}{1576}\left[1 - 0.156\left(\frac{z - 10322}{1576.4}\right)\right]^{5.38} exp\left\{-\left[1 - 0.156\left(\frac{z - 10322}{1576}\right)\right]^{6.38}\right\} \qquad [3.32]$$

And the associated cumulative distribution function is:

$$F(z) = exp\left\{-\left[1 - 0.156\left(\frac{z - 10322}{1576}\right)\right]^{6.38}\right\} \qquad [3.33]$$

which is a Generalized Extreme Value (GEV) distribution which average value (mean) is 11,916 containers.

Finally, from Figure 3.2, the following comments can be derived: first, there exists an imbalance of inventory yard at short scale (between short periods of time) because of the dissipation and accumulation of inbound and outbound containers, respectively. Clearly there exists a dynamic behavior of inventory levels in the storage yard since large oscillations and small damping arise.

Second, it can be observed that at long term the inventory yard behavior could be approximate to a sinusoidal function. In fact, three different sinusoidal functions could be defined: average inventory level and upper and lower bound inventory level. Though, the most useful for terminal operators is the upper bound inventory level which determines the minimum capacity requirement of the yard.

Third, it is worth mentioning the maximum peaks that the inventory yard registers. The imbalance between those peaks and the average space requirement or how likely those extreme values are over a period may modify decision-making process of terminal operators during the design process of the yard and its storage capacity. That is why special attention and analysis is provided in section 3.6.

3.5.1 Discussions on practical considerations

In the previous section it was found that the analytical model includes the stochastic variables with regard to the amount of unloaded containers per vessel and dwell time with the probability distribution functions. Thus the model considers mathematically the stochastic behavior of the process since the input and output flows are random.

Nonetheless, in order to calculate analytically the import yard inventory of the storage system random variables are approximated to the theoretical distribution functions and expected values are used, similar to other studies related to storage and inventory systems that consider stochastic demand (i.e. Schmitt et al., 2010).

Thus, the stochasticity of the formulation could be simplified due to uncertainties in such manner are reduced. Then the yard inventory values may become more attenuated than those registered in real life. That is: there is a gap between the real case fluctuations and those obtained from the formulation introduced in this thesis.

In order to quantify this gap, a long enough Monte Carlo series of yard inventory, which could predict the observed values in real life, is generated. Figure 3.4 depicts both time series.

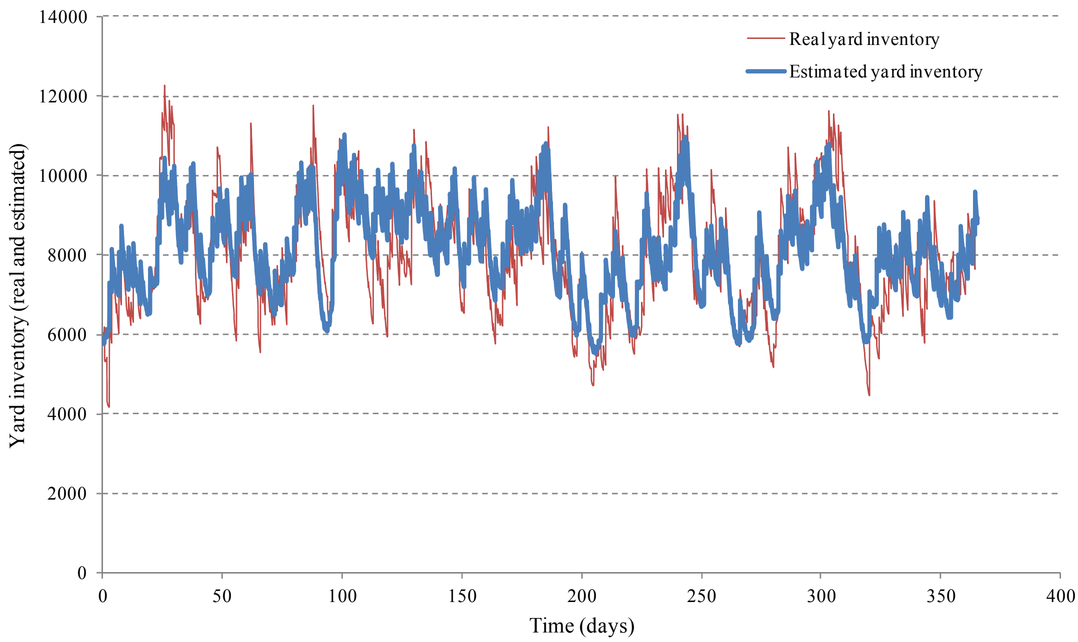


Figure 3.4: Comparison of estimated yard inventory and real (simulated) time series.

To compare both yard inventory series, the root mean squared error (RMSE) and mean absolute error (MAE) are calculated. These are generally used to measure how close forecasts are to eventual outcomes in time series analysis, for which the formulation is given in Box et al. (1994).

The RMSE provides a relatively high weight to large errors since the differences between the estimated and corresponding observed values are each squared and then averaged over the sample. Then, the MAE, which is always lower or equal to the RMSE, indicates the average error between the estimated and real values and measures the accuracy of the estimated time series.

For the numerical case analyzed in this chapter, the RMSE is 11.20% and the MAE is 7.75%. Both these errors demonstrate that the estimated yard inventory series is quite close to the real series and that no large errors exist between both time series. Nonetheless, the main differences between both arise in the peak registration, in which the maximum peak of the hypothetical observed (simulated) series is 10% higher than the estimated one in this thesis, whereas the differences between the average values are only about 1.2%.

Complementary to the numerical case analyzed, Table 3.1 shows the deviation between both series for different variability values regarding the number of unloaded containers per vessel. Because multiple vessels are considered, the covariance of the random variables is calculated. The highest variability rate is indicated with three positive symbols and the deterministic case is indicated with a zero, according to its variability rate.

Table 3.1: Deviations between the predicted and analytical data with respect the variability of input data. The symbol "+++" indicates the highest variability and "0" the deterministic case.

Covariance (n_{fs},n_{ds})	MAE(%)	RMSE (%)
+++	8.38%	15.31%
++	4.71%	8.13%
+	1.96%	3.40%
0	0.00%	1.03%

It was found that the maximum deviation between the hypothetical real data from the simulation and analytical data obtained from the mathematical model is about 8.4%, which denotes that the accuracy of the model is acceptable. The RMSE, which places a higher weight on large errors (peaks), is also acceptable. Therefore, it can be confirmed that the mathematical model developed is reliable, as it shows the stochastic behavioral properties of the container yard system.

3.6 Analysis of extreme inventory values

Oftentimes, in stochastic analysis, it is really interested to know the likelihood that a particular extreme value will occur in a given and representative period of time. This issue is especially important in this thesis because one of the potential utilities of this chapter is, for instance, to define the optimal storage capacity of the yard regarding the storage space requirement.

Therefore, the objectives of the analysis are to asses and use the potential of extreme value theory for improving the knowledge of extreme yard inventory behavior. In particular we are interested in finding the probability distribution function of those maximum values (those values placed in the tail of the histogram) in order to determine the probability that an extreme value will exceed a limiting value or an inventory peak will occur.

The procedure for estimating extreme values and its probabilities can be achieved, according to the extreme value theory, by two different approaches: (1) the block maximum method or annual maxima (AM) which usually follows the Generalized Extreme Value distribution (GEV); and (2) the Peaks over Threshold method (PoT) which consists on fitting the Generalized Pareto Distribution (GPD) to the peaks of clustered excesses over a threshold.

On one hand, the first method typically uses a single observation per year. So, since time series only covers a few decades, the sample sizes of annual maxima data are usually small. Consequently, the estimates of the parameters of the GEV distribution and associated return values will have larger variances. On the other hand, PoT method makes use of several observations per year, namely of larger peaks which exceed a certain threshold determined by the user. Therefore, this method is expected to generally perform better than AM method since the more observations are used, the more accurate the estimates of the parameters tend to be.

However, the PoT method presents a critical point in the choice of threshold (which is analogous to the choice of block size in the AM method) because of subjectivity criteria. Threshold choice involves balancing bias and variance. A too low threshold is likely to violate the asymptotic basis of the model, leading to bias but a too high threshold will generate fewer excesses with which to estimate the model, leading to high variance.

Even so, as explained by De Haan and Zhou (2009), by choosing the threshold in an intelligent way, either by visual inspection or by using a theoretically selection procedure, it is possible to improve the tail estimation substantially.

3.6.1 Fitting procedure of inventory extreme values

In this chapter, the peak over threshold method is chosen to analyze inventory peaks because we are not just interested in extreme values but also in the exceedances over a given threshold. Figure 3.5 illustrates this concept with an example.

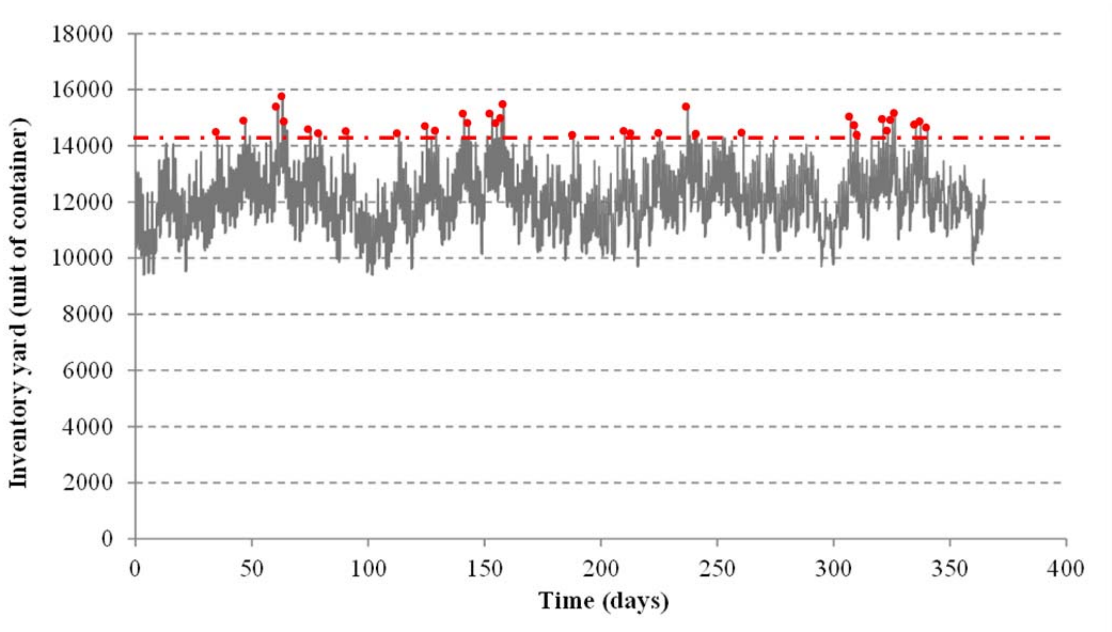


Figure 3.5: Inventory peaks over an arbitrary threshold (during a year)

As it was previously stated, the classical asymptotically model for excesses above a high threshold is the GPD (Pickands, 1975). This distribution function is used as a tail approximation to the population distribution from which a sample of excesses $(x-u)$ above some suitable high threshold are observed. The GPD is parameterized by scale ($\overline{\sigma}$) and shape parameters (ξ) and can equivalently be specified in terms of threshold excesses $x-u$ or, as here, exceedances $x>u$, as:

$$H(x|u,\overline{\sigma},\xi) = Pr(X<x|X>u) = \begin{cases} 1-\left(1+\xi\dfrac{(x-u)}{\bar{\sigma}}\right)^{-1/\xi} & \xi\neq 0 \\ 1-exp\left(-\dfrac{(x-u)}{\bar{\sigma}}\right) & \xi=0 \end{cases} \quad [3.34]$$

where:

$$\bar{\sigma} = \sigma + \xi(u-\mu). \quad [3.35]$$

When $\xi=0$, the GPD is said to have a type I tail and amounts to the exponential distribution with mean $\overline{\sigma}$; when $\xi>0$, it has a type II tail and it is the Pareto distribution; and when $\xi<0$, it has a type III tail and it is a special case of the beta distribution.

As can be seen in Scarrott and MacDonald (2012), there are many threshold estimation approaches in extreme value applications. In this chapter, the choice of the threshold will be done by considering an important property of the PoT method, which is the threshold stability property. This property briefly consists on: if the GPD is a correct model for the excesses above a given threshold (u_1), then the GPD is also a correct model for the excesses above any other threshold higher ($u_2>u_1$) with the same shape but shifted scale $\bar{\sigma}_{u_2}=\bar{\sigma}_{u_1}+\xi(u_2-u_1)$. In practice, this method requires fitting data to the GPD distribution several times, each time using a different threshold. The stability in the parameter estimates can then be checked.

Once main theoretical considerations are introduced, an example is illustrated. In this case, the probability distribution function which better fits those extremes values over a chosen threshold registered in the yard inventory will be found. Previous numerical sample which histogram and cumulative distribution function (CDF) depicted in Figure 3.6 is used. Consequently, the exceedances probability and return level estimations are provided. Results are obtained by using the Extremes Toolkit (extRemes) loaded into *R* software and designed to facilitate the use of extreme value theory.

Before fitting total yard inventory to GPD distribution, the threshold u, which guarantee the abovementioned stability property, is chosen. Figure 3.7 shows plots from having fit the GPD model for a threshold range from 10,000 to 15,750 containers stored in the yard.

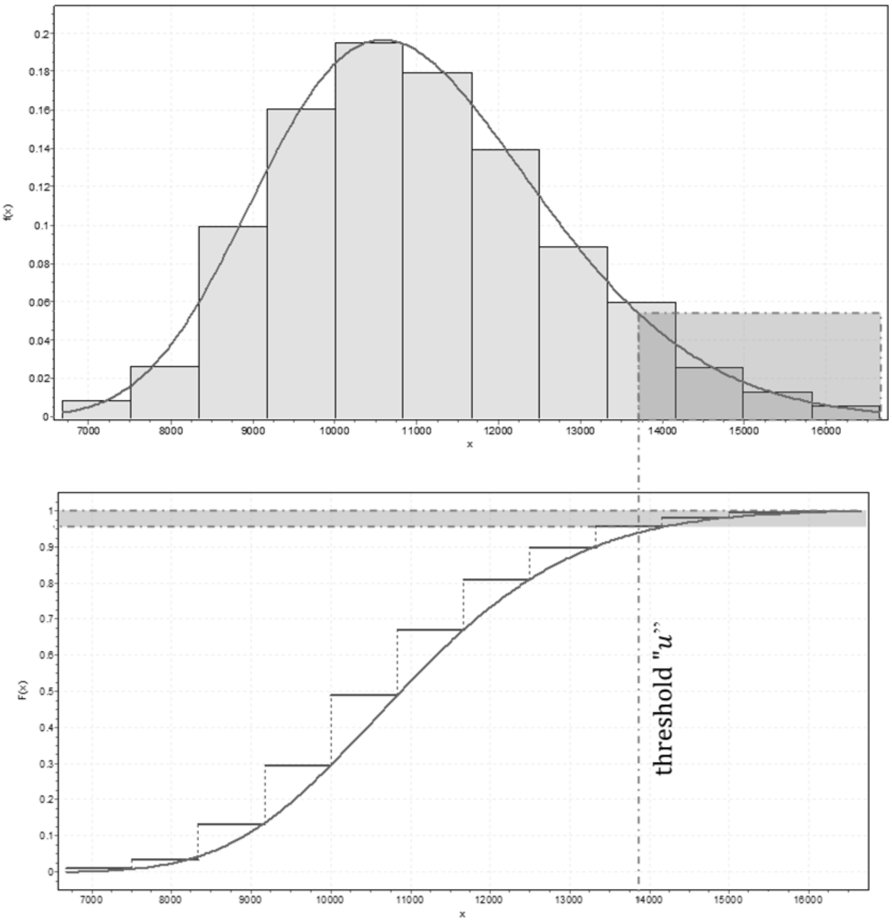


Figure 3.6: Histogram and empirical CDF of yard inventory. Extreme values are placed in the right tail of the distribution.

Figure 3.7 suggests that a threshold of 15,145 containers stored in the yard is appropriate for the GPD model. The reason is because shape and scale parameters remain almost constant for lower values of 15,145 units but from that threshold value onwards the variability of these parameters increase and the stability property is not satisfied for higher values.

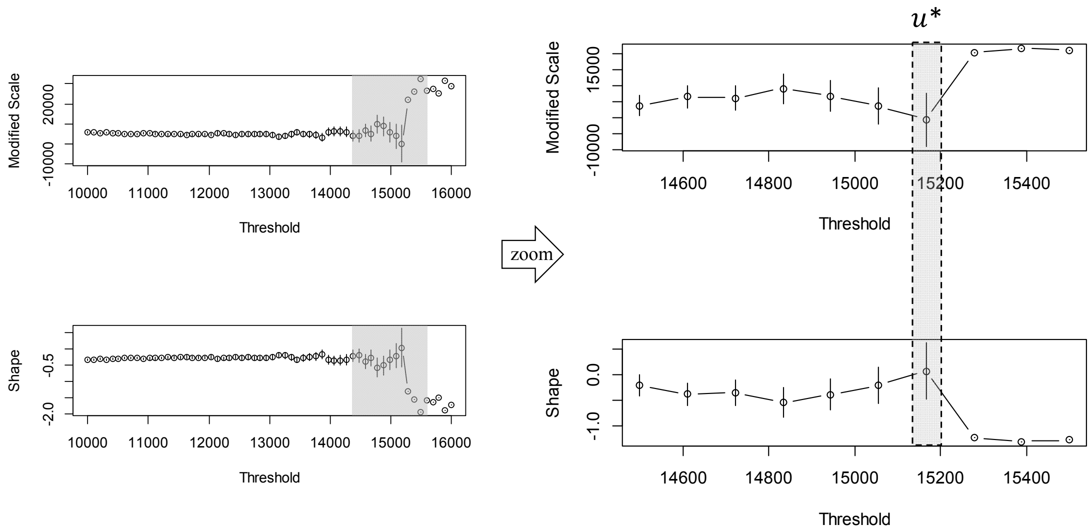


Figure 3.7: Fit threshold ranges versus shape and scale parameters stability plot.

Assuming that the threshold is 15,145 containers, the following results are derived:

- The number of exceedances over the threshold is 60 which represent the 1.65% of total data and the maximum inventory value (peak) corresponds to 15,785 containers.

- The estimation of the scale and shape parameters of the GPD distribution are calculated by implementing in *R* the maximum likelihood estimator method (MLE) whose values (for a confidence interval of 95%) are: $\overline{\sigma}$= 475.510 and ξ= 0.012 whose estimated standard errors are 132.727 and 0.247, respectively. As the shape parameter ξ is higher than 0, it can be stated the distribution has a type II tail which corresponds to the Pareto distribution whose density and cumulative functions (equation [3.36]) are drawn in Figure 3.8.

$$H(x|u) = 1 - \left(1 + (0.012)\frac{(x - 15145)}{475.51}\right)^{-1/0.012} \qquad [3.36]$$

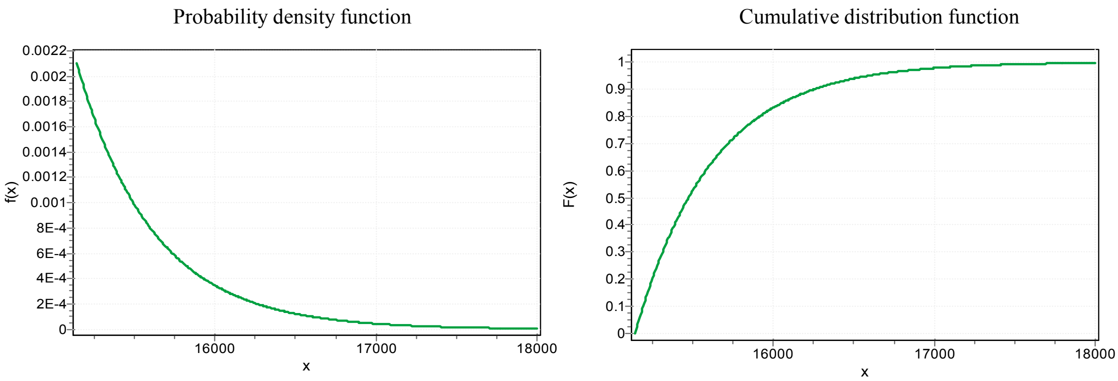
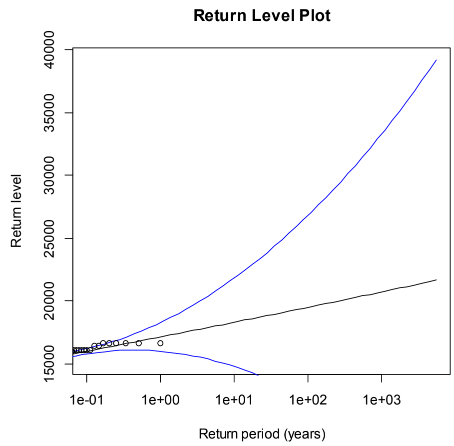


Figure 3.8: Probability density and cumulative distribution function of the resulting GPD (exponential tail)

- The different likelihood ratio tests were used to compare and to decide if the null hypothesis is rejected or not. For our particular case, the likelihood ratio test does not reject the exponential hypothesis and the likelihood statistic is 0.0024, lower than 3.8415 which correspond to the theoretical critical value for 1 degree of freedom of the χ^2distribution. Consequently, the null hypothesis cannot be rejected again.

- The estimation of the p-value is 0.9610 which means that the results are highly likely to the null hypothesis. So, it is concluded that the GPD distribution converge successfully. The p-value also indicates that the probability that the yard inventory is lower or equal to 15,145 (threshold value) is over 96% or, in other words, the probability of being exceed is around 4%.

- Finally, the estimation of return values (the *q*-return value means that once per *q* year, this value could be reached) based on the resulting GPD distribution function of extreme yard inventory values are shown in Figure 3.9. In this figure, return level curves corresponding to the 95% confidence interval are also depicted.



T (years)	2	5	10	25	50	100
Unit of containers	17485	17948	18301	18772	19132	19495

Figure 3.9: Return level plot for yard inventory and expected peaks values associated to different years

- From Figure 3.9 it can be stated that, for example, one each 10 years an extreme value of 18,301 containers could be reached in the yard inventory or even a peak of 19,495 containers once each 100 years or 1% chance of being exceeded in any one year.

The sample illustrated corresponds to the total yard inventory but this exercise can be formulated separately according to the particular requirements of each type of containers.

3.7 Conclusions

This chapter proposes a mathematical formulation based on a probabilistic and stochastic approach for the estimation of yard inventory in container terminals. The model developed considers that the container dwell time and number of (un)loaded container per vessel are random variables which are approximated to the typical theoretical distribution functions calibrated according to historical data. This study also includes an analysis of extreme inventory values with the aim of predicting the likelihood that a peak may occur during a period of time.

The results from the numerical case show that the estimated yard inventory (by using the formulation introduced in this chapter) is close to hypothetical observed values (MAE is about 8.75%) and that the differences between the average yard inventory is less than 2%.

This finding confirm that the formulation can be useful for terminal operators when evaluating, for example, risk investment analysis or even deciding on the amount of equipment and storage capacity of the terminal in initial stages. If terminal operators have complete knowledge of both the regular and the extreme behavior of storage space requirements, they will manage its resources more efficiently since fixed but mainly operating costs could be estimated more accurately.

In such context, it is suggested to include the proposed formulation in a software application in order to be useful and practical for terminal operators (using own data and adapting the assumptions to their characteristics).

Chapter 4

Determination of the optimal storage capacity for efficient terminal performance

4.1 Introduction

In the initial planning stage of a container terminal, facility planners have to solve terminal design problems by analyzing different point of views such as economic and technical feasibility as well as the performance of handling equipment and the terminal processes as a whole.

This chapter focuses on the yard planning and design problem, particularly defining optimal storage space capacity by considering, on one hand, storage space requirements and, on the other hand, the effects on terminal performance when yard inventory becomes closer to capacity level.

Thus, the goal is to determine the optimal storage space utilization (understood as the relationship between storage space requirements and storage space capacity) assuming that storage space requirements are known in advance. A minimization cost function model is provided to determine optimal space capacity by taking into account the impact of space utilization on the main cost factors.

The rest of the chapter is organized as follows. Section 4.2 analyzes the effect of storage space utilization on terminal performance and proposes a cost model for the case where the terminal operator cost and external cost of trucks and vessels (in terms of waiting cost) are minimized. In Section 4.3, a numerical experiment and sensibility analysis of the main cost factors are presented. The results and discussion are also provided. The final section summarizes the contribution and concludes.

4.2 Optimal storage space utilization

4.2.1 Effects of storage space utilization on terminal performance

Under normal working conditions (when there are no operational delays), the elapsed time required for handling and transportation equipment to perform a cycle depends mainly on the type of operation, kinematic characteristics, lifting capacity, and so on. In such a situation, equipment average gross productivity is higher because no external factors affect it. As a consequence, average cycle time, interpreted as the inverse of the productivity rate, will be lower.

However, when storage space utilization increases, the gross productivity of YCs becomes lower because: (1) stacks become higher and as a consequence the amount of rehandling movements highly increases (therefore retrieval times becomes longer); (2) YC interference is more likely to occur (even more so in perpendicular layouts); and (3) container accessibility is reduced (Le-Griphin and Murphy, 2006).

If YC cycle time is longer (gross YC rate is lower), the waiting time for transportation vehicles becomes longer. In addition, a higher volume of containers means a larger workload for each YC, which leads to longer queues and longer traffic congestion in track lanes between blocks and between the yard and wharf. Therefore, the expected cycle time of transporters is increased and the amount of idle transporters to serve YCs and QCs is diminished.

Finally, QC performance is also affected by delays in YC cycle times and subsequent delays in transport vehicles. Furthermore, as the amount of YCs used for vessel (un)loading operations is lower because YC workload is higher, QC cycle times take even longer. Therefore, QC gross productivity becomes lower and vessel turnaround time is highly affected.

In conclusion, it can be suggested that there exists a linear relationship between the yard performance efficiency and the performance of the rest of terminal operations (according to Henesey et al., 2002, terminal subsystems can be optimized independently but the performance of each one is affected by of the other subsystems). Therefore, when YC cycle time increases due to higher space utilization, transportation vehicles and QC cycle times increase by the same proportion that YC does.

In order to illustrate the impact of storage space utilization on cycle times, Figure 4.1 is introduced in which QC cycle time is represented by different space utilization rates. The real data represented in this figure were collected from a container terminal in the Port of Busan (South Korea) during 2011 and 2012.

These data were previously analyzed by Woo et al., (2013) who found a linear relationship between QC cycle time and storage space utilization (for rates within the range [0.5-0.8]). The parameters of the rectilinear function were $\alpha = 0.7546$ (y-intercept) and $\beta = 1.795$ which is the constant of proportionality between both parameters in Figure 4.1.

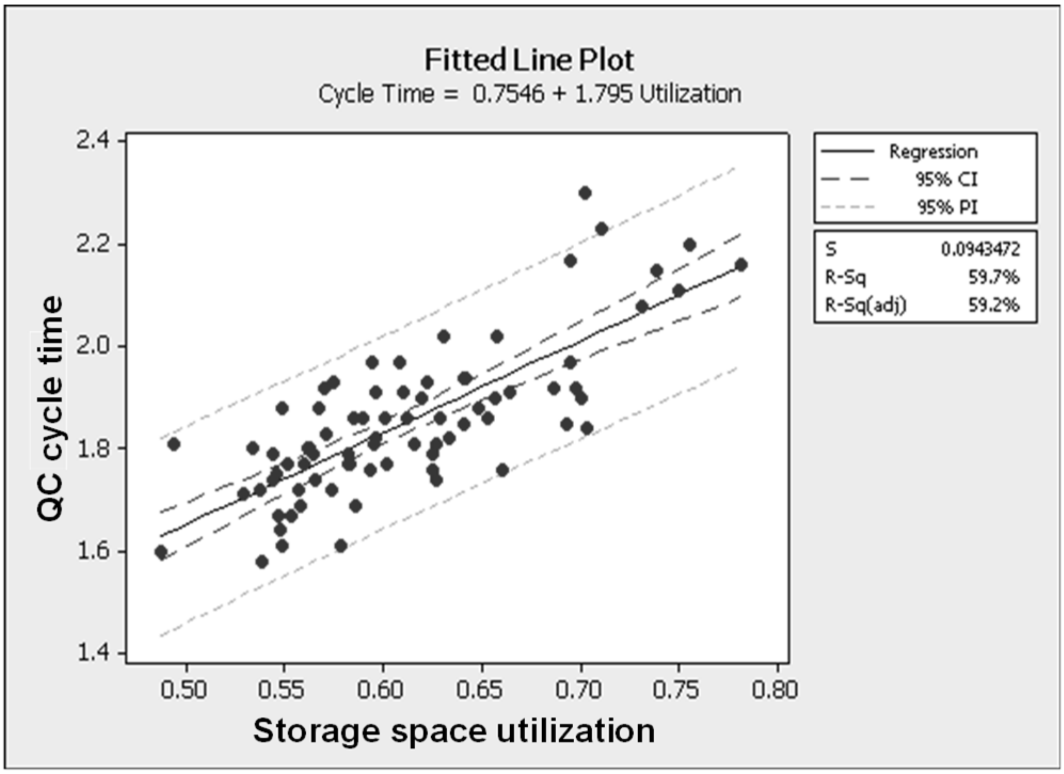


Figure 4.1: Storage space utilization impact on QC cycle times (empirical data from Busan Newport)

Although the QC cycle times for the space utilization rates lower than 0.5 were not collected from the terminal, in this chapter it is assumed that they were close to 1.65 minutes, which is equivalent to a gross productivity of over 36 lifts per hour. This hypothesis is assumed because operational delays are not expected to arise in normal working conditions (space utilization range [0-0.5]).

4.2.2 Methodology

In this section the formulation for optimizing storage space utilization in a container terminal for two different terminal layouts (parallel and perpendicular) is introduced. This formulation is based on various cost factors that depend directly on space utilization (storage capacity) and yard inventory.

However, the storage yard is distributed according to the direction of the containers passing through the terminal such as inbound, outbound and transshipment. Therefore, optimal storage space utilization will differ for the import area compared with that for the export and transshipment area; as a consequence, a separate analysis is provided.

Problem description

First, it is worth briefly introducing the trade-off between the storage capacity (space provided) and total costs of both terminal operators and external agents such as road trucks and vessels. Figure 4.2 illustrates an example.

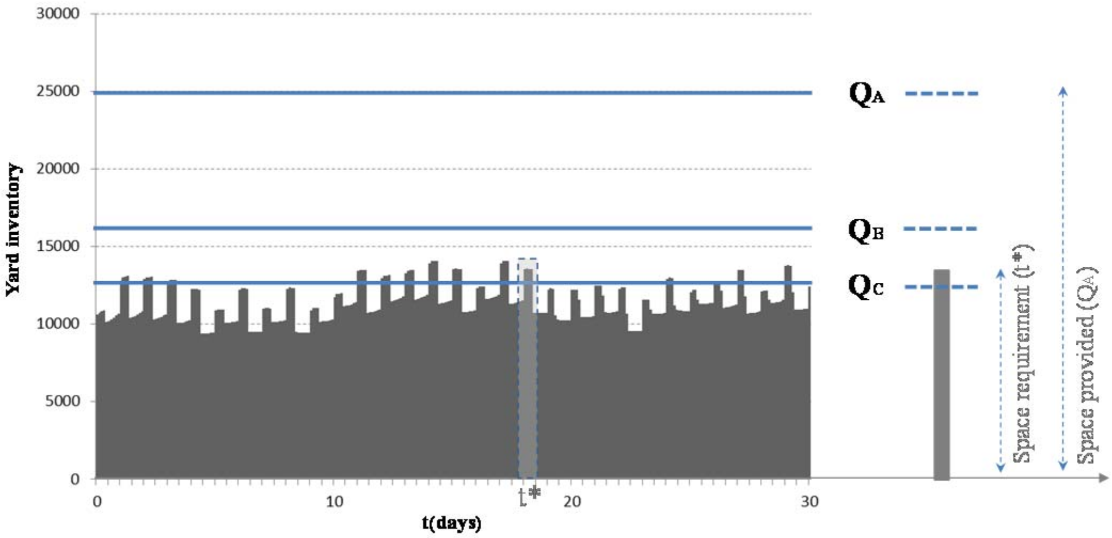


Figure 4.2: Trade-off between the space provided and related costs

For a given space requirement (shadow bars in Figure 4.2), terminal operators are required to decide on the amount of space provided according to their costs (e.g. Q_A, Q_B or Q_C indicated in Figure 4.2). If the space provided is large (i.e. Q_A), the initial investment due to the construction of ground cost will be high but operating costs will be low because no operating delays are likely to occur since the space utilization rate is low. Nonetheless, if the space provided is lower than the former case ($Q_B<Q_A$), ground construction costs will be lower but operating costs will increase due to the congestion effects on handling processes and lower container accessibility (higher stack height and larger number of rehandles during retrieval operations). In summary, there is a trade-off.

Moreover, one more scenario should be considered (i.e. Q_C). In such a case, the space utilization rate is close to its maximum and during a few periods of time, the space requirement is higher than the space provided. In such situations, extra space will be required (e.g. from off-dock warehouses) and therefore extra costs due to overcapacity will derive. The former case is known in storage system logistics as a mixed strategy because private and rental storage space is combined.

Cost analysis of a container terminal

The cost analysis developed in this study considers, on one hand, the terminal operator costs, and, on the other hand, external costs related to road trucks and vessels. For defining the formulation of cost functions, the following notation is presented as follows:

a) Input data regarding geometrical variables

L	Number of bays per block.
W	Number of stacks in a bay.
H	Maximum stacking height.
l_q	Length of the quay (m).
l_b	Length of a bay (m).
w_r	Width of a stack (m).
w_h	Width of a horizontal aisle between adjacent blocks including the width of a lane for driving (m).
v_e	Speed of empty travel of a transporter vehicle (m/min).

v_l Speed of loaded travel of a transporter vehicle (m/min).

b) Input data regarding fixed overhead and operating costs

c_G Construction cost per square meter converted to annual cost (investment capital cost and construction of the ground).
c_R Rental cost per unit of time (day).
c_{YC}^F Fixed overhead cost of per minute of a YC (investment for acquiring).
c_{YC}^o Operating cost per minute of a YC including labor, fuel, maintenance and overhead costs.
c_{QC}^F Fixed overhead cost of per minute of a QC (investment for acquiring).
c_{QC}^O Operating cost per minute of a QC including labor, fuel, maintenance and overhead costs.
c_{TR}^F Fixed overhead cost of transport vehicles per minute (investment for acquiring).
c_{TR}^O Operating cost per minute of a TR including labor, fuel, maintenance and overhead costs.
c_{ET} External truck cost per unit of time.
c_V Vessel cost per unit of time.

c) Decision and main variables

Q Storage space capacity in unit of slots (decision variable).
$U(t,Q)$ Storage space utilization

$$U(t,Q) = \frac{\sum_z q_z(t)}{Q} \qquad 0 \leq U(t,Q) \leq 1$$

$q_z(t)$ Storage space requirement (yard inventory).

$N_z(t)$ Number of handled containers of type z (import, export and transshipment).

$\Delta t_z^{CT_{YC}}$ Delay on YC cycle time for handling containers of type z due to yard congestion. It depends on $U(t,Q)$.
$\Delta t_z^{CT_{TR}}$ Delay on TR cycle time for handling containers of type z due to yard congestion. It depends on $U(t,Q)$.
$\Delta t_z^{CT_{QC}}$ Delay on QC cycle time for handling containers of type z due to yard congestion. It depends on $U(t,Q)$.

And the following additional assumption is considered:

- As it was stated in section 4.2.1, it is assumed that there exists a linear relationship between cycle time delays on different handling equipment. Then, the impact over QC cycle time (in percentage) will be considered as a reference to estimate operating delay time over the rest of terminal equipment such as TR and YC. The QC cycle times are ruled according to the following expression which derives from Figure 4.1.

$$E\left[t_z^{CT_{QC}}\right] = y\big(U(t,Q)\big) = \begin{Bmatrix} \alpha + \beta U(t,Q) & U \geq U_0 \\ \alpha + \beta U_0 & U < U_0 \end{Bmatrix} \qquad [4.1]$$

Then, the increasing percentage observed in QC cycle time ratio, assuming that for space utilization rates within the range [0-0.5] cycle time is not affected, is:

$$\Delta t_z^{CT_{QC}}(U(t,Q)) = \left(\frac{\beta(U(t,Q) - U_0)}{y(U_0)}\right) \quad [4.2]$$

where U_0=0.5, α=0.7546 and β=1.795.

Next, the objective cost function includes the following cost factors:

- **Costs related to the container terminal operator**

a) Construction cost of ground space for blocks and aisles

The construction cost depends mostly on the terminal and block layout, quay length (l_q), number of storage blocks, distance between blocks and between the yard and the wharf, and on unit cost per square meter (Lee and Kim, 2013). It will be calculated by:

$$C_G(Q) = c_G[(w_r W + w_h)R(Q) + w_h]l_q \quad [4.3]$$

$$C_G(Q) = c_G[l_b B(Q) + 2w_h]l_q \quad [4.4]$$

In which expression [4.3] corresponds to parallel layout and expression [4.4] to perpendicular layout. For both cases, the quay length is fixed because it is considered as a basic strategic decision parameter. However, the amount of rows ($R(Q)$) and the amount of perpendicular blocks ($B(Q)$) depend on the decision variable of the problem, that is, the storage capacity (Q).

b) Rental cost due to overcapacity of the storage yard

When there are fluctuations in space requirement it is suggested to consider a mixed strategy of rented and privately operated storage space. In this chapter, this strategy is also consider in such way when there exists a lack of slots terminal operators are required to provide storage space to their customers by renting additional space in auxiliary warehouse.

The rental cost ($C_R(Q)$) will depend on the space ($q_z(t) - Q$) and time required (T_R) regarding the storage capacity of the yard (Q).

$$C_R(Q) = c_R \sum_t \sum_z [q_z(t) - Q]T_R \quad [4.5]$$

c) Fixed overhead and operating cost of handling equipment

The fixed overhead cost of handling equipment is related to the amount of equipment required which depends at the same time on the terminal throughput.

However, the number of handling and transportation equipment units to satisfy demand is a complex problem. Actually, when handling processes are affected by operational delays, terminal operators are required to provide more resources in order to keep the same service level to customers. For instance, if QC gross productivity is decreasing due to higher space utilization and vessel turnaround time needs to be minimized (highest priority in container terminals), the operator will supply additional QC units in order to keep a competitive number of lifts per hour. Consequently, an additional QC requires more transporter vehicles and YCs to avoid higher QC waiting times.

Hence, it is reasonable to assume that fixed overhead costs (purchasing cost) are proportional to the amount of time required to handle containers that goes through the terminal. On the other hand, operating costs depend on fuel consumption, maintenance and variable overhead costs which are related to total operating time of handling equipment.

The cost functions per each type of equipment are introduced as follows:

Quay cranes

$$C_{QC}(Q) = (c_{QC}^{F} + c_{QC}^{O})\left\{\sum_{t}\sum_{z}\left(N_z(t)\cdot\left\{E\left[t_z^{CT_{QC}}(U(Q))\right]\right\}\right)\right\} \quad [4.6]$$

where the expected QC cycle time depends on space utilization and it is estimated according to expression [4.2]. This cycle time (per lift) includes idle time for next container, pick-up from wharf, hoisting, trolley movement, lowering, guides positioning, lowering and set into corresponding hold.

Yard cranes

$$C_{YC}(Q) = (c_{YC}^{F} + c_{YC}^{O})\left\{\sum_{t}\sum_{z}\left(N_z(t)\cdot\left\{E\left[t_z^{CT_{YC}}\right] + \Delta t_z^{CT_{YC}}(U(t,Q))\right\}\right)\right\} \quad [4.7]$$

where:

$$\Delta t_z^{CT_{YC}}\big(U(t,Q)\big) = E\left[t_z^{CT_{YC}}\right]\left(\frac{\beta(U(t,Q)-U_0)}{y(U_0)}\right) \qquad U(t,Q)\geq U_0 \quad [4.8]$$

The expected cycle time of YC ($E\left[t_z^{CT_{YC}}\right]$) is equivalent to the expected service time which depends on the type of handled container as can be seen below:

$$E\left[t_I^{CT_{YC}}\right] = E\left[t_{unloading}\right] + E\left[t_{delivery}\right] + E\left[t_{rehandles}\right] \quad [4.9]$$

The total service time required for handling an inbound container ($E\left[t_I^{CT_{YC}}\right]$) is the time required for receiving a container in a vessel discharging operation from a transporter vehicle $E\left[t_{unloading}\right]$ and the time required for retrieving a container from the storage yard and delivering to an external truck ($E\left[t_{delivery}\right]$). The retrieval operation also involves rehandling moves when the target container cannot be picked-up directly.

In this particular chapter, the amount of rehandles is estimated according to the formulation introduced in Kim (1997) in which the average amount of rehandles per pick-up depends on the stacking height (H) and the number of stacks per bay (W). That is:

$$\frac{H(Q)-1}{4} + \frac{H(Q)+2}{16W} \quad [4.10]$$

The stacking height depends on the yard capacity Q (decision variable). For higher capacity values (Q), the average stacking height will be lower and consequently the amount of rehandles per pickup. So, it can be said that rehandling operating cost is quite sensitive to yard capacity.

$$E\left[t_O^{CT_{YC}}\right] = E\left[t_{receiving}\right] + E\left[t_{loading}\right] \qquad [4.11]$$

On the other hand, the service time required for a YC to handle an outbound container is the combination of the following processes: (1) time required to receive a container from an external truck and; (2) time required to transfer a container from the yard to a transporter vehicle during vessel loading operation.

Lastly, the YC service time regarding transshipment containers corresponds to the service time for receiving a container from a transporter vehicle during discharging operation and service time required for delivering a container to a transporter vehicle during vessel loading operation. Then, total estimated service time is:

$$E\left[t_T^{CT_{YC}}\right] = E\left[t_{unloading}\right] + E\left[t_{loading}\right] \qquad [4.12]$$

<u>Transport vehicles</u>

$$C_{TR}(Q) = (c_{TR}^F + c_{TR}^O)\left\{\sum_t \sum_z \left(N_z(t) \cdot \left\{E\left[t_z^{CT_{TR}}\right] + \Delta t_z^{CT_{TR}}(U(t,Q))\right\}\right)\right\} \qquad [4.13]$$

where:

$$\Delta t_z^{CT_{TR}}\left(U(t,Q)\right) = E\left[t_z^{CT_{TR}}\right]\left(\frac{\beta(U(t,Q) - U_0}{y(U_0)}\right) \qquad U(t,Q) \geq U_0 \qquad [4.14]$$

The expected cycle time of TR ($E\left[t_z^{CT_{TR}}\right]$) includes the following elements:

- $E[t_z^T]$: Expected round-trip travel time of transport vehicles between a random position of the quay and a random position in the yard. The average round-trip travel time depends on the travel distance for empty and loaded travel and on the corresponding average speed.

  This time is estimated according to the formulation introduced by Kim et al. (2008), which for the parallel layout can be calculated as:

  $$E[t_z^T] = \frac{1}{2}\left[\frac{(2N(Q)^2 + 3N(Q) + 1)}{3N(Q)^2} l_q + \left((w_r W + w_h)R(Q) + w_h\right)\right]\left(\frac{1}{v_e} + \frac{1}{v_l}\right) \qquad [4.15]$$

  where N(Q) is the amount of block columns and R(Q) is the amount of block rows in the parallel layout.

  And for the perpendicular layout the travel time can be estimated as:

  $$E[t_z^T] = \frac{1}{2}\left(\frac{2}{3} l_q + 2w_h\right)\left(\frac{1}{v_e} + \frac{1}{v_l}\right) \qquad [4.16]$$

- $E[t_z^S]$: Expected YC service time for delivering or receiving a container of type z (inbound, outbound or transshipment) from/to a transporter vehicle during discharging or loading vessel operation.

  $$E[t_I^S] = E\left[t_{unloading}\right] \qquad [4.17]$$
  $$E[t_O^S] = E\left[t_{loading}\right] \qquad [4.18]$$
  $$E[t_T^S] = E\left[t_{unloading}\right] + E\left[t_{loading}\right] \qquad [4.19]$$

- $E[t_z^W]$: Expected waiting time of transport vehicles for being served by YC. For each kind of container, the waiting time can be estimated as follows:

$$E[t_I^W] = E[t_{unloading}^W] \quad [4.20]$$
$$E[t_O^W] = E[t_{loading}^W] \quad [4.21]$$
$$E[t_T^W] = E[t_{unloading}^W] + E[t_{loading}^W] \quad [4.22]$$

Since the amount of equipment units is function of total expected time (including operating delays) it can be assumed that expected waiting time is constant. Otherwise the queuing theory should be applied

To sum up, the cycle time of transport vehicles consists of the travel, waiting and operation times.

Finally, the **total cost for the terminal operator** ($C_{CTO}(Q)$) will be defined according to the following expression:

$$C_{CTO}(Q) = C_G(Q) + C_R(Q) + C_{QC}(Q) + C_{YC}(Q) + C_{TR}(Q) \quad [4.23]$$

- **External cost associated to the container terminal**

In this case the cost involved in the terminal system such as external trucks and vessels is considered. These cost factors are related to the value of time which depends directly on the turnaround time at the terminal. As higher is turnaround time (because of higher space utilization) higher is the related cost for both vessels and road trucks because its opportunity cost increase as they are not transporting cargo (main business activity).

a) Vessel costs

The total system cost for vessels is related to the total time required for loading and unloading all type of containers. This vessel time cost also depends on the average number of QC that served each vessel.

Then, the total value of time for the arriving vessels is:

$$C_V(Q) = \frac{c_V}{g_{QC}} \sum_t \sum_z N_z(t) \left(E\left[t_z^{CT_{QC}}(U(t,Q)) \right] \right) \quad [4.24]$$

where g_{QC} is the QC gang per vessel (number of QC per operation).

b) External truck costs

The system time cost for external trucks for receiving or delivering operation depends on the travel time, waiting time and service time.

Inbound containers

$$C_{ET(I)}(Q) = c_{ET} \sum_t N_I(t) \{ E[t_{pickup}^{T_{ET}}] + E[t_{pickup}^{W_{ET}}] + E[t_{delivery}^{S_{YC}}] + E[t_{rehandles}^{S_{YC}}] \} \quad [4.25]$$

where the expected travel time of external trucks between gate and a random position in the yard to pick-up an inbound container (according to Kim et al., 2008), for the parallel layout is:

$$E\left[t_{pickup}^{T_{ET}}\right] = \frac{1}{2}\left[\frac{(N(Q)+1)^2}{2N(Q)^2} l_q + ((w_r W + w_h)R(Q) + w_h)\right]\left[\frac{1}{v_e} + \frac{1}{v_l}\right] \quad [4.26]$$

and for the perpendicular layout can be estimate like:

$$E\left[t_{pickup}^{T_{ET}}\right] = \frac{1}{2}\left[\frac{l_q}{2} + 2w_h\right]\left[\frac{1}{v_e} + \frac{1}{v_l}\right] \quad [4.27]$$

The expected waiting time for external trucks for being served by YC ($E\left[t_{pickup}^{W_{ET}}\right]$) and YC service time for delivering ($E\left[t_{delivery}^{S_{YC}}\right]$) and rehandling movements ($E\left[t_{rehandles}^{S_{YC}}\right]$) are equivalent to the expected values employed in YC operating cost function.

Outbound containers

The formulation of time cost for external trucks for a delivery operation is similar to trucks for carrying-out containers with the difference that in delivery operation rehandling movements are not required. Then:

$$C_{ET(O)}(Q) = c_{ET}\sum_t N_O(t)\left\{E\left[t_{dropoff}^{T_{ET}}\right] + E\left[t_{dropoff}^{W_{ET}}\right] + E\left[t_{receiving}^{S_{YC}}\right]\right\} \quad [4.28]$$

where $E\left[t_{dropoff}^{T_{ET}}\right]$ is calculated using same expressions than [4.26] or [4.27], for parallel and perpendicular layout, respectively.

Lastly, the **total external cost** for the system ($C_{EXT}(Q)$) will be defined according to the following expression:

$$C_{EXT}(Q) = C_V(Q) + C_{ET(I)}(Q) + C_{ET(O)}(Q) \quad [4.29]$$

It should be mentioned that all the detail of expressions and numerical values for different block layouts (L,W,H) are introduced and analyzed in depth in Lee and Kim (2010a) and Lee and Kim (2013).

- **Objective function**

To sum up, the objective cost function can be written as:

$$Minimize_{U(Q)}[C_{CTO}(Q) + C_{EXT}(Q)] \quad [4.30]$$

where $Q \in S(Q) = [0, \infty)$

The minimization cost model combined fixed and variable costs and determine the optimal storage capacity assuming that the space requirement is given. Then:

- When the space utilization increases, construction cost decreases because lower space is provided while operating costs increases because of the effect of congestion in terminal performance. However, travel distance for road trucks and transport vehicles is reduced and therefore corresponding operating and external costs are reduced. In the same way, vessel turnaround time increase and as a consequence corresponding external costs.

  Moreover, for lower space utilization rates additional space is required. Then, rental cost arises and as a consequence terminal operator costs.

- On the opposite side, when the space utilization decreases, operating costs are not affected by congestion effects and therefore those are not increased but construction cost increases because space provided is larger.

Therefore is proof that there exists a trade-off between cost factors regarding the storage capacity. Then it can be assured that a minimum total cost point exist which satisfy the property of the optimal space utilization.

4.3 Numerical study

In this section a numerical example is provided to illustrate how to choose the optimal storage capacity and the space utilization rate according to the formulation developed in this chapter.

Input data used for numerical examples are collected from different sources: (1) data related to geometrical variables and expected times from previous papers (i.e. Lee and Kim, 2010b and Lee and Kim, 2013) and; (2) data related to fixed overhead and operating costs is collected from a container terminal in the Port of Busan (South Korea). These data is shown in Table 4.1.

Table 4.1: Input data related to unitary costs and geometrical block and aisles data.

Input data	Value	Input data	Value
Unitary costs			
$\boldsymbol{c_G}$	88.15\$/m^2/year	c_{QC}^F	3.85\$/min
$\boldsymbol{c_R}$	12.00 \$/day	c_{QC}^O	1.85\$/min
$\boldsymbol{c_{YC}^F}$ *(9-wide)*	0.875\$ /min	c_{TR}^F	0.067\$/min
$\boldsymbol{c_{YC}^o}$ *(9-wide)*	0.637\$ /min	c_{TR}^O	0.532\$/min
$\boldsymbol{c_{YC}^F}$ *(6-wide)*	0.454\$ /min	c_{ET}	2.430\$/min
$\boldsymbol{c_{YC}^o}$ *(6-wide)*	0.580\$ /min	c_V	10.55\$/min
Block and aisles geometrical input data			
$\boldsymbol{l_b}$	6.458 m	v_e	300 m/min
$\boldsymbol{w_r}$	2.838 m	v_l	200 m/min
$\boldsymbol{w_h}$	26 m	g_{QC}	2

Moreover, the yard inventory data used for the numerical study is the result of the sample illustrated in chapter 3 (Figure 3.2) where N_I =313,663 inbound containers, N_O =384,864 outbound containers, N_T =284,942 transshipment containers. The average yard inventory for the import yard is 3,808 containers with a maximum inventory peak of 4,936 containers. The average yard inventory for the export and transshipment yard is 8,108 containers with a maximum peak of 11,531 containers.

4.3.1 Results

The numerical study considers two different terminal layout (parallel and perpendicular), a block layout characterized by (L=34; W=9; H=6) and a quay length of 800m. The expected cycle times regarding the block layout considered (Lee and Kim, 2013) are:

Table 4.2: Input data related to expected times of terminal equipment and external trucks for a block layout (34,9,6)

		Parallel layout	Perpendicular layout
Yard Cranes	$E\left[t_{receiving}\right]$	1.59 min	2.30 min
	$E\left[t_{delivery}\right]$	2.78 min	3.60 min
	$E\left[t_{loading}\right]$	1.34 min	2.30 min
	$E\left[t_{unloading}\right]$	1.31 min	2.30 min
	$E\left[t_{rehandles}\right]$	1.63 min	1.63 min
Transport vehicles	$E[t_z^T]$	Expression [4.15]	Expression [4.16]
	$E[t_z^W]$	0.104 min	0.550 min
	$E[t_z^S]$	0.299 min	0.590 min
External trucks	$E\left[t^{TET}\right]$	Expression [4.26]	Expression [4.27]
	$E\left[t^{WET}\right]$	0.507 min	0.950 min
	$E\left[t^{SYC}\right]$	0.299 min	0.590 min

As it was previously mentioned, the optimal storage space utilization will differ for the import area than for the export and transshipment area, therefore the results of the numerical case have been solved separately for each terminal layout.

1) Parallel layout

- **Import area**

The total annual costs associated to the import storage area are depicted in Figure 4.3 for different space utilization rates.

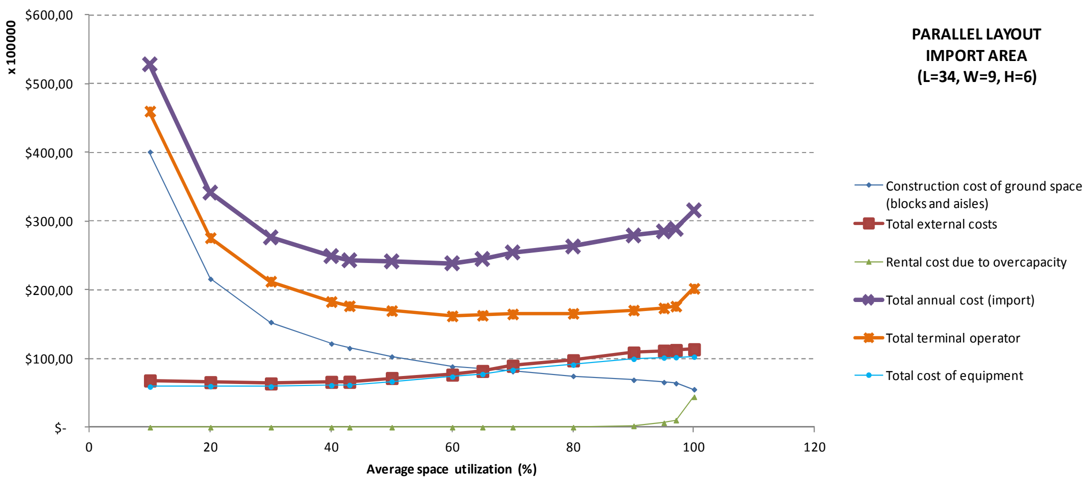


Figure 4.3: Optimal space utilization for the import area and parallel layout

As it can be observed the total system cost is a convex function which minimum value is registered at 62% of space utilization rate which, for this sample, is the optimal value for designing the import yard (6,140 slots). The terminal operator cost curve is similar to an exponential one because for lower space utilization rates cost are really high due to construction costs and then as space utilization decrease terminal operator costs decrease until these are stabilized because operating costs are mitigated by lower constructions costs. However, due to rental cost this curve grew up for space utilization rates higher than 90%.

External costs increase for lower values of space utilization due to as higher is the storage space longer will be the travel distance from the gate to the block storage for external trucks. Nonetheless, from 30% of space utilization onwards, total external costs increase due to congestion problems and operational delays occur in the terminal. This effect is also registered in the total cost of equipment where the impact of the space utilization on the operating cost is well seen. For higher space utilization rates, the container accessibility decrease and rehandles are required in retrieving processes.

- **Export and transshipment area**

Figure 4.4 depicted the related cost for the export and transshipment area in relation to different rates of space utilization. In such case, the optimal space utilization is 65% which is equivalent to a capacity of 12,470 slots.

Differently from the import area costs, in this case the effect of the space utilization in external and operating cost is smoother due to the impact of rehandling movements does not arise. Maybe for that reason, the space utilization ratio for the export and transshipment area is slightly higher than for the import area.

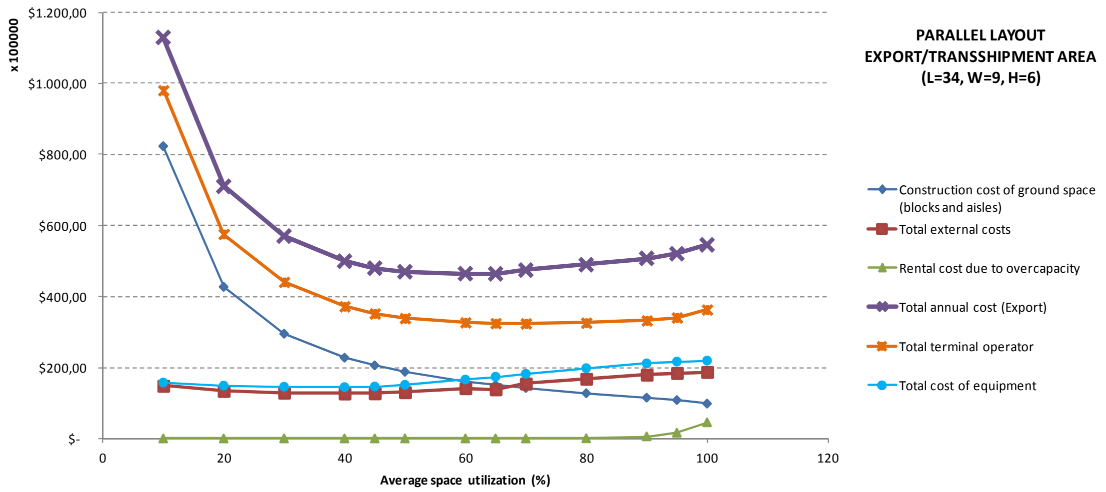


Figure 4.4: Optimal space utilization for the export and transshipment area and parallel layout

- **Summary**

To sum up, Table 4.3 illustrates the total amount of each cost factor for both import and export and transshipment area. Then total costs for the terminal operator and for the whole system are indicated as well.

The total number of slots for the import area is 6,140 units (33% of the total space provided) and the total number of slots for the export and transshipment area is 12,470 units which is equivalent to 4 blocks for inbound containers and 7 blocks for export and transshipment containers. The average stacking height for both storage areas is around 4 tiers.

The average annual cost (overall system) is slightly higher for the import area than the export and transshipment area, 3,880$/slot and 3,720$/slot, respectively. This difference is mainly generated by YC operating costs because in the import area is much higher than in the export and transshipment area (470$/slot versus 275$/slot). However, the cost differences between storage areas are minimized because the operating unit cost for transport vehicles and QC is much higher for the export and transshipment area because transshipment containers are handled twice.

Table 4.3: Optimal storage space utilization and related costs for the import area and export and transshipment area for parallel layout and L=34; W=9; H=6.

	IMPORT	EXPORT/ TRANSSHIPMENT	TOTAL
Storage space capacity (slots)	**6,140**	**12,470**	**18,610**
Optimal space utilization	**62%**	**65%**	**63%**
Construction cost of ground space (blocks and aisles)	8,827,600 $	15,093,105 $	23,920,710 $
Rental cost due to overcapacity	-$	- $	-$
Total cost of YCs	2,875,180 $	3,414,565 $	6,289,745 $
Total cost of QCs	3,534,320 $	10,890,370 $	14,424,690 $
Total cost of TRs	951,170 $	3,095,390 $	4,046,560 $
External truck costs	4,532,800 $	4,722,810 $	9,255,605 $
Vessel cost	3,122,965 $	9,157,860 $	12,280,825 $
Total terminal operator cost (annual)	**16,188,270 $**	**32,493,430 $**	**48,681,705 $**
Total overall system cost (annual)	**23,844,035 $**	**46,374,100 $**	**70,218,135 $**

2) Perpendicular layout

- **Import area**

The resulting cost curves regarding the import yard of a container terminal with a perpendicular layout are depicted in Figure 4.5.

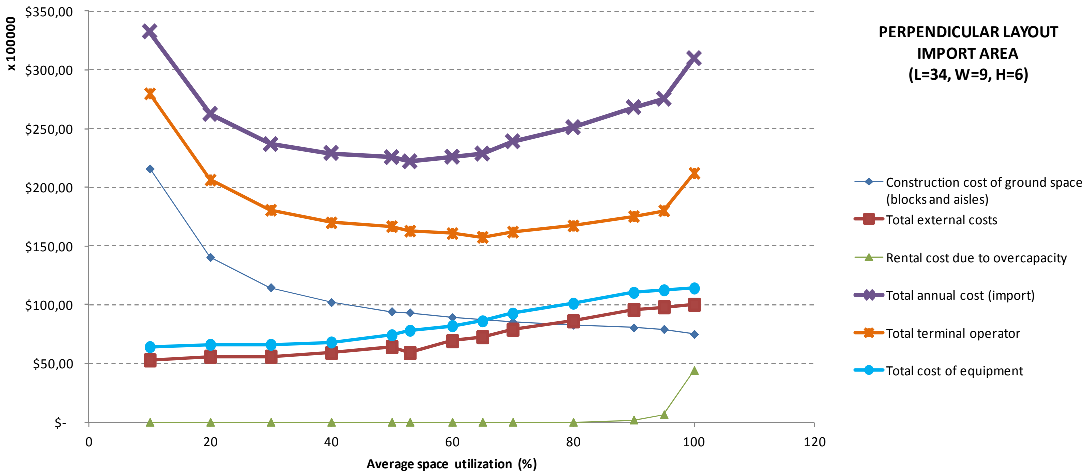


Figure 4.5: Optimal space utilization for the import area and perpendicular layout

In such case, the minimum total cost point (optimal value) occurs at about 53 percent of the total space provided for storage. This space utilization rate is equivalent to provide 7,186 slots organized in 4 blocks.

The YC operating equipment cost (included in equipment cost) is really important in the total amount of terminal operator costs (over 23% of the terminal operator cost belongs to YCs), due to higher cycle times are expected (receiving and delivering processes takes places at the edge of the block storage) and higher delays occur when space utilization increases. This effect is also reflected in the total terminal operator cost which curve is convex (costs increase for higher space utilization rates).

External costs mainly related to road trucks are also highly influenced by congestion effects on the storage yard, since the YC cycle time is higher for the perpendicular layout than for the parallel layout. Therefore, total system cost curve is convex (decrease for lower space utilization rates and increase for higher utilization rates).

- **Export and transshipment area**

Export and transshipment area for the perpendicular layout has a higher optimal space utilization rate than import area. In this case, the minimum cost is registered at 61 percent of the total space provided for storage, which is equivalent to a storage capacity of 13,285 slots organized in 8 blocks. The resulting cost curves are shown in Figure 4.6.

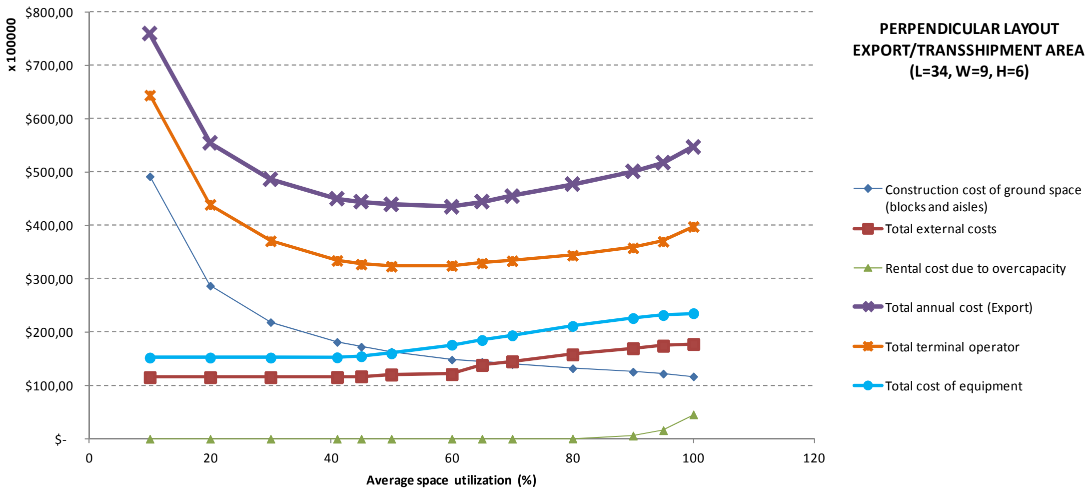


Figure 4.6: Optimal space utilization for the export and transshipment area and perpendicular layout

In such case, YC operating costs is much lower in comparison to the import area. It represents about 15% of the terminal operator cost. Contrarily, QCs operating costs is the most important operating cost which is close to 32% of the total cost of the terminal operator. The convex shape of total system and terminal operator cost is smoother than for the parallel layout because of the effect space utilization in operating costs is lower.

- **Summary**

In Table 4.4 costs related to the optimal space utilization rate for both storage areas are presented. As can be seen, the total amount of slots provided are 20,471 segregated into two different parts according to the following proportion: 35% for import and 65% for export and transshipment.

The average stacking height of the import yard is 3-tiers high and the average stacking height for the export and transshipment yard is about 4 tiers high.

Table 4.4: Optimal storage space utilization and related costs for the import area and export and transshipment area for perpendicular layout and L=34; W=9; H=6

	IMPORT	EXPORT/ TRANSSHIPMENT	TOTAL
Storage space capacity (slots)	**7,186**	**13,285**	**20,471**
Optimal space utilization	**53%**	**61%**	**58%**
Construction cost of ground space (blocks and aisles)	9,329,740 $	14,835,320 $	24,165,060 $
Rental cost due to overcapacity	- $	- $	- $
Total cost of YCs	3,763,255 $	4,859,270 $	8,622,520 $
Total cost of QCs	3,280,230 $	10,371,920 $	13,652,150 $
Total cost of TRs	756,425 $	2,388,930 $	3,145,355 $
External truck costs	2,853,990 $	3,428,485 $	6,282,475 $
Vessel cost	3,043,455 $	7,591,975 $	10,635,430 $
Total terminal operator cost (annual)	**17,129,650 $**	**32,455,440 $**	**49,585,085 $**
Total overall system cost (annual)	**23,027,095 $**	**43,475,900 $**	**66,502,990 $**

Although YC operating cost for the import yard is higher than for the export and transshipment area, the total system unitary cost for the import yard is lower (3,200 $/slot) than for the export/transshipment yard (3,275 $/slot).

3) Comparison between parallel and perpendicular layout and discussion

- Results from the numerical case show that for the same space requirement alongside a year the optimal space provided for the import yard considering a perpendicular layout is 17% higher than for a parallel layout and 6.5% higher for the export/transshipment area.
- Storage space provided for the import yard is higher than for the export/transshipment yard in unitary terms. Under the assumption that the terminal layout is perpendicular it is stated that the space utilization for the import yard is 53% and for the export/transshipment is 61%. This means that more space is required by inbound containers.
- For the parallel layout, the additional requirement comparing import and export/transshipment yard area is slightly higher. Particularly from the numerical case, the optimal space utilization is 62% versus 65%.
- Even though the optimal total space provided for the perpendicular layout is 10% higher than for the parallel layout, the total system costs for the parallel layout are about 7% higher which is in accordance with previous studies such as Kim et al. (2008) and Lee and Kim (2013).
- Unitary costs for the parallel layout are 16% higher than perpendicular layout (3,775 $/slots and 3,250 $/slot, respectively). This is because the fact that for the parallel layout construction cost, transporter vehicles operating cost and cost related to external trucks in the terminal are higher since longer travel distance are required.

- YC operating cost is much higher for the perpendicular layout than for the parallel layout because YC travel distance within the block is longer since road trucks and transporters are placed at the block edge. Particularly, from the numerical case it is 36% higher.

4.3.2 Further numerical experiments

To show the variability of the optimal space utilization rate additional numerical experiments have been carried out.

The first set of experiments (E1 and E2) is related to the block layout. In such case, two additional numerical experiments are developed to determine the optimal size of the storage capacity. The goal under this experiments is to analyze the effect of the maximum height on YC operating costs and therefore on the optimal space utilization.

Then, a sensitivity analysis on the unitary construction cost, equipment operating costs and external cost is done (experiments E3-E8). Since the effect of fixed cost with the space utilization is in the opposite way than variable costs such as operating equipment and external cost is interested to evaluate it. The results are summarized in Table 4.5.

Table 4.5: Sensitivity analysis results: optimal space utilization and storage capacity

		Parallel layout		**Perpendicular layout**	
	Block layout	**Import Yard**	**Export/transshipment yard**	**Import Yard**	**Export/transshipment yard**
Base case	L=34; W=9;H=6	62% 6,140 slots	65% 12,470 slots	53% 7,186 slots	61% 13,285 slots
E1	L=27; W=6; H=4	70% 5,442 slots	72% 11,585 slots	-	-
E2	L=40; W=9; H=5	-	-	59% 6,454 slots	62% 13,068slots
E3	L=34; W=9;H=6 c_G/2	53% 7,178 slots	55% 14,740 slots	48% 7,934 slots	55% 14,717 slots
E4	L=34; W=9;H=6 2c_G	68% 5,600 slots	80% 10,110 slots	55% 6,923 slots	68% 11,923 slots
E5	L=34; W=9;H=6 Op costs/2	70% 5,436 slots	68% 11,918 slots	56% 6,798 slots	65% 12,455 slots
E6	L=34; W=9;H=6 2op.costs	52% 7,320 slots	55% 14,740 slots	45% 8,460 slots	53% 15,272 slots
E7	L=34; W=9;H=6 External/2	68% 5,600 slots	65% 12,470 slots	52% 7,320 slots	60% 13,507 slots
E8	L=34; W=9;H=6 2external	54% 7,051 slots	56% 14,460 slots	48% 7,934 slots	57% 14,225 slots

The following statements are derived from previous results:

- In the first experiment (E1) where the block layout has a maximum height of 4 tiers and 6 stacks per bay, the optimal space utilization is about 70-72% and no big differences arise between the import and export/transshipment yard areas (for parallel layout). In this case, the space utilization is higher than the base case because operating costs are lower, so it is reasonable that the space utilization increases.

- A similar effect occurs in experiment E2, where the block layout has a maximum height of 5 tiers. The optimal space utilization for the import yard is 59% and for the export/transshipment area is 62%. In this sample, the differences between both areas are not as larger as in the base case.
- Results from experiments E3 and E4 show that when the construction cost is higher, the optimal space utilization increase, as a consequence it is suggested to construct a smaller storage area. However, when construction cost is lower, the optimal space utilization point becomes smaller because operating and external cost becomes more important controlling the effect of total cost curve. For instance, and according to the experiments, the optimal space utilization can reach the 80 percent for the export and transshipment area in a parallel layout and 68 percent for the perpendicular layout.
- When operating costs are reduced (E5) the optimal space utilization is increased. The effect of the space utilization in costs is not as dramatic as the base case; therefore it is affordable higher utilization rates of the storage yard. Contrarily, when the operating costs increase the optimal space utilization decrease (E6).
- Similar effects and consequences arise in scenarios E7 and E8, where the cost related to external elements is changed (road trucks and vessel). When external costs are reduced, the optimal space utilization rate is higher but when external costs are larger, then the optimal space utilization point decrease.

4.4 Conclusions

This chapter addressed an integrated yard planning problem for determining the optimal storage space capacity taking into account the terminal performance and the yard inventory dealing explicitly with stochastic effects and seasonal fluctuations (output from the model developed in chapter 3).

The analysis proposes an optimization model to determine how much space should be provided for the storage area. The objective is to minimize the total integrated cost which consists of the cost for the terminal operator and external costs related to road trucks and vessels. The effect of the space utilization on terminal performance is included in the cost formulation in such way that when yard inventory rates are close to capacity operating and equipment overhead costs increase. Moreover, a mixed strategy in which private and rental storage space is combined is considered in the cost model. The optimization model has been applied for two different yard layouts (parallel and perpendicular) and separately for the inbound and export and transshipment storage area because operating processes and design requirements differ.

It was found, in the numerical case where the stacking height was 6 tiers, that the optimal space utilization for the import storage area is about 62% for the parallel layout and 53% for the perpendicular layout and for the export and transshipment area is 65% about for the parallel layout and 61% for the perpendicular layout. Nonetheless, regarding the parallel layout, the optimal space utilization rates ranges from [52-70%] and [55-80%] for import and export and transshipment area, respectively. For the perpendicular layout, optimal space utilization is lower because YC operating costs are higher. Therefore, the optimal space utilization are within the range [45-60%] and [51-68%], for import and export and transshipment area, respectively. The main factors affecting the optimal results are construction cost, operating cost and the stacking height. The optimal space utilization is higher for a block layout with lower stacking height because operating cost is lower since rehandling movements are lower. That is the main reason why the space utilization for the import yard is lower than for the export and transshipment yard.

Regarding the comparison between the parallel and perpendicular layout, it was found that the space provided for the perpendicular layout is 10% higher than for the parallel layout but total integrated costs for the parallel layout are 6% higher. This is because the fact that for the parallel layout construction cost, transporter vehicles operating cost and cost related to external trucks in the terminal are higher as longer travel distance are required.

Chapter 5

Space allocating strategies for improving import yard performance

5.1 Introduction

Multi-level stacking is one of the solutions most commonly used by terminal operators to increase the storage capacity, especially in those seasons alongside the year when the space requirement is high and the number of ground slots is not enough. However, increasing the yard storage productivity and density has some negative effects on the yard performance because over-stacking involves rehandling movements during pickup operations. As a consequence, decreasing the productivity and efficiency of handling process derives in higher operating costs and delays on road truck turnaround times.

A rehandling movement is an unproductive YC move required to reallocate the containers stacked over the target container during the retrieval process. In general terms, the containers stored for a long time in the terminal (hereafter “old” containers) will be retrieved firstly than the containers that have just arrived to the terminal (hereafter “new” container). Furthermore, according to the arrival sequence, old containers will be beneath by new containers, which suppose an additional disadvantage.

As it is observed, the stacking problem is really complex because of the uncertainty regarding which container will be retrieved first and even more for import containers because the information available on the departure time is unknown while containers are stacked, since trucks’ arrival time at the terminal to pick up the containers is random.

In such context, the storage and stacking strategies are presented as a potential solution to the storage space allocation problem. As it was previously mentioned in the literature review, the target of the allocating problem is to determine the optimal available position for each container arriving to the terminal for minimizing the incidence of rehandling in future retrieval processes.

Thereby, the goal of this chapter is to introduce new allocating strategies for import containers in order to improve the efficiency of handling operations. The strategies will define the generic rules and actions for allocating import containers in the yard with the aim of minimizing rehandling moves.

Differently from already existing storage strategies for import containers, the new strategies will take into account the container arrival and departure rate, the storage yard capacity and the additional effects derived from mixing containers from different vessels in the same stack.

This chapter is organized as follows: section 5.2 analyzes previous storage strategies and introduces the three different new strategies and its operating procedure. Section 5.3 presents the mathematical model used to estimate the expected number of rehandles when containers with different departure probability are mixed and Section 5.4 provides the results of a numerical case. Finally, conclusions are drawn in Section 5.5.

5.2 Import storage strategies

5.2.1 Overview

In the literature review we have seen that there are two strategies for space allocation for import containers: the non-segregation and segregation strategies. These strategies were introduced by De Castilho and Daganzo (1993) and were later analyzed by Kim and Kim (1999) and Huynh (2008).

The non-segregation strategy consists of stacking new containers on top of old containers without taking into account the arrival time, the dwell time of the stored containers in the yard and the available information on containers at the time of placement. This strategy tends to mix containers from different ships in the yard, and consequently it can generate a large amount of extra moves per container (see De Castilho and Daganzo (1993) for a detailed explanation). This type of extra move is called a rehandling move (sometimes known as a shifting move) and is deployed to remove the containers stored over the target container (requested by inland transportation).

On the other hand, the segregation strategy does not allow containers from different ships to be mixed. The containers from each ship are located in a specific storage area or block. In that case, the number of extra moves per container can decrease but some sub-blocks will have to be moved to store new incoming containers. This extra work requires new extra operating moves to transfer the old containers to the area where new containers will be stored. These moves are called clearing moves and are carried out before a new container ship arrives at the terminal. Since containers are requested by inland transportation randomly, some rehandling moves will be also necessary.

To sum up, we have seen that there are two kinds of unproductive moves depending on the strategy used: rehandling and clearing moves. The first type of move is related to the vertical position of the container within the stack, and clearing moves are used to replace old containers still in the sub-block.

So, this study aims to determine under which conditions new containers can be stacked on top of old ones, based on the number of rehandling moves generated. Rehandling moves depend on the container dwell time and arrival time, and on the applied strategy. De Castilho and Daganzo (1993) found a solution in general terms; the objective of this thesis is to further refine these previous findings and define specific strategies for intermediate cases, that is, cases that cannot be explained using solely a non-segregation or segregation strategy.

5.2.2 Strategies

In the following part of the chapter, more detailed storage strategies for import containers are introduced to try to reduce unproductive moves and minimize their associated operating costs. Before defining the strategy and the operating mechanism, it is necessary to mention some key aspects and variables associated with the proposed strategies:

- The container arrival time is taken into account because it will be necessary to determine the probability of the container being picked up. This probability increases with storage duration, which allows new containers to be placed and reduces the number of rehandling moves.
- The time between ship arrivals (inter-arrival time) can affect container departure probability, so we will avoid storing new containers on top of ones that are likely to be picked up sooner; otherwise, the expected number of moves per retrieval would increase, because the containers needed would be buried under new ones.
- The average time that containers are stored in the container yard (dwell time). There are specific kinds of goods that are requested by road or rail to leave the terminal before their arrival at the terminal; but others remain stored in the terminal for long periods of time, thus reducing the terminal throughput.

Each strategy has two stages: in the first stage, the containers from different ships are segregated (static strategy); and in the second stage, each strategy has its own procedure to mix the containers from different vessels, trying to make efficient use of the storage space by applying a combination of both static and dynamic strategies.

1) First Stage

As mentioned above, containers from different ships are segregated in the storage yard. As a consequence, the import block is divided into different sub-blocks whose size depends on the volume of containers unloaded from the vessel and the criteria for the maximum stacking height, which depend on the storage equipment. The stacking height has an upper bound limited by the RMG span but the optimal height will be prescribed by demand and unproductive moves. Generally, we will use the total available height.

Once the containers are unloaded from the vessel and afterwards transferred to the storage yard, RMG cranes store inbound containers in the terminal, maximizing the available height and the block width. As a consequence, the number of bays used depends on the number of containers unloaded, the number of rows and the stacking height (expression [5.1]), that is:

$$b = \frac{n}{r \cdot h} \qquad [5.1]$$

where b is the number of bays used by cargoes unloaded from vessel V_i, n the number of containers unloaded from vessel V_i, r the number of rows in which width is divided and h is the maximum height available.

The **filling sequence** during the first stage is defined as follows:

The groups of containers will be placed in an area with dimensions r, h and b b_i . Once goods are stored in the yard, the containers can be retrieved from the terminal. Thenceforth, the amount of containers will decrease by a specific rate according to the characteristics of the goods. Consequently, the bay occupancy rate will decrease as time increases. The operating movements for retrieving containers from the yard and loading them onto trucks or trains are carried out during the inter-arrival time of two consecutive vessels.

The process described is repeated until the block is full to capacity, i.e., when a new import batch of containers arrives at the terminal and there is not enough space to accommodate it. Under such circumstances, the terminal operators will try to rearrange the different groups of bays (sub-blocks) created during the first stage to receive the new cargo.

The handling effort carried out during the first stage consists of the operation needed to store containers in the yard and to retrieve containers when requested by the transportation carriers. Storing the containers carried by different ships in separated bays aims to reduce the number of rehandling moves. We have seen that these directly depend on the stack height but they are also related to the configuration of the stacks. Generally, if all the containers have the same probability of leaving the terminal (under the same characteristics and dwell time in the terminal), the number of rehandling moves per container will be minimized and will just be related to the sequencing order for leaving the terminal, considered to be random.

In those cases where the available space does not allow the segregation of containers from different ships because the space is scarce, the terminal operators will try to manage their terminal resources optimally to increase the capacity and to satisfy the clients' demand. This is when storage and stacking strategies become important and useful. The alternatives suggested from this stage are described in the second stage.

2) Second Stage

The second stage consists of a decision-making process, which will help the terminal operator to choose the best option. The decision-making process is based mainly on two criteria:

- Which groups of containers should be mixed to reduce the number of unproductive moves (rehandles)?
- Is it worth reallocating old containers to keep clear areas for new containers (clearing moves)?

The answer to the above questions depends, for instance, on the number of old containers in each group, the containers' probability of leaving the terminal and the space the new containers may require.

The proposed **strategies** are:

- ***Strategy 1 (S1)***

  The first strategy consists in starting to fill the oldest group of sub-blocks of the storage yard (the one composed by the containers that have been at the storage yard for a longer time), that is, stacking new containers on top of the ones that are already stored in the yard and belong to the oldest group of containers (see Figure 5.1).

  However, a longer time in the terminal entails a higher probability of leaving, which in turn entails an increase in rehandling moves. However, the amount of containers in the oldest stacks will be lower, so, it will be very likely that this stack will be almost filled with new containers from the same ship.

  This additional expected number of rehandling movements is due to the fact that the stacks are made up of containers with different times of leaving the terminal and different probabilities of being requested. In addition, the containers that are supposed to leave the terminal sooner (a longer time at the terminal) are placed under containers that have spent a shorter time in the terminal. The total expected number of rehandles, however, will depend on the number of remaining containers and the probability of leaving the terminal.

- ***Strategy 2 (S2)***

  The second strategy follows the same operative as the first strategy did, although the filling order in the import block is just the opposite: it starts mixing those groups of containers with a shorter time at the terminal with those that have just arrived, in other words, the last group that has been stored in the terminal with the new inbound containers (see Figure 5.1).

  The stacks in S_1 contain few old containers and many new containers, which means that there are few containers with a high probability of leaving the terminal and, therefore, generating rehandling movements. The stacks in S_2 contain mainly old containers and few new containers, so that the probability of leaving the terminal of both new and old containers is almost the same, i.e., the difference in probability of leaving the terminal depends on the inter-arrival time.

  According to the configuration of the stacks, we can foresee a similar behavior or a higher chance of leaving the terminal for both kinds of containers. In other words, the stacks will be quite homogeneous as regards the probability of leaving the terminal (for smaller values of inter-arrival time). Under such circumstances, the increase in rehandling movements produced by the mixture will depend on the inter-arrival time between the two groups and, therefore, their associated probability.

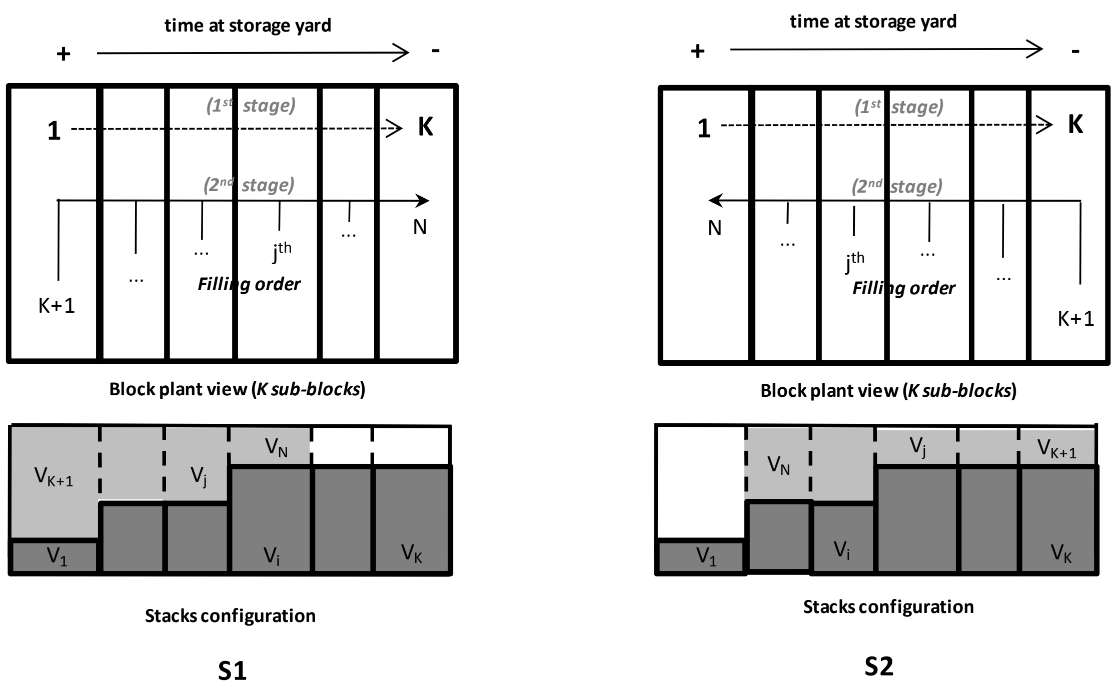


Figure 5.1: General scheme of strategies S_1 and S_2.

- ***Strategy 3 (S3)***

The third strategy requires clearing movements and rehandles during the operational planning. It consists in replacing old containers that are still in the terminal when new cargo is ready to be unloaded in the terminal. These new containers will be stored in those bays with fewer remaining containers, which in turn have the highest probability of leaving the terminal (Figure 5.2).

Once the destination sub-block is chosen, RMG cranes will move the remaining containers and store them on top of stacks made up of the containers that were already stored in the import block. These stacks, therefore, mix old containers: the containers that were stored in the target sub-block and the containers that have been replaced from the first sub-block. On the other hand, the new containers will be placed in the cleared area (first sub-block). The internal movements of containers are called clearing movements and are carried out between ships' arrivals.

The replaced containers are stored on top of the stack, thus reducing the chance of being rehandled again because they are supposed to leave the terminal sooner than the rest of the units from the same stack.

The handling and operating costs in this strategy will be determined by the amount of replaced containers and rehandling moves. Few containers in the group of bays will entail few clearing moves.

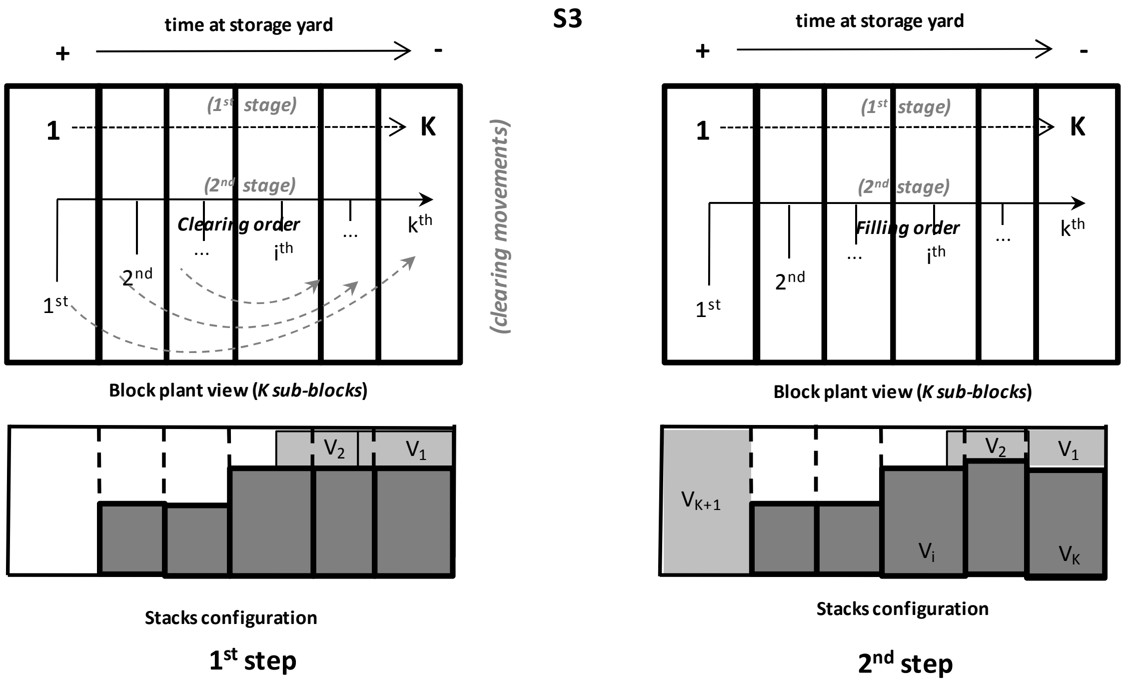


Figure 5.2: General scheme of strategy S_3.

5.3 Model development

The previous sections have proved that the higher the stacks are, the higher the amount of unproductive moves or rehandles will be. The efficiency of operations will thus decrease, which in turn entails an increase in operating costs.

The objective of the model developed is to determine the expected amount of total rehandles for different import storage yard strategies. This will allow us to compare the different strategies proposed and decide which is the most convenient depending on the most important variables.

5.3.1 Assumptions and notations

The analysis is based on the following assumptions and notations.

Assumptions:

- Ships' inter-arrival time is constant.
- The number of containers is constant for all ships.
- The dwell time in the storage area follows a Weibull distribution. Other authors such as Watanabe (2001) and Zhang et al. (2003) assumed an exponential distribution to characterize the containers' departure process. This exponential distribution function is a specific case of the Weibull distribution.
- The import block is divided into *K* groups of bays (sub-blocks) and each sub-block has the same capacity.
- The maximum stack height is limited.

- The applied strategies are described in section 5.2.2.
- It is not allowed to mix containers from more than two different ships in the same sub-block.
- It is assumed that the time-planning horizon is cyclical (Figure 5.3).
- Secondary rehandles have not been taken into consideration in the model.

When a container is rehandled, it is moved to another stack within the same bay, which may or may not generate more rehandles (secondary rehandles), depending on where the containers are moved to.

According to the literature, it is valid to make the following assumption:

- Let´s consider homogeneous stacks (composed of containers with the same departure probability at time *t*). If rehandles are generated, the rehandled containers moved to other stacks may in turn generate new rehandles. These additional rehandles (secondary) represent an insignificant percentage relative to the total number of rehandles. According to Kim and Kim (1999), only 4% of the total rehandles were secondary, assuming a bay width of 6 rows and a stacking height of 6 tiers. They concluded that the majority of rehandles is generated by stacking containers higher. Therefore, the basic factor determining rehandles is the stacking height and not the secondary rehandles.
- Other authors such as Imai et al. (2002, 2006) do not take those additional moves into consideration. They assumed that rehandled containers are moved back to their original stack once the target container was retrieved from the storage area, and, thus, the generation of secondary rehandles is avoided.

Figure 5.3 shows the arrival planning during a specific period of time, which recurs cyclically (cyclic-time). This hypothesis was also introduced by Kim and Kim (1999) and will be used to solve the numerical case.

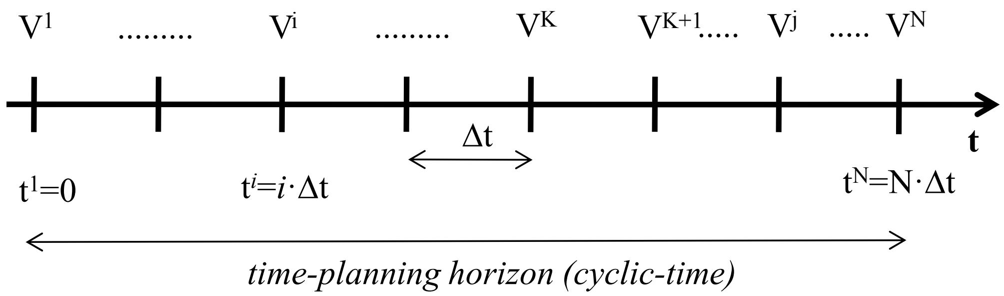


Figure 5.3: Diagram of arrival rates at the terminal and time-planning horizon.

Notation:

N Overall number of vessels arriving at the terminal.

K Number of sub-blocks in the import storage block. Each sub-block stacks containers from the same vessel (same capacity).

i Index that can stand for the values covered by [1,K] (sub-blocks).

j	Index that can stand for the values covered by [K+1,N].
n	Volume of containers unloaded from each vessel.
h	Maximum number of containers per stack.
ΔT	Ship inter-arrival time, which is constant.
t^i	Arrival time of vessel V^i, $i \in [1, K]$.
t^j	Arrival time of vessel V^j, $j \in [K+1, N]$.
V^i	Label assigned to vessels whose containers are stored in the K sub-blocks, $i \in [1, K]$.
V^j	Label for the vessels arriving at the terminal after the specific time t_j.
$\delta_j^{S_y}$	Number of sub-blocks needed to accommodate the new inbound containers from vessel V_j, using strategy S_y, $y \in [1,3]$.
$C_j^{S_y}$	Set including all the container combinations for each strategy S_y, $y \in [1,3]$.
$s_{(i,j)}$	Number of stacks combining containers from vessels V_i and V_j.
ΔR_{ij}	Increase in the amount of rehandles relative to a homogeneous stack, expressed as a percentage.

5.3.2 The model

Overview on probabilistic functions

As it was already introduced in Chapter 3, the container dwell time is typically considered to be a non-negative continuous random variable, whose probability distribution function is $F(t) = Pr(T \leq t)$ and the corresponding survivor function is $Pr(T > t) = 1 - F(t)$=$S(t)$ (since we are just dealing with inbound container in this chapter the random variable T^I is simplified to T). In this thesis, it is assumed that the distribution function is approximated to a Weibull distribution.

Next, the probability that the event of interest (a container leaving the terminal) occurs in the interval $(t + dt]$, given that it has not occurred by t, is:

$$h(t) = \lim_{dt \to 0} \frac{P(t \leq T \leq t + dt | T \geq t)}{dt} = \frac{f(t)}{S(t)} \qquad [5.2]$$

This function, $h(t)$, is known as the hazard function and represents the instantaneous rate at which the event of interest will occur at time t, given that it has not occurred up to this time. It follows that the probability of the container leaving at time interval $(t, t + dt]$ is approximately $h(t)\Delta t$ for infinitesimal values of Δt (Kiefer, 1988).

For the particular case of exponential distribution, the instantaneous rate or hazard function exhibits no time dependence (the hazard rate is constant), which entails that the probability of leaving at the following time interval does not depend on the amount of time the container has stayed in the yard.

Calculation of vertical rehandles for a homogeneous stack

This section focuses on calculating the rehandling movements per stack made up of same-ship containers (therefore, these containers have the same probability of leaving the terminal by time t). As stated in section 4, during the first stage of the proposed strategies, while filling the first K sub-blocks, the containers are segregated depending on which vessel they come from.

Kim and Kim (1999) shows that the amount of rehandles per container depends on the tier it occupies within the stack. A container on top of the stack will entail no rehandles at all, whereas a container stored on the ground will entail $(h-1)$ rehandles, h being the amount of containers stacked over it.

The vertical rehandles per stack will be quantified by calculating the expected number of rehandles (per stack and time t), where each container requires a specific amount of rehandles (depending on the vertical position of the container), that is:

$$E[R(t)] = \sum_{R=0}^{h-1} R \cdot P_R(t) \qquad \forall\, t \geq 0 \qquad [5.3]$$

where R is the amount of possible rehandles per container and $P_R(t)$ the probability that R rehandles are required at t.

The next step, therefore, consists of defining the probability of needing R rehandles in a stack with h containers ($P_R(t),\ R \in [1, h-1)$]. For instance, let's consider a hypothetical case where a stack is made up of three containers and we want to calculate the probability of needing R rehandles, where, in this case, $R = \{1,2\}$.

To determine the probability of $R=2$ rehandles we will first need to define all the possible instances requiring two rehandles. This only applies to a possible instance: the container on the ground leaves the terminal at t and, in turn, the two containers stacked over it (tiers 2 and 3) do not leave the terminal at the same time.

Therefore, the probability will be determined by two events: "the container on the ground leaves the terminal" and "the containers over the container on the ground remain at the terminal". It can be expressed analytically as the product between the probability of a container leaving the terminal $f(t)$ at t and the probability of the two remaining containers staying at the terminal $S(t)$.

On the other hand, the probability of $R=1$ in a three-container stack at t will result from adding: the probability of the 'in-between' container (second tier) leaving the terminal $f(t)$ (whereas the two other containers stay at the terminal, $S(t)$), and the probability that another container has already left the terminal $F(t)$ and that another container $f(t)$ (with another container over it) leaves the terminal at t.

Considering stacks with h containers, the following expression is obtained:

$$P_{R=h-1}(t) = f(t) \prod_{r=1}^{h-1} S_r(t) = f(t)(1-F_r)^{(h-1)} \qquad [5.4a]$$

$$P_{R=h-2}(t) = f(t) \prod_{r=1}^{h-1} S_r(t) + \binom{h}{1} f(t) F(t) \prod_{r=1}^{h-2} S_r(t) \qquad [5.4b]$$

$$\vdots$$

$$P_{R=1}(t) = f(t)\prod_{r=1}^{h-1} S_r(t) + \binom{h}{1} f(t)F(t)\prod_{r=1}^{h-2} S_r(t) + \cdots + \binom{h}{h-3} f(t)F^{(h-3)}(t)\prod_{r=1}^{2} S_r(t) + + \binom{h}{h-2} f(t)F^{(h-2)}(t)\prod_{r=1}^{1} S_r(t) \quad [5.4c]$$

The probability density function, $f(t)$, stands for the probability of a container leaving the terminal at a specific time, given that this container has been stored at the terminal until this time, which derives from the conditional probability or *hazard* function, $h(t)$, (equation 3), where the numerator, $f(t)$, is the probability of leaving the terminal at t, whereas the denominator stands for the condition the container has survived until t.

By having defined the expected value of the number of rehandles in a stack at t and by combining expressions [5.3] and [5.4] we obtain an analytic expression determining the average number of rehandles for a stack made up of h containers from a vessel V^i (with the same probability of leaving the terminal) and for a specific period of time,$[t^i, \infty]$, that is:

$$E_i[R] = \int_{t^i}^{\infty} E_i[R(t)]dt \qquad \forall\, t_i \geq 0 \quad [5.5]$$

Calculation of vertical rehandles for a heterogeneous stack

We hereby aim to calculate the rehandles required by a stack made up of containers from different vessels and, therefore, with different probabilities of leaving the terminal.

The starting point is the arrival of vessel V^{K+1}, whose freight is to be stacked over the containers that are already stored at the terminal (old containers) at the time the vessel arrives, t_{k+1}, or whenever it is necessary to replace the remaining containers in a specific sub-block to clear space for new inbound freight (strategy S_3).

Thus, first we need to know the amount of containers in each sub-block at time $t_j, j \geq K+1$, since the occupancy rate of the yard will determine the suitability of the strategies suggested in this thesis. The occupancy rate is determined mainly by the container departure rates (by means of the parameters characterizing Weibull's distribution, c and λ) and the time elapsed between vessel arrivals (ΔT).

Depending on these parameters we obtain the probability of having z containers, $z \in [0, h]$, in a stack at a given time t, whereas at the beginning there were h containers coming from the same vessel per stack (bear in mind that the segregation strategy is applied during the first stage to fill the first K sub-blocks).

Assuming that all the containers in the stack come from the same vessel and, therefore, they share the same characteristics and probability of leaving the terminal, the analytic expression defining the probability of having z, $z \in [0, h]$, containers stored in the yard at t is:

$$P_h(t) = \prod_{z=1}^{h} S_z(t) = \prod_{z=1}^{h} \left(1 - F_z(t)\right) \quad [5.6a]$$

$$P_{h-1}(t) = \binom{h}{1} F(t) \prod_{z=1}^{h-1} S_z(t) = \left(\frac{h!}{(h-1)!}\right) F(t) \prod_{z=1}^{h-1} (1 - F_z(t)) \qquad [5.6b]$$

$$\vdots$$

$$P_1(t) = \binom{h}{h-1} S(t) \prod_{z=1}^{h-1} F_z(t) = \left(\frac{h!}{(h-1)!}\right) \left(1 - F(t)\right) \prod_{z=1}^{h-1} F_z(t) \qquad [5.6c]$$

$$P_0(t) = \prod_{z=1}^{h} F_z(t) \qquad [5.6d]$$

Since this stack is made up exclusively of containers coming from the same vessel, the distribution function $F_z(t)$ will be the same for all the containers in this stack. Therefore, $F_z(t) = F(t)\ \forall z$. Thus, the previous expressions can be synthesized as follows:

$$P_z(t) = \binom{h}{h-z} S(t)^z F(t)^{h-z} \qquad [5.7]$$

Derived from equation [5.7], the expected value of the number of containers in a stack at t, $E[H(t)]$ will be given by:

$$E[H(t)] = \sum_{z=0}^{h} z \cdot P_z(t) \qquad \forall\, z\epsilon[0, h] \qquad [5.8]$$

Since the container arrival times at the terminal differ and taking into account that the reference time corresponds to the arrival time of the containers unloaded from the first vessel (V^1 in $t^1=0$), it will be necessary to know the occupancy rate of each sub-block when a new vessel V^j in $t^j, j \geq K+1$ arrives.

Therefore, if we consider a specific time, t^j, and if we analyze the occupancy rate of the terminal at this same time (Figure 5.4: stack configuration at $t < t^j$), the final configuration of the stacks per sub-block can be determined once the containers from vessel V^j (Figure 5.4: stack configuration at $t > t^j$) are stacked and, then, it will also be possible to quantify the vertical rehandles a specific stack of the analyzed sub-block requires (see Figure 5.4). The standard configuration of stacks will be $(z,\ h-z)$ where z, $z \in [0, h]$ are the containers from vessel V^i, $i \leq K$, and $h - z$ is the amount of containers from vessel V^j, $j \geq K+1$, per stack.

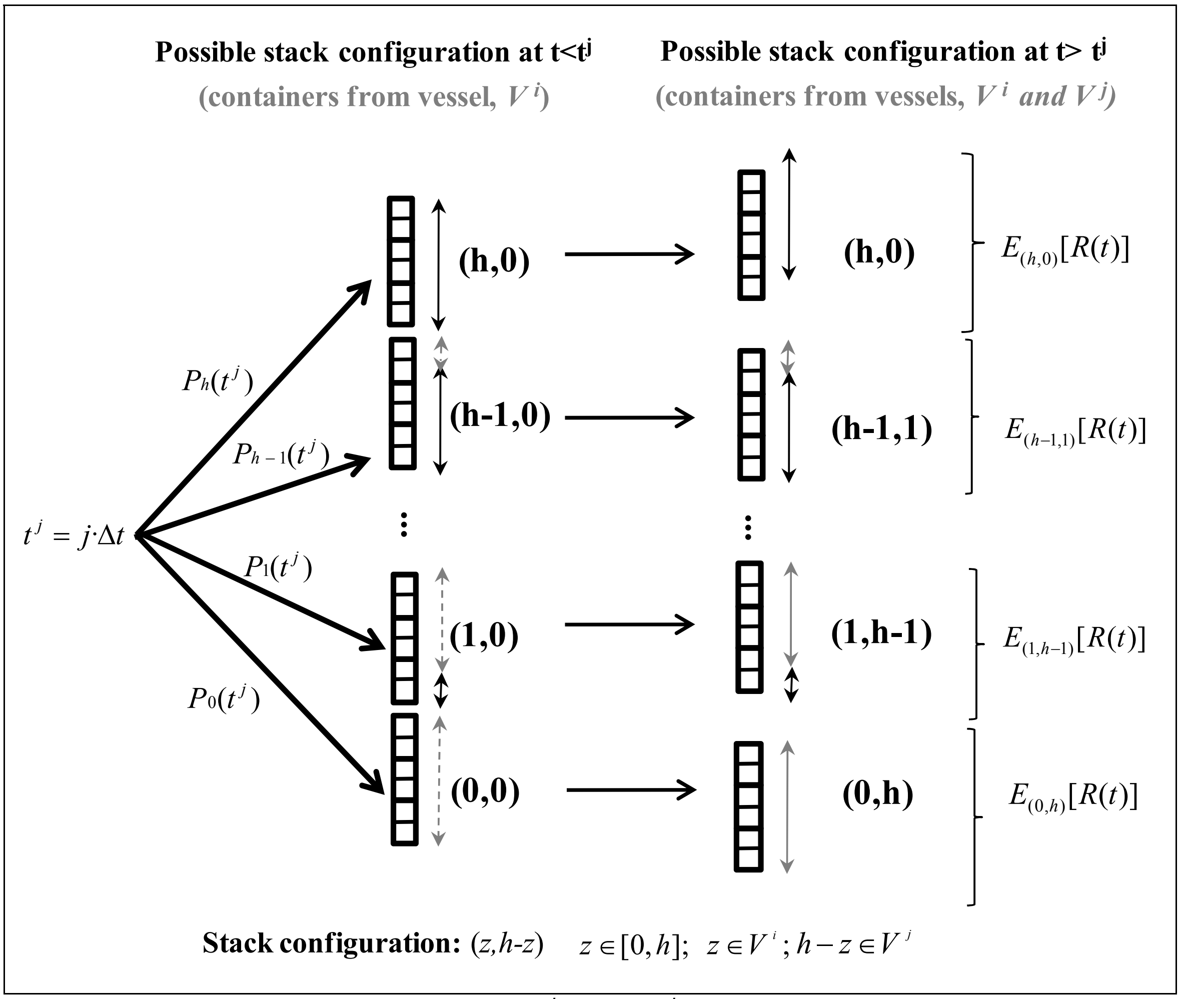


Figure 5.4: Possible stack configuration at $t < t^j$ and $t > t^j$.

Figure 5.4 allows the derivation of an analytic expression quantifying the expected value of the rehandles required by a stack with z containers from vessel V^i, $i \in [1, K]$, and $(h - z)$ containers from vessel V^j, $j \in [K + 1, N]$. This analytic expression will be given by:

$$E_{ij}[R(t)] = \sum_{z=0}^{h} P_z(t^j - t^i) \cdot E_{z,h-z}[R(t)] \qquad \forall t > t^j \tag{5.9}$$

Finally, by integrating the expected value of the rehandles for a period of time covered by $[t^j, \infty]$, we obtain the number of resulting rehandles when mixing containers from vessels V^i and V^j from t^j on, that is:

$$E_{ij}[R] = \int_{t^j}^{\infty} E_{ij}[R(t)]dt \qquad \forall t > t^j \tag{5.10}$$

Calculation of the total number of rehandles for each strategy

This section develops the model that will determine the volume of both vertical and horizontal (clearing moves) rehandles from the expressions developed in the previous sections and for each strategy.

A specific implementation procedure of the model will be used for each strategy, even though the defined methodological scheme applies to all the strategies.

One of the main variables for evaluating rehandles is the occupancy rate of the *K* sub-blocks at the time when containers from vessels V^j , $j \in [K+1, N]$ arrive. These containers will be allocated to these *K* sub-blocks.

The occupancy rate of the yard can be defined from the hollow matrix **B**, whose components, $b_{m,i}$, represent the number of empty slots in the sub-block i at t_j, when vessels V^j, $j \in [K+1, N]$, arrive (to simplify the notation, the parameter $m = j - K$, $m \in [1, N-K]$, has been introduced). Therefore, each row in the matrix shows the occupancy rate of the yard at each t^j, whereas each column presents the occupancy rate of each block at t^j, $j \in [K+1, N]$. Therefore, this matrix consists of *K* columns and $(N-K)$ rows, that is:

$$\mathrm{B}_{[(\mathrm{N-K})\ \mathrm{x}\ (\mathrm{K})]} = \begin{bmatrix} b_{1,1} & \cdots & b_{1,K} \\ \vdots & \ddots & \vdots \\ b_{(N-K),1} & \cdots & b_{(N-K),K} \end{bmatrix} \qquad [5.11]$$

where the matrix components $b_{m,i}$, will be given by:

$$b_{m,i} = n - E_i\left[H\left(t^j\right)\right] \cdot s_i \quad m = (j-K) \in [1, N-K]; j \in [K+1, N];\ i \in [1, K] \qquad [5.12]$$

In the former expression [5.12], the term $[E_i[H(t^j)] \cdot s_i]$ represents the expected number of remaining containers in the sub-block i when vessel V^j arrives (t^j). Parameter s_i represents the number of stacks in the sub-block i and $E_i[H(t^j).)]$ is determined by expression [5.8].

Therefore, the matrix **B** and its components $b_{m,i}$ will be useful for allocating the new containers arriving at the terminal by filling the empty slots, depending on the order each strategy establishes.

In order to compare the strategies, parameter $\delta_j^{S_y}$ is defined. This parameter determines the amount of sub-blocks required to accommodate the containers arriving at the terminal from vessels V^j, $j \in [K+1, N]$. This parameter will consequently show the amount of sub-blocks with containers from different vessels.

Since the order of filling the sub-blocks differs in each strategy, the value of the parameter $\delta_j^{S_y}$ will vary from one strategy to another and, in turn, from one vessel to another, since the volume of slots will also change depending on time t^j). This is why parameter $\delta_j^{S_y}$ will be specified for each vessel arrival and strategy specifically, $\delta_j^{S_y}$ being the amount of sub-blocks with containers from vessel V^j, $j \in [K+1, N]$, for strategy S_y, $y \in [1,3]$.

Finally, for each strategy, $\delta_j^{S_y}$ will be:

$$\delta_j^{S_1} = \min_{i\in[1,K]}\left\{i|\ n - \sum_{r=1}^{i-1} b_{(m+x),r} \le b_{(m+x),i}\right\} \quad [5.13]$$

$$\delta_j^{S_2} = \min_{i\in[1,K]}\left\{i|\ n - \sum_{r=K+2-i}^{K} b_{(m+x),r} \le b_{(m+x),(K+1-i)}\right\} \quad [5.14]$$

$$\delta_j^{S_3} = \min_{i\in[1,K]}\left\{i|\ b_{(m+x),(m+x)} \le \sum_{\substack{r=K+1-i \\ r>m+x}}^{K} b_{(m+x),(r-x)}\right\} \quad [5.15]$$

where $b_{m,i}$ is obtained from the hollow matrix **B**, defined by expressions [5.11] and [5.12] $m = (j-K)$ and $x = \delta_{j-1}^{S_y}$. It is worth mentioning that for $j = K+1$, the auxiliary variable will be zero.

For instance, let's suppose a block is made up of 5 sub-blocks (*K*) with a capacity of 180 slots and that demand is characterized by N=7, ΔT=2 days and a departure rate defined by c=1 and λ=0.230. Using expressions [5.11] and [5.12], the resulting hollow matrix **B** is:

$$B_{[2x5]} = \begin{bmatrix} 162 & 151 & 135 & 109 & 67 \\ 169 & 162 & 151 & 135 & 109 \end{bmatrix}$$

Once the matrix components are defined, we proceed to calculate parameter $\delta_6^{S_y}$. In strategy S_1, for instance, when containers from vessel V^6 begin to be stacked in the first sub-blocks, we notice that in sub-block *K*=1 and at the arrival time of such vessel (t^6=12 days), there are 162 empty slots (component $b_{1,1}$). Therefore it will be necessary to occupy slots in sub-block *K*=2, where 29 from vessel V^2 $(n - b_{1,2})$ will still remain. In sub-block *K*=1 there will be 162 containers from vessel V^6 and 18 from vessel V^1, and, in sub-block *K*=2, 18 containers from vessel V^6 and 29 containers from vessel V^2. The term $\delta_6^{S_1} = 2$ indicates that all available slots in *K*=1 are occupied as well as some empty slots in sub-block *K*=2.

Applying the same procedure to the other strategies results in parameter values of $\delta_6^{S_2} = 3$ and $\delta_6^{S_3} = 1$. In the case of strategy S_3, 18 containers from vessel V^1 are placed with the remaining containers from vessel V^5 within sub-block *K*=5. During the inter-arrival time between V^5 and V^6, 67 containers ($b_{1,5}$) departed from this sub-block.

The next step is defining the set $C_j^{S_y}$, whose terms (represented as the pair (i,j) indicate which containers from V^i and V^j, $j \in [K+1, N]$, are mixed together in the same stack in each strategy.

The analytic expression of set ($C_j^{S_y}$) depending on the strategy applied (S_y) per each vessel V^j, will be:

$$C_j^{S_1} = \left\{(i,j);\ \left(1+\delta_{j-1}^{S_1}\right) \le i \le \left(\sum_{l=K+1}^{j} \delta_l^{S_1}\right) \ and\ (K+1) \le j \le N\right\} \quad [5.16]$$

$$C_j^{S_2} = \left\{ (i,j);\ \left((K+1) - \sum_{l=K+1}^{j} \delta_l^{S_2} \right) \le i \le \left(K - \sum_{l=K+1}^{j} \delta_{l-1}^{S_2} \right) \ and\ (K+1) \le j \le N \right\} \qquad [5.17]$$

$$C_j^{S_3} = \left\{ (i,i');\ 1 \le i \le (N-K)\ and\ \left((K+1) - \sum_{l=1}^{i} \delta_l^{S_3} \right) \le i' \le \left(K - \sum_{l=1}^{i} \delta_{l-1}^{S_3} \right) \right\} \qquad [5.18]$$

Once each combination of containers V^i and V^j is obtained ($C_j^{S_y}$), the total set C^{S_y} per strategy, which represents the entire group container combination (i, j), is defined as follows:

$$C^{S_y} = C_{K+1}^{S_y} \cup \dots C_j^{S_y} \dots \cup\ C_N^{S_y} \qquad [5.19]$$

Continuing with the example introduced before, and based on the obtained values of $\delta_6^{S_y}$, we proceed to determine the container combinations (i, j) (for strategies S_1 and S_2) and (i, i′) (for strategy S_3). It is worth noting that $\delta_{j-1}^{S_y}$=0 in all strategies, as containers coming from that vessel (V^5) are not mixed with other ones since they are stacked in an independent sub-block. The container combinations (i, j) are as indicated in Table 5.1:

Table 5.1: Stack configurations and container combinations for each strategy and h=3

Strategy	Analytic expressions $C_j^{S_y}$	Stack configurations *(i,j)* or *(i,i′)*
S_1	$C_6^{S_1} = \left\{ (i,6);\ 1 \le i \le \left(\sum_{l=6}^{6} \delta_l^{S_1} \right) and\ j=6;\ \delta_6^{S_1} = 2 \right\}$	{(1,6), (2,6)}
S_2	$C_6^{S_2} = \left\{ (i,6);\ \left(6 - \sum_{l=6}^{6} \delta_l^{S_2} \right) \le i \le 5\ and\ j=6;\ \delta_6^{S_2} = 3 \right\}$	{(3,6), (4,6), (5,6)}
S_3	$C_6^{S_3} = \left\{ (i,i');\ i=1\ and\ \left(6 - \sum_{l=1}^{1} \delta_l^{S_3} \right) \le i' \le 5;\ \delta_l^{S_3} = 1 \right\}$	{(1,5)}

Having established the container combination ((i, j) for strategies S_1 and S_2 and (i, i′) for strategy S_3) it is possible to determine the amount of stacks ($s_{(i,j)}\ or\ s_{(i,i')}$) with containers from vessels V^i and V^j (strategies S_1 and S_2) and the combination of containers from vessels V^i (strategy S_3).

Subsequently, the resulting number of rehandles for the stacking groups within the storage area can be calculated as:

- **Strategy S1**

Strategy S_1 consists mainly in stacking new containers in the sub-blocks with the oldest containers, i.e., the filling order starts at sub-block i=1 and finishes at i=K, which limits the capacity of the import area. On the other hand, this strategy requires no clearing moves at all ($E^{S_1}[R_h]$), so that the expected value of rehandles for the whole block will be:

$$E^{S_1}[R_T] = E^{S_1}[R_v] = \sum_{\substack{(i,j)\in C^{S_1} \\ j=K+1,\dots,N}} \left(\int_{t^j}^{\infty} s_{(i,j)}\, E_{(i,j)}[R(t)]dt \right) + \sum_{i=M^{S_1}+1}^{K} \left(\int_{t^i}^{\infty} s_{(i,i)}\, E_{(i,i)}[R(t)]dt \right) \quad [5.20]$$

where:

$$M^{S_1} = \sum_{j=1}^{N} \delta_j^{S_1} \quad [5.21]$$

- **Strategy S2**

Strategy S_2 is quite similar to the previous one. The difference lies in that the filling order is the opposite, i.e., it starts at i=*K* and finishes at the first sub-block of the storage area, i=*1*. This strategy does not require any clearing move either; therefore, $E^{S_2}[R_h]$=0.

$$E^{S_2}[R_T] = E^{S_2}[R_v] = \sum_{\substack{(i,j)\in C^{S_2} \\ j=K+1,\dots,N}} \left(\int_{t^j}^{\infty} s_{(i,j)}\, E_{(i,j)}[R(t)]dt \right) + \sum_{i=1}^{M^{S_2}-1} \left(\int_{t^i}^{\infty} s_{(i,i)}\, E_{(i,i)}[R(t)]dt \right) \quad [5.22]$$

where:

$$M^{S_2} = \sum_{j=K+1}^{N} \delta_j^{S_2} \quad [5.23]$$

- **Strategy S_3**

This strategy differs from the two previous ones in that it requires replacing the containers still stored in the sub-blocks to allow new containers to be stacked in the same sub-block. Clearing moves will thus be required to replace the containers from the first vessels in the rest of the sub-blocks of the storage area.

Therefore, the total amount of rehandles for strategy S3 will equal the total amount of vertical rehandles and clearing moves. The clearing moves will in turn equal the amount of containers remaining in the sub-block when a new vessel arrives at the terminal.

$$E^{S_3}[R_T] = E^{S_3}[R_v] + E^{S_3}[R_h] \quad [5.24]$$

$$E^{S_3}[R_v] = \sum_{\substack{c_{ii'}\in C^{S_3} \\ i=1,\dots,N-K}} \left(\int_{t^j}^{\infty} s_{(i,i')}\, E_{(i,i')}[R(t)]dt \right) + \sum_{i=1}^{K} \left(\int_{t^i}^{\infty} s_{(i,i)}\, E_{(i,i)}[R(t)]dt \right) + \sum_{j=K+1}^{N} \left(\int_{t^j}^{\infty} s_{(j,j)}\, E_{(j,j)}[R(t)]dt \right) \quad [5.25]$$

On the other hand, the clearing moves will be:

$$E^{S_3}[R_h] = E_i[H(t^j - t^i)]s_{(i,i)} \qquad \forall i \in [1, K], j \in [K+1, N] \qquad [5.26]$$

where:

$E[H(t^j - t^i)]$ is the expected amount of containers in a stack at t^j taking into account that containers arrived at the terminal at t^i.

It is worth noting that in the formulation defined in this section the first term (vertical rehandles required by strategies S_1, S_2 and S_3) corresponds to the group of sub-blocks with containers from different vessels, whereas the second term of the formulation refers to the group of homogeneous sub-blocks, i.e., the sub-blocks with containers coming from the same vessel.

On the other hand, the analytic expression determining the clearing moves (strategy S_3) refers to the group of containers stacked in a sub-block in the first stage of the strategy (freight segregation).

5.4 Numerical case

In this section, the proposed methodology is tested using empirical data from the layout of a standard container terminal. The results obtained after applying the proposed strategies will allow us to decide which strategy is the most suitable depending on the basic parameters of the problem.

5.4.1 Input data

The import storage yard has five sub-blocks ($K=5$) with the same capacity, which equals the number of containers per vessel. Each sub-block is divided into ten slots (length) and six rows (width), according to the guidelines defined by Petering (2009). Containers are stacked up to three or five tiers high, where h=3 represents a container terminal with moderate volume, while h =5 represents a terminal operating close to its maximum capacity (congested). The terminal will be operated by RMG, which have a maximum operative stacking height of six containers.

The containerships' arrival time is determined by the long-term schedule. It is assumed that the arrival rate of import containers follows a cyclic pattern equivalent (in terms of time) to seven ships arrivals (Figure 4), that is, the capacity of the import storage yard is designed to accommodate, at least, the unloaded container volume from seven ships ($N=7$). The amount of unloaded import containers per ship is 180 (n) when the stacking height is three tiers and 300 (n) when it is five tiers high.

The ship inter-arrival time ΔT is assumed to be constant. Different scenarios have been defined by increasing ΔT from 0 to 4.5 days. We assume that the dwell time in the storage t follows a Weibull distribution with parameters c and λ, whose values are: c=1, λ=0.230 (scenario (a)) and c=1.5 λ=0.073 (scenario (b)).

In the case of c=1, the dwell time, t, follows an exponential distribution. The terminal departure rate (λ) has been calibrated so that the dwell time reaches 4 or 5 days (the normal values for this type of freight in these terminals).

5.4.2 Results

A sensitivity analysis of rehandles depending on the vessel arrival rate and the container dwell time at the terminal was performed for each scenario. The ratio ($\Delta T/E[t]$) presenting the relation between arrival and departure rates were also calculated. The terminal arrival rate is determined by the interval between consecutive vessel arrivals (ΔT), whereas the departure rate depends on the average container dwell time at the terminal ($E(t)$).

In the hypothetical case where the dwell time is assumed to follow an exponential distribution (scenario (a)), the average time will equal $E(t) = 1/\lambda$. In scenario (b), where the dwell time is assumed to follow a Weibull distribution ($c \neq 1$), the average time is determined by $E(t) = \lambda^{-1/c}\Gamma(1 + 1/c)$.

By applying expressions (14-16) we obtain the values for parameter $\delta_j^{S_y}$ for each simulated scenario shown on tables 2 and 3. We thus know which sub-blocks hold containers from vessel V^j (see Figure 6).

Tables 2 and 3 show two values for $\delta_j^{S_y}$, one for each vessel V^j arriving at the terminal at t^j, for $j = \{6,7\}$. The results obtained are represented: $\delta_6^{S_y}/\delta_7^{S_y}$, where the first component represents the amount of sub-blocks necessary to stack the containers from the vessel V^6 at t^6, while the second component indicates the amount of sub-blocks necessary to store the containers from vessel V^7 at t^7, taking into account which sub-blocks have been used to store the containers from vessel V^6.

It is worth mentioning that in strategy S_3, the first component represents the amount of sub-blocks necessary to store the remaining containers from sub-block *K*=1, from vessel V^1, and the second the amount of sub-blocks necessary to stack the containers from vessel V^2 in sub-block *K*=2, since new containers will be stacked in the sub-blocks that have just been cleared, *K*=1 and *K*=2, respectively.

Table 5.2: Results obtained for parameter $\boldsymbol{\delta_6^{S_y}/\delta_7^{S_y}}$ assuming scenarios (a) and (b) and h=3

	Scenario (a)						**Scenario (b)**					
Δt/E(t) (%)	**11.5**	**23.0**	**34.5**	**46.0**	**69.0**	**103.0**	**9.7**	**19.4**	**29.1**	**38.8**	**58.2**	**87.4**
S_1	3/3	2/2	2/2	2/2	1/1	1/1	-	2/3	2/2	2/2	1/1	1/1
S_2	-	3/2	3/2	2/2	2/1	2/1	-	-	-	3/2	2/1	2/1
S_3	-	2/1	1/1	1/1	0/0	0/0	-	3/0	2/1	1/1	0/0	0/0

Table 5.3 Results obtained for parameter $\boldsymbol{\delta_6^{S_y}/\delta_7^{S_y}}$ assuming scenarios (a) and (b) and h=5

	Scenario (a)						**Scenario (b)**					
Δt/E(t) (%)	**11.5**	**23.0**	**34.5**	**46.0**	**69.0**	**103.0**	**9.7**	**19.4**	**29.1**	**38.8**	**58.2**	**87.4**
S_1	3/3	2/2	2/2	2/2	2/2	1/1	-	2/3	2/2	2/2	2/2	1/1
S_2	-	3/2	3/2	3/2	2/2	2/2	-	-	-	3/2	3/1	2/1
S_3	-	2/1	1/1	1/1	1/1	0/0	-	-	2/1	1/1	1/1	0/0

The results shown in Table 5.2 and Table 5.3 show that strategy S_2 requires more sub-blocks to be occupied than the other strategies proposed. This is caused by the filling order of the sub-blocks, which consists of filling the slots of the sub-blocks with the newest containers in the terminal and, therefore results in fewer empty slots.

The sub-blocks in the case where strategy S_3 is applied are less occupied, since clearing moves are carried out once most containers have left the terminal.

In some specific cases (when the inter-arrival time is relatively short), there are not enough empty slots available for placing the inbound freight and, therefore, capacity problems arise. This phenomenon is intensified in the case where the ratio relating the arrival and departure rates is low and strategy S_2 is applied.

By considering the particular case in which the dwell time at the terminal follows an exponential distribution, the vessels' inter-arrival time equals 1.5 days and the ratio $\Delta T/E(t)$ equals 34.5%, we obtain the yard layout shown in Figure 5.5. This figure depicts which sub-blocks in the storage area hold containers from different vessels and also depicts the configuration of each stack after applying the strategies proposed in this thesis.

For instance, in the case where strategy S_2 is applied, the standard stack in sub-block 3 is made up of a container from vessel V^3 on the ground and two containers from vessel V^6. This figure also shows that at t_6, when containers from vessel V^6 are being stored in sub-blocks 5, 4 and 3 (in this order), there are 64 containers from vessel V^3 and 37 containers from vessel V^6 stacked in the sub-block (represented in the Figure 5.5 as 64/37).

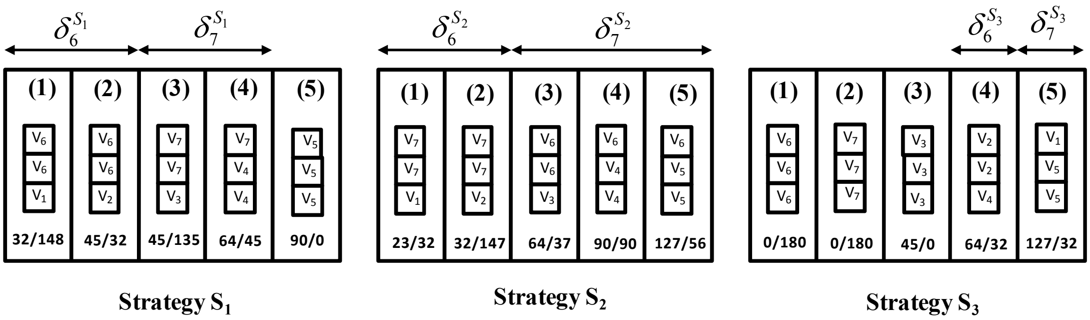


Figure 5.5: Layout of the import block after applying the different storage strategies. Stack configuration for each strategy (scenario (a), ΔT =1.5 and h=3).

Table 5.4 presents sets C^{S_y}, (defined in equation [5.19]), corresponding to the values of $\delta_j^{S_y}$; j=6,7 and for each of the strategies proposed in this thesis.

Table 5.4: Container combination for each strategy (scenario (a), ΔT =2.0 and h=3 and h=5).

	Strategy	$\delta_6^{S_y}$	$\delta_7^{S_y}$	C^{S_y}
3 tiers high	S_1	2	2	$C^{S_1} = C_6^{S_1} \cup C_7^{S_1} = \{(1,6), (2,6), (3,7), (4,7)\}$
	S_2	2	2	$C^{S_2} = C_6^{S_2} \cup C_7^{S_2} = \{(4,6), (5,6), (2,7), (3,7)\}$
	S_3	1	1	$C^{S_3} = C_6^{S_3} \cup C_7^{S_3} = \{(1,5), (2,4)\}$
5 tiers high	S_1	2	2	$C^{S_1} = C_6^{S_1} \cup C_7^{S_1} = \{(1,6), (2,6), (3,7), (4,7)\}$
	S_2	3	2	$C^{S_2} = C_6^{S_2} \cup C_7^{S_2} = \{(3,6), (4,6), (5,6), (1,7), (2,7)\}$
	S_3	1	1	$C^{S_3} = C_6^{S_3} \cup C_7^{S_3} = \{(1,5), (2,4)\}$

Let's now consider that there are many stacks holding containers from different vessels. We aim to quantify the rehandles these stacks are expected to require and compare the value obtained with the value we would obtain in the case where the same stack were made up of containers from the same vessel.

To compare the two results, an indicator, $\Delta R_{(i,j)}$, is defined. It determines the percentage increase in the amount of rehandles required for handling a stack with containers from vessels $V^i, i \in [1, K]$ and $V^j, j \in [K+1, N]$ relative to a homogeneous stack (c_{ij} *versus* c_{ii}), made up only of containers from the same vessel V^i, that is:

$$\Delta R_{(i,j)} = \frac{E_{(i,j)}[R] - E_{(i,i)}[R]}{E_{(i,i)}[R]} \qquad [5.27]$$

Having defined the sets (C^{S_y}) for each strategy, the resulting container combination for the stack and sub-block and the indicator ($\Delta R_{(i,j)}$), we can represent the increases generated depending on the inter-arrival time (*ΔT*), as shown on Figure 5.6 and Figure 5.7.

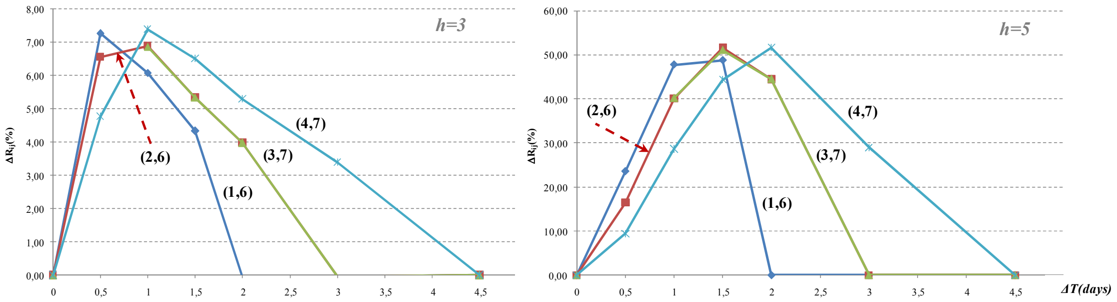


Figure 5.6: Increases (%) relative to the average number of rehandles obtained for a homogeneous stack (E[R]=1.25) for strategy S_1 (scenario (a), ΔT =1.5 and h=3 and h=5).

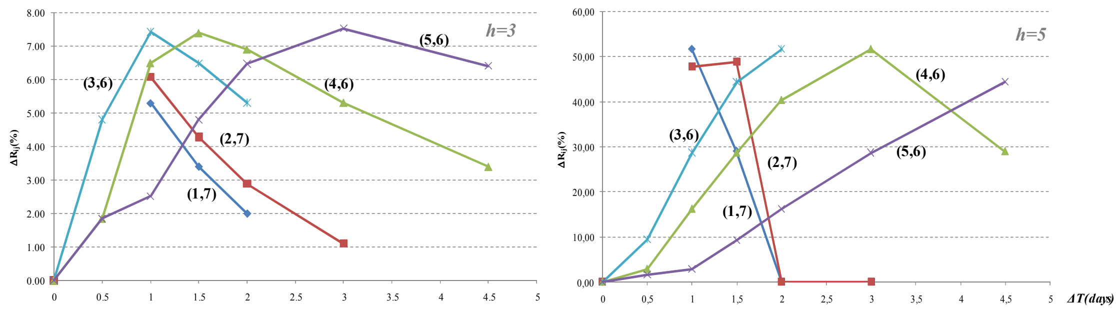


Figure 5.7: Increases (%) relative to the average number of rehandles obtained for a homogeneous stack (E[R]=4.85) for strategy S_2 (scenario (a), ΔT =1.5 and h=3 and h=5).

Above figures show that when strategy S_1 is applied and as the inter-arrival time increases, the increase in rehandles diminishes for each set. However, when strategy S_2 is applied, the increases are still higher until certain values of *ΔT*, but once this threshold is reached, the increases start diminishing.

This is due to the fact that the longer the inter-arrival time is, the higher the probability of the container leaving the terminal is, i.e., there are more containers leaving the terminal when new inbound vessels arrive. The expected value of the number of rehandles will consequently decrease. This is why strategy S_2, which combines containers from vessels arriving almost simultaneously, generates a higher amount of rehandles.

Particularly, combination (5,6) for strategy S_2 is the most unfavorable container combination with regard to the number of rehandles, since the vessels arrive consecutively and, therefore, there is not enough time for most containers from vessel $i=5$ to leave the terminal. For the specific case of h=3, a minor increase of 7% is recorded, whereas for a higher stacking height (h=5), the recorded increase may reach up to 50%. However, combinations (1,6) and (1,7) for strategies S_1 and S_2, respectively, are the most favorable combinations for time intervals ΔT >1 day.

It is worth mentioning that the resulting combinations (mixing containers from different vessels) are specific to each ΔT, such that some situations will result in impossible combinations. For example, combination (3,6) is only possible in the case that ΔT<2 days (applying strategy S_2), since all the containers from vessel V^6 are allocated to sub-blocks 4 and 5. Combinations (4,6) and (5,6) can be found in the sub-blocks 4 and 5, respectively.

Finally, by applying the methodology proposed in this chapter and expression [5.27], we obtain an increase in the expected value of rehandles depending on $\Delta T/E(t)$, the strategy, the distribution type (exponential or Weibull) and the stacking height (three or five tiers high). The results are presented graphically in Figure 5.8 through Figure 5.11.

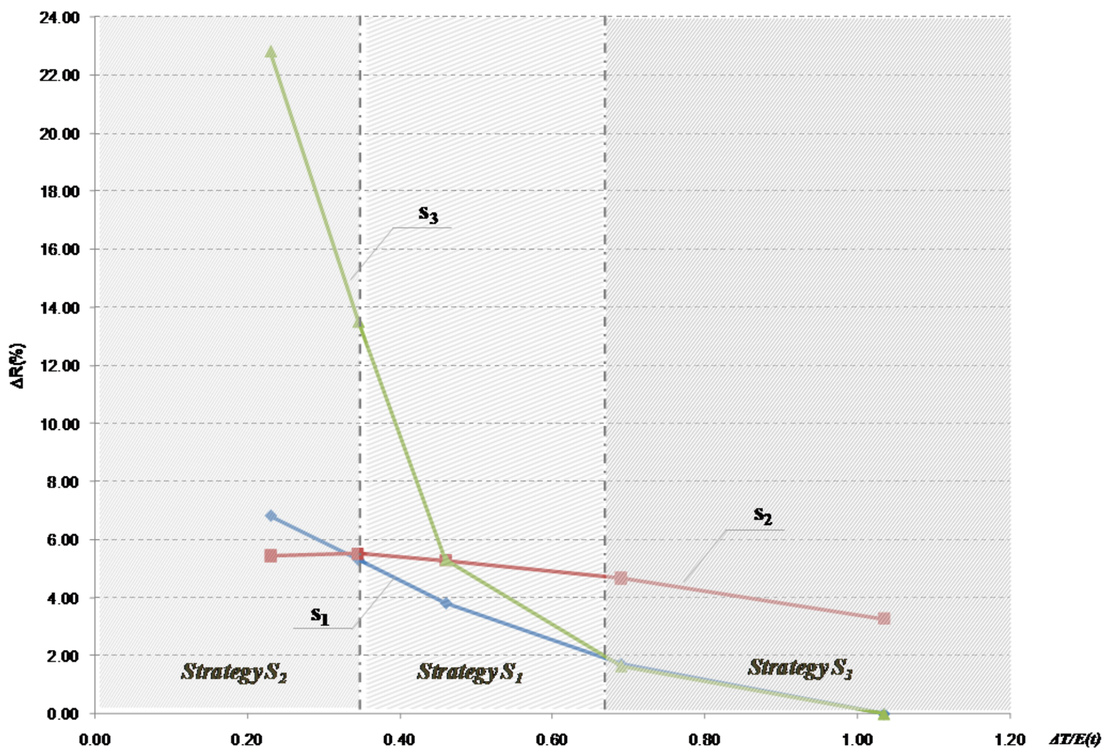


Figure 5.8: Optimum strategy depending on ΔT/E(t) for scenario (a) and a stacking height of 3 (h).

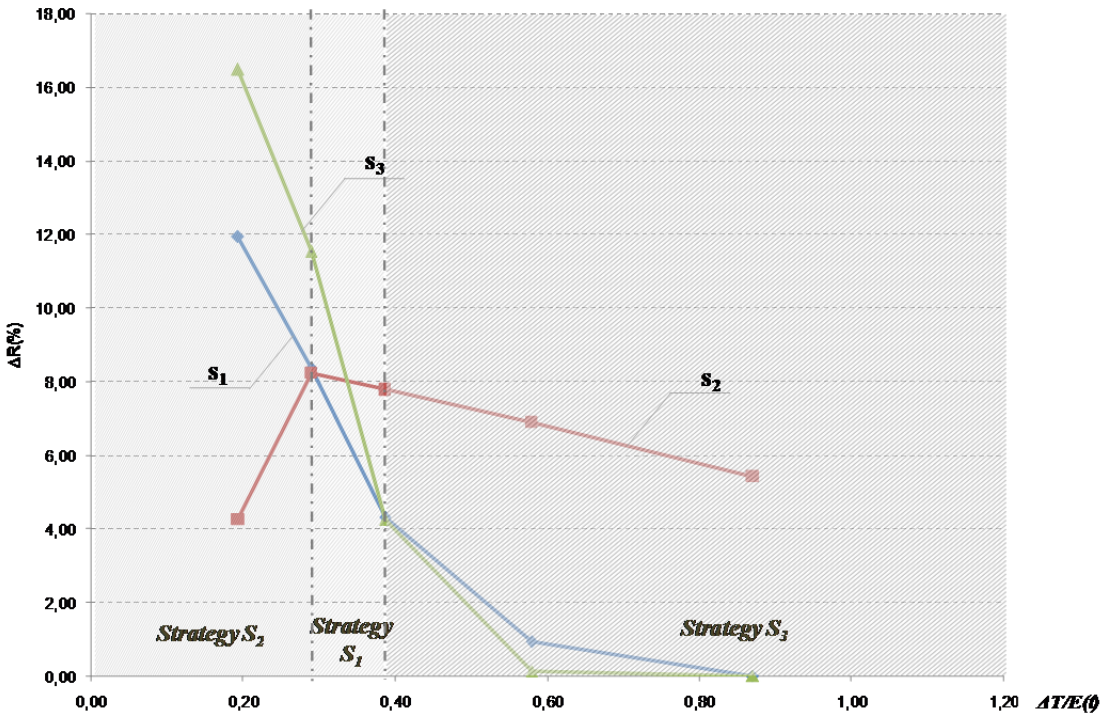


Figure 5.9: Optimum strategy depending on ΔT/E(t) for scenario (b) and a stacking height of 3 (h).

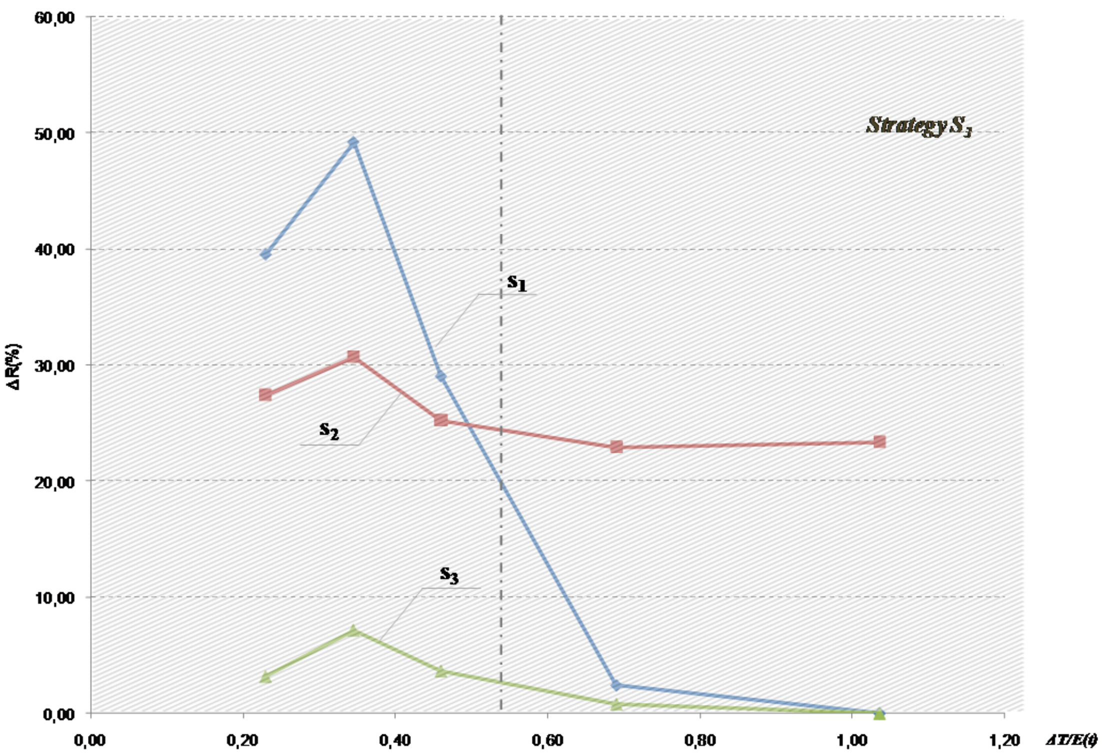


Figure 5.10: Optimum strategy depending on ΔT/E(t) for scenario (a) and a stacking height of 5 (h).

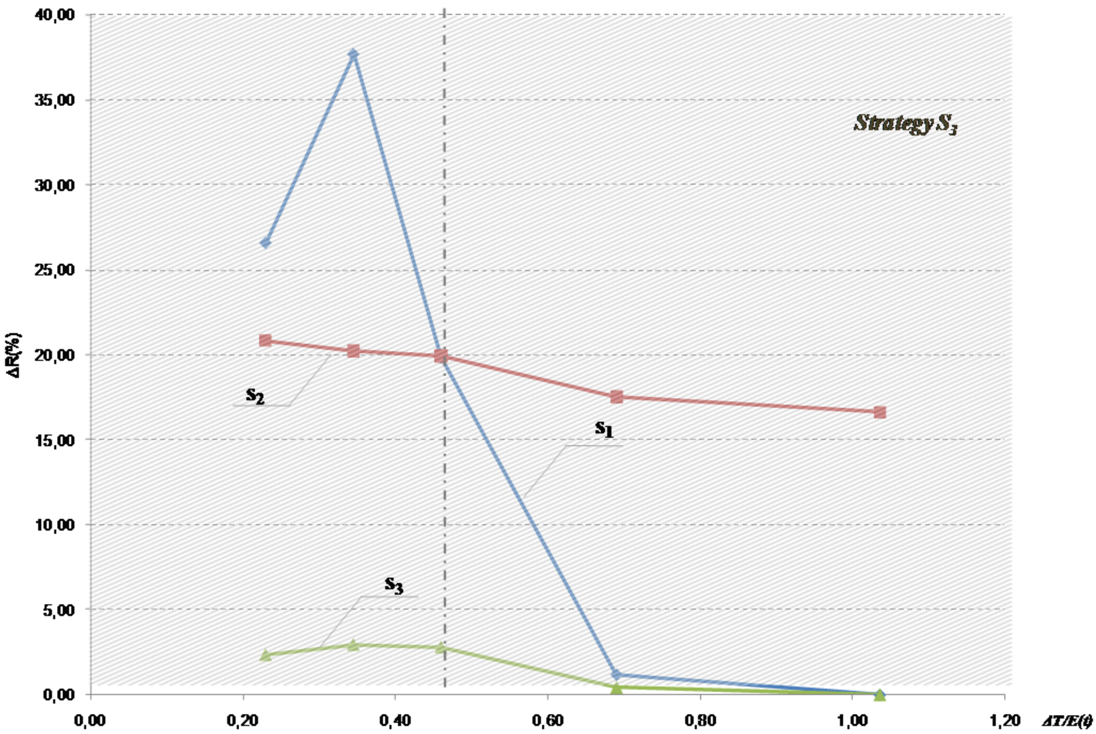


Figure 5.11: Optimum strategy depending on ΔT/E(t) for scenario (b) and a stacking height of 5 (h).

From the model results, presented above, the following conclusions can be made:

- For terminals with low traffic (h=3), when the relation between the freight arrival and departure rates is close to unity, the total number of rehandles obtained for strategies S_1 and S_3 converges to zero, i.e., the stacks' behavior is close to that of homogeneous stacks, requiring the same amount of rehandles.
- From the previous statement we can infer that the longer the inter-arrival time is, the fewer containers will remain in the sub-blocks of the storage area and, therefore, the lower the increase in rehandles generated by heterogeneous stacks will be. Consequently, the longer the inter-arrival time is, the fewer clearing moves will be required and the more applicable strategy S_3 will be.
- Figure 5.8 and Figure 5.9, in which the stacking height considered is three tiers and n=180, show that when the freight arrival rate is less than 35% of the average dwell time, in scenario (a), and less than 30% in scenario (b), the optimum strategy is S_2. On the other hand, in cases where the ratio is greater than 65% in scenario (a) and greater than 40% in scenario (b), strategy S_3 proves to be the best in terms of the number of rehandles generated. For an intermediate scenario, S_1 would be the optimum strategy.
- For terminals with high traffic (h=5), Figure 5.10 and Figure 5.11 show that for both scenarios ((a) and (b)) the optimum strategy is S_3 for all the situations analyzed. The peak generated when containers arrival rate is around 40% of the average dwell time is worth mentioning. Its cause resides in the fact that containers which have recently arrived at the terminal are stacked over ones that will not stay long at the terminal, thereby

generating a considerable increase in the amount of rehandles (i.e., combination (1,6) when $\Delta T \approx 1.5$). Once that ΔT threshold is exceeded, the containers that arrived first at the terminal will have departed and, therefore, the increase of the number of rehandles due to the mixture will not occur.

- By comparing the different stacking heights considered and the feasibility of the different strategies, we can see that when the stacks are short, clearing moves take more importance than vertical rehandles, thus S_1 and S_2 become the optimum strategies. On the other hand, when stacks are higher, vertical rehandles increase significantly and S_3 becomes the most suitable strategy. The additional clearing moves required for S_3 are fewer than the number of vertical rehandles.
- By comparing the two scenarios (a and b), we can see in the hypothetical case that time is distributed following a Weibull function (c=1.5) and containers take longer to leave the terminal than in the case of an exponential distribution (c=1). The most optimal strategy changes from one scenario to the next.

5.4.3 Discussion

The results obtained allow us to conclude that the optimal strategy depends on the terminal's state of congestion. A distinction can be made between terminals operating below their capacity, which have relatively short stack heights (h=3), and ones operating at full capacity (congested), making it necessary to increase stack heights (h=5).

Regarding terminals that are not congested (i.e., short stack height, h=3), the following suggestions can be made:

- When the inter-arrival time is short (low values of $\Delta T/E(t)$), S_2 was found to be the most favorable strategy, even though in some low-capacity terminals this strategy can converge to a freight non-segregation strategy. Both De Castilho and Daganzo (1993) and later Huynh (2008) recommended applying the mixed strategy when the stacks are not very high and the dwell time is high, which equates to low values of the $\Delta T/E(t)$ ratio. In these cases, the containers departure probabilities are very similar and the container arrival rate is very high.
- Strategy S_1 becomes the optimum strategy for intermediate values of $\Delta T/E(t)$ (when the average dwell time in the yard approximately doubles the inter-arrival time). This strategy, even though it may initially appear to be unproductive because new containers are stacked over containers with a high probability of leaving the terminal, can be widely applied when the inter-arrival time is high with regard to the expected container dwell time. Thus, some containers in the storage area are allowed to leave the terminal during the time interval before new freight arrives. However, the time intervals are not long enough to make the operating cost of the clearing moves affordable.
- Lastly, S_3 is the optimum strategy in the case where there are few containers remaining in the terminal and, consequently, few clearing moves per sub-block are required. This strategy will apply to terminals having low arrival rates and that operate in accordance with a freight segregation strategy (De Castilho and Daganzo, 1993).

The higher the inter-arrival time is, the fewer clearing moves will be needed, and, therefore the more applicable this strategy will be.

- By comparing the results by studying the dwell time variability (for a fixed ΔT), we can conclude that the higher the containers' dwell time (lower ratio values), the better strategy S_2 or S_1 becomes, which agrees with Huynh (2008). He concluded that as dwell time increases, the number of rehandles required retrieving a container from the yard decreases when applying a freight segregation strategy.

On the other hand, for terminals operating close to their capacity (maximum height is limited by the operating system RMG) or terminals having to increase their storage capacity by way of higher container stacking (i.e. h=5), results show that:

- Strategy S_3 stands out as the most suitable strategy for all values of $\Delta T/E(t)$. When stack height increases, the overall number of vertical rehandles per stack is proportional to the square of the stacking height, an effect that has been confirmed in other studies such as Kim and Kim (1999). Therefore, reducing vertical rehandles and increasing clearing moves allows S_3 to reduce the operating costs and manage the yard more optimally.
- In contrary, strategies like S_1 and S_2 based on a mixture of containers with different departure probabilities, offer very negative results since containers with a forecasted imminent departure from the terminal are located in the lower tiers of the stack.
- Dynamic strategies, analyzed by Taleb-Ibrahimi et al. (1993), improve the usage of the available space in the terminals by virtually eliminating the wasted space between the storage areas in the yard and also improve terminal productivity. In a similar way, strategy S_3 replaces containers (dynamic strategy) to make the most of the free space in the terminal and to reduce the number of rehandles.

It is worth mentioning that these conclusions have been drawn from expected and average values, which are useful for deciding which strategy to apply in the yard; however, simulation tools would be required to capture a detailed picture of the process.

5.5 Conclusions

This chapter has analyzed the performance of different storage strategies aiming to reduce the number of unproductive moves in the import container storage area. These strategies have been evaluated using the methodology described in this thesis. The model that was developed enables the quantification of the expected number of rehandles (vertical rehandles and clearing moves) that result from combining containers with different departure probabilities in the same stack.

Thus, the main contributions of this chapter are the following:

- This model takes into account the different probabilities of leaving the terminal with regard to the time at which each container arrives. Therefore each container has a different probability of departure depending on time. This enables us to quantify the number of rehandles that result from having a mix of containers with different probability of departures in the same stack. This approach differs from previous studies which assumed that all containers have the same departing probability.

- Three new storage strategies were defined for inbound containers, allowing the operations to be analyzed more in depth than the strategies developed in previous contributions. De Castilho and Daganzo (1993) followed by Kim and Kim (1999) only considered two cases for import: segregation and non-segregation.
- More specifically, we can observe that strategies S_1 and S_2, which are comparable to the non-segregation strategy, are recommended for terminals with a short average stacking height and a ship headway-to-container dwell time ratio less than 0.5, or when container dwell time is high. In contrary, for terminals with a small storage area and high traffic volume (when storage capacity must increase by way of higher container stacking), strategy S_3 becomes preferable for inbound yard management, requiring fewer rehandling moves and thus demonstrating the advantage of dynamic strategies in these situations.

Future possible research lines might consist of further evaluating select variables playing a role in the import storage yard management process, such as considering the volume of containers as variable depending on the vessel or modeling the inter-arrival time as a random variable.

Foreword of chapters 6 and 7

In this thesis, as stated in the first chapter, the storage pricing problem is addressed from two different approaches with regard to the arrival and departure processes of import containers to/from the storage yard, namely the deterministic and stochastic approaches.

In the deterministic approach, it is assumed that the amount of unloaded containers per vessel is constant and that all calling vessels at the terminal have the same properties regarding the unloading process. On the contrary, the stochastic approach, whose formulation derives from chapter 3 considers multiple vessels and that the incoming and outgoing container flows are random. The particularity in comparison with the model in chapter 3 is that the migration to a remote warehouse is included. Further, there is an additional issue that differs between both studies developed, but in such a case it refers to demand elasticity.

The first part considers that demand is dependent on the storage charge (elastic). Thus, the model incorporates the reactions of customers in two different ways: a direct reduction due to the introduction of a storage charge and an indirect effect due to the migration to an off-dock warehouse.

On the contrary, the second approach assumes that the demand of the terminal is price-independent (inelastic) because it is assumed that the terminal has some market power. In such a case, only migration to an off-dock warehouse is considered.

To sum up, the following table shows the main characteristics of chapter 6 and 7.

Table 6.0: Main issues of chapter 6 and chapter 7

	Chapter 6	**Chapter 7**
Container arrival process	Deterministic arrival	Stochastic arrivals Multiple vessels
Demand elasticity	Storage charge affects customers' decisions in two ways: the number of containers using the yard terminal is reduced and the picking-up time is altered.	The picking-up time is altered. It is assume that customers minimized its own cost

Finally, it should be mentioned that the introduction to the problem and its description are just included in chapter 6 since are common for both chapters.

Chapter 6

Pricing storage strategies for improving storage yard performance: deterministic approach

6.1 Introduction

Alongside this thesis it has been realized that many terminals are currently operating at or close to capacity due to continuously increasing container trade but it also can be consequence of longer stays of containers at the yard. Thus the yard space profitability decrease and operating costs increase due to higher occupancy levels of yard space.

In such context, the dwell time - the duration of stay of a container at a terminal before shipping (exports) or leaving by rail/road transport (imports)- is sometimes used as an indicator of the terminal efficiency: the higher the dwell time, the lower terminal efficiency (Choo Chung, 1993).

The average dwell time in Europe's main ports ranges between 4 and 8 days. In the ports of Hamburg, Bremen, Rotterdam and Antwerp it is approximately 6.4 days for import cargo and 4.6 days for export cargo. In the Italian ports of La Spezia and Gioia Tauro it is higher than for Northern European counterparts, averaging 7.4 days for vessel to truck and 5.6 days for truck to vessel (Dekker, 2005). The overall dwell time in the Port of Los Angeles is approximately 4 days for loaded containers, and in Asian ports such as Singapore and Hong Kong it is approximately 2 to 3 days.

At that point, when facing port's and terminal capacity shortage, port authorities and terminal operators aim to reduce container dwell time at the storage yard terminal to reduce total logistics cost and to guarantee a more optimal use of the existing capacity. Usually the abovementioned target can be achieved through price incentives (i.e.: storage penalty) by persuading shippers, carriers and owners to pick up their containers earlier, that is, encouraging fast clearance.

The pricing storage schedule can adopt different formulations, such as linear in the storage time after a free-time (an initial period free of charge). A storage charge proportional to time at the terminal is applied in most container terminals around the world. The main difference in price schedules relies on the duration of the free time.

It is customarily accepted as three to five days (Goss and Stevens, 2001; Heggie, 1974), but even among the most important ports (Table 6.1), it varies from three to ten days—which is the case of the Egyptian ports.

Table 6.1: Import Storage charges and free time at major container terminals (charge per TEU) (CMA-CGM, 2012)

	Terminal	Free time	Thereafter	Cost per TEU day
EUROPE	Southampton (UK)	6 days	7–13 days 14 onwards	20.00 GBP 45.00 GBP
	Rotterdam (ECT)	9 days	10–16 days 17–23 days 24 onwards	€4.83 €10.35 €12.78
	Hamburg (HHLA, Eurogate)	3 days	4 onwards	N.A.
	Zeebrugge (OCHZ, APMT) Antwerp (Dry)	5 days	6-10 days 11-20 days 21 onwards	€7.50 €10.00 €15.00
	Barcelona (TCB)	5 days	6-7 days 8-14 days 15-21 days 22-28 days 29-42 days 43 onwards	€2.00 €5.00 €10.00 €15.00 €20.00 €40.00
ASIA	Singapore (PSA)	3 days	0-7 days 8-28 days 29 onwards	SGD 12.00 SGD 13.00 SGD 34.00
	Hong Kong	5 days	6 onwards	HKD 277.00
	Colombo-Sri Lanka (Jaya Container Terminal)	3 days	0-3 days 3-8 days 9 onwards	USD 8.00 USD 15.00 USD 23.00
USA	Long Beach	4 working days	5-9 days 10 onwards	USD 21.83 USD 43.60
	New York/New Jersey	4 working days	5-8 days 9-12 days 13 onwards	USD 98.00 USD 145.00 USD 295.00
MIDDLE EAST	Egypt (all ports)	10 days	11 onwards	USD 12.00

Table 6.1 shows little consistency in storage pricing policies, showing that terminals often do not price according to their costs, commercial policies or indirect charges apply instead.

In general terms, terminal operators do not derive large profits from storage charges because their main activity is container transshipment between different modes of transport but they would like to satisfy, targets by introducing storage pricing, namely the following:

1) To avoid customers storing containers at the storage yard for long periods.
2) To guarantee the efficiency of terminal performance and greater profitability of storage space.

3) To provide an additional service to customers (i.e. storage), which is currently in high demand, especially for those users that do not have warehouse facilities.

However, customers have other options for the temporary storage of their inbound containers as off-dock warehouses are also available. These auxiliary storage facilities, unlike the terminal yard, have fewer capacity constraints but are in remote locations. These facilities present some advantages compared with port terminal yards because they charge lower storage fees than terminal yards, although there are transportation costs for moving a container from the yard to the remote warehouse. Nonetheless, customers might prefer to move containers to an auxiliary warehouse rather than paying the yard storage charge, and this would be particularly attractive for a relatively long period of storage.

As an example of remote warehouses related to port facilities can be found, from the point of view of shipping companies, in Maersk and CMA-CGM who are currently managing new storage facilities outside ports in Brazil, Arabia or even West Africa with the aim of enhancing seaport efficiency and relieving congestion (Ng et al., 2013).

6.2 Problem description

This thesis assumes a generic storage charge that is proportional to the length of storage time beyond the flat-rate time limit (Figure 6.1). Thus, the storage price schedule at the terminal storage yard, $\tau(t)$, can be expressed by the zero or non-zero flat rate (a) before time t_0 and the storage price proportional to the length of time (b) when $t > t_o$, that is:

$$\tau(t) = \begin{Bmatrix} a & t \le t_o \\ a + b(t - t_0) & t > t_o \end{Bmatrix} \quad \forall\, a, b, t_o \ge 0 \qquad [6.1]$$

where t_0 is the duration of the flat rate (in days) and t the time containers spend at the terminal after being unloaded from the vessel.

It should be mentioned that a linear structure is considered for the simplicity of calculation, but one could adopt any other complex formulation, such as quadratic or exponential with the aim of achieving a better adjustment in terms of practical storage schemes.

Off-dock warehouses or remote terminal yards play an important role as these auxiliary facilities have lower rates than port container terminal yards. Depending on where the warehouse is located and how long a container needs to be stacked, the cargo owner or carriers will choose the best option for storing the container: keeping the container at the port terminal or moving it to an off-dock warehouse. Usually, these auxiliary remote facilities are more attractive for long-term storage.

The total cost at time t of the off-dock warehouse for customers, $c(t)$, will consist of a fixed cost (handling, transportation, etc.), c_0, and a rate proportional to the length of stay at the off-dock warehouse, c_1. This off-dock warehouse cost not known to the terminal operator. For simplicity, it is supposed that both c_0 and c_1 are the same for all the terminal customers. Thus, the storage price is expressed as follows:

$$c(t) = c_0 + c_1 t \qquad \forall\, c_0, c_1 \ge 0 \qquad [6.2]$$

where t is the time elapsed in the off-dock warehouse.

Taking into account that the total time spent at the container yard (dwell time) will be t_s (known to the customer in advance), each customer has two different choices:

1) Storing the container in the yard until delivery time (t_s) or;
2) Picking up the container and moving it to an off-dock warehouse until delivery.

Combining equations [6.1] and [6.2] provides the threshold time t_p at which the customer would be indifferent to the choice between the two alternatives because the storage cost is identical for both facilities, that is:

$$t_p = \frac{c_0 + bt_0 - a}{b - c_1} \quad [6.3]$$

Therefore, customers with a t_s value greater than that for t_p will prefer to move their container to off-dock warehouse storage, and conversely, customers will choose to leave containers at the terminal when t_s is lower than t_p (Figure 6.1).

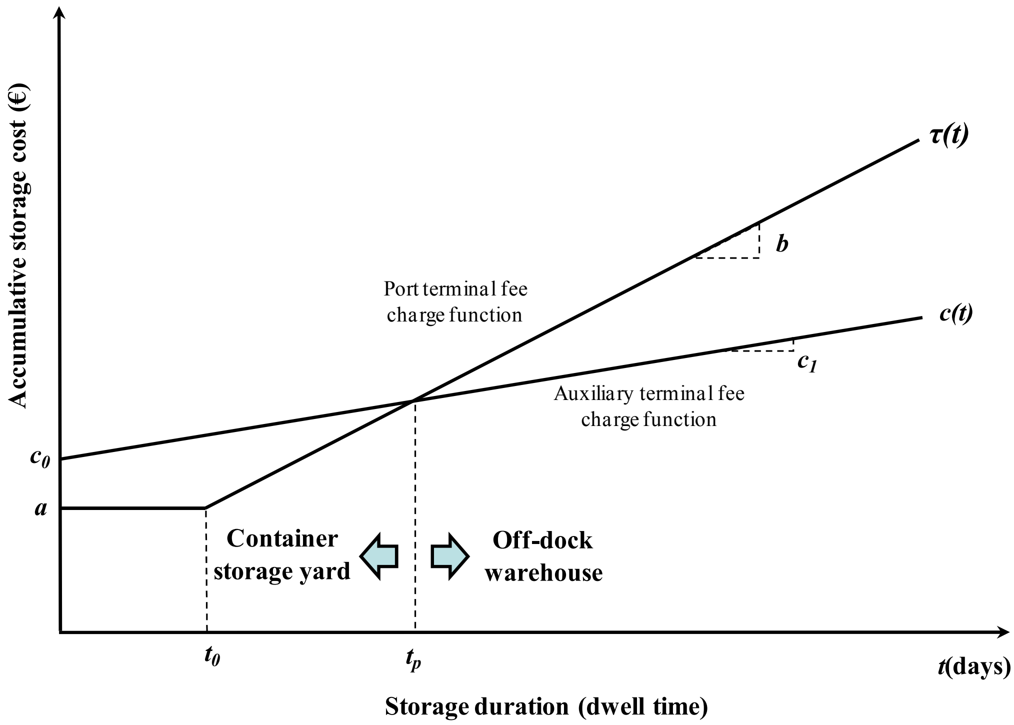


Figure 6.1: Price storage schemes applied by the port container terminal and off-dock warehouse.

To ensure that customers have two different choices for storing their import containers, there must be a threshold time t_p, that is: $t_p = \frac{c_0+bt_0-a}{b-c_1} \geq 0$. Otherwise all customers will leave their containers at the port container yard or will move directly to the off-dock warehouse to minimize their own costs. If terminal operators seek to avoid congestion costs by reducing the number of containers at the storage yard, they will define tariff schemes with a lower value of t_p. Terminal operators will analyze their own cost structures and will consider the optimal number of containers to guarantee maximum profit or at least to cover costs. Further, assuming that the off-dock warehouse storage cost is lower than the storage cost at the port terminal ($0 \leq c_1 < b$), which is reasonable as logistics and rental costs are more expensive in port areas, it can be determined that $c_0 + bt_0 > a$.

However, the latter condition includes some particular cases to which special attention should be paid. Assuming these cases ($\mathrm{c}_0 < a < c_0 + \mathrm{bt}_0$) means that the storage charge at the container yard is more expensive than at the off-dock warehouse for short stays, which contradicts the purpose of introducing a storage price. In addition, the variable c_0 includes the transportation cost from the terminal to the off-dock warehouse and handling costs (receiving and stacking it in the yard) whereas variable (a) does not includes the transportation cost to the auxiliary warehouse, which makes sense assuming that the flat-rate value (a) should be lower than c_0 ($\mathrm{c}_0 > a$).

To sum up, the objective of the present chapter and the following one is to determine the optimal storage pricing schedule for import containers considering different objective functions.

The remainder part of Chapter 6 is structured as follows: first, the analytical model to estimate the amount of import container at the storage yard with the storage pricing schedule applied is introduced. In such chapter, the container arrival process is deterministic and the demand is slightly elastic to price changes. Then, in section 6.4, the maximization objective function is developed. In such section, the cost formulation for yard operations and revenues function are presented as well. In section 6.5 a numerical sample is addressed which is complemented with a sensitivity analysis. Finally, in section 6.6, first conclusions about storage pricing are done.

6.3 Analytical model to estimate import yard inventory when a storage pricing is introduced: deterministic approach

The model developed in this section estimates the amount of inbound containers at the storage yard when the storage charge is introduced. In such case, it is assumed that the demand is somewhat elastic since the amount of containers that get into the yard terminal is reduced according to the storage price applied.

6.3.1 Problem statement and assumptions

Suppose v cargo vessels arrive, with a period ΔT of time span, at a terminal with a temporary storage yard of total capacity of θ containers. The amount of containers unloaded per vessel is n, delivered by the customers at a certain rate (see Figure 6.2). A price P is charged to each container for the operations taking place in the terminal, regardless of its use of the yard. The purpose of the model is to study the effects of a tariff for yard storage and to find out which price scheme a profit-maximizing terminal should apply.

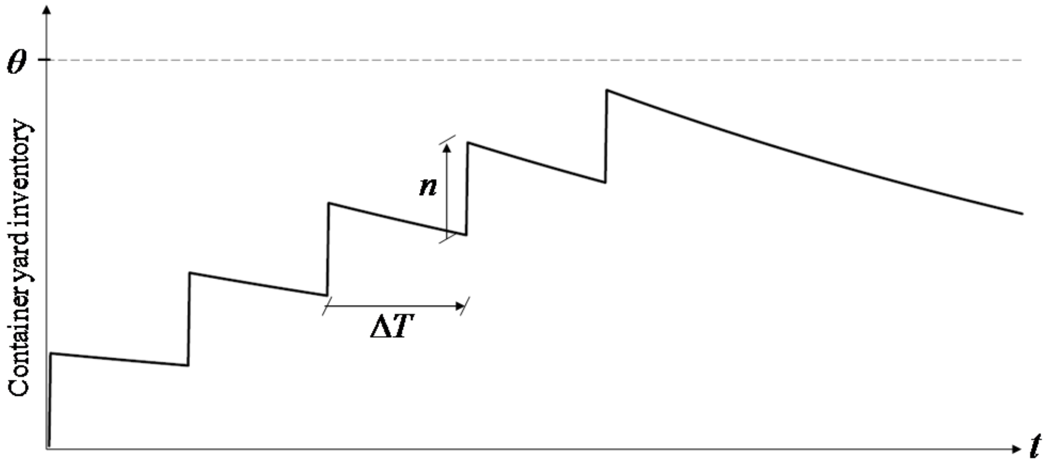


Figure 6.2: Terminal yard storage in a cycle of v=5 unloadings

General assumptions of the model are as follows:

- The terminal operator maximizes profit for a cycle of v unloadings, a time-horizon planning introduced by Kim and Kim (1999). Containers from previous cycles do not interfere (cycles are spanned enough).
- The terminal has some degree of market power (oligopolistic scenario).
- Containers, if accorded with the terminal before unloading, can be picked-up right after their unloading without being charged the yard tariff. This assumption has operative consequences: for instance, these containers could be stored (for less than one day) in a temporary buffer yard within the terminal.
- Both unloading and delivery times are considered deterministic.
- A continuous distribution of delivery times approximates the actual discrete process (Figure 6.3). Watanabe (2001) suggested an exponential function for this approximation; to allow a more general delivery pattern we use the Weibull cumulative distribution (of which the exponential is a limit case).

  With $t - t^i$ being the time since the i^{th} unloading, the expression for the containers remaining at the storage yard (in absence of a tariff) will be:

$$f^i(t) = \begin{cases} ne^{(-\lambda(t-t^i)^k)} & t \geq t^i = (i-1)\Delta T \\ 0 & t < t^i = (i-1)\Delta T \end{cases} \qquad [6.4]$$

  where λ is the rate of delivery (and 1/λ the mean delivery time) and k the shape parameter—which allows for an increasing, decreasing, or constant rate of delivery over time setting k<1, 0<k<1 or k=1, respectively.

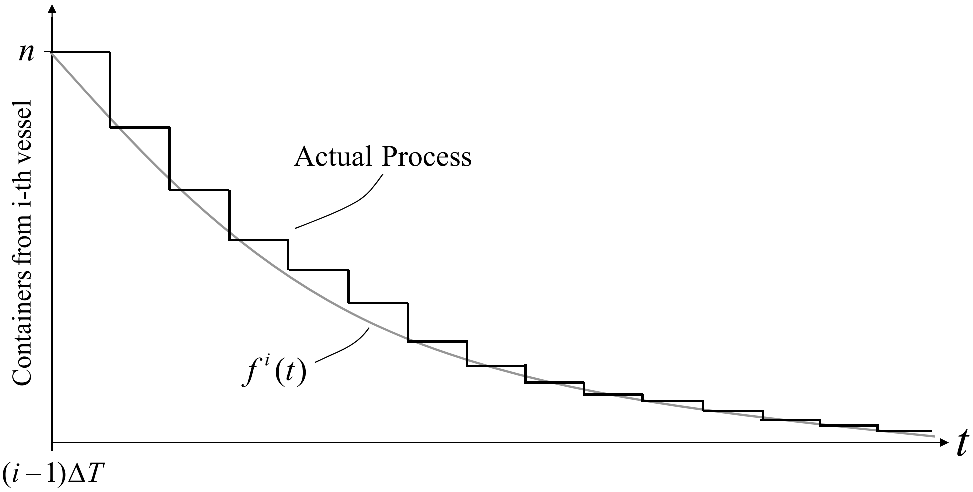


Figure 6.3: Approximation of the delivery times after the ith unloading

The following sections introduce the functions describing customer behavior and terminal costs and revenue.

6.3.2 Customers' choice

In Section 6.2 it has been determined that customers with delivery time less than t_p will prefer to pay the storage charge and keep the container at the yard terminal until delivery-their duration of stay remaining unchanged, following the original delivery distribution seen in equation [6.4]. Those with delivery time greater than t_p wil pick up the container before delivery and will pay the remote warehouse cost instead.

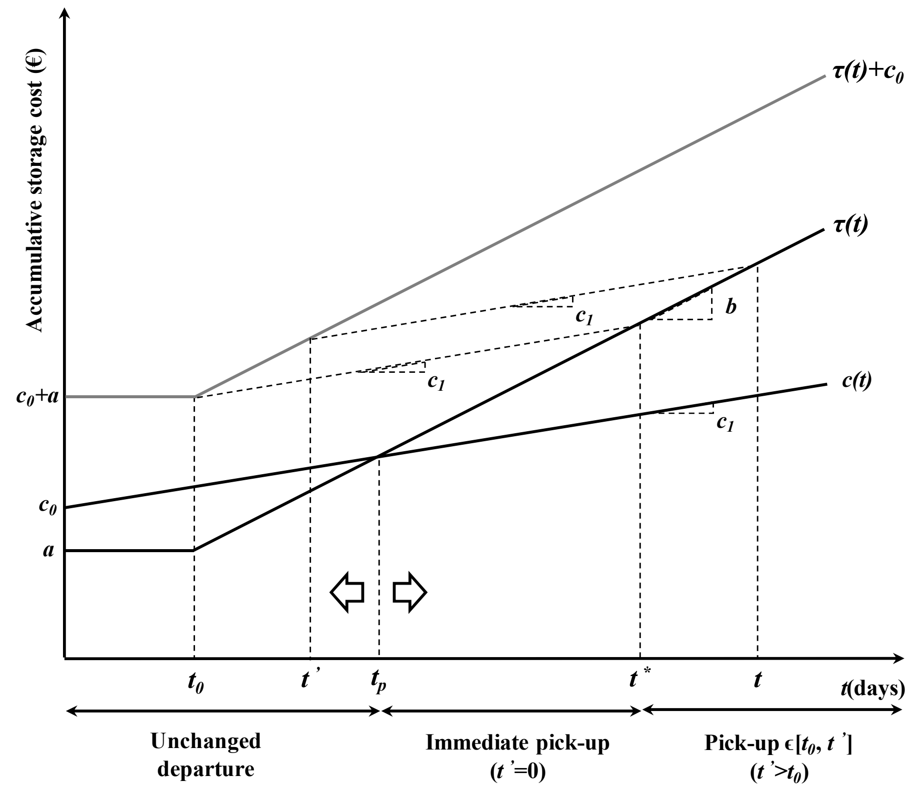


Figure 6.4: Cost to customers (paying the tariff or the warehouse cost) and departure decisions

Nonetheless, as it can be observed in Figure 6.4, there are another type of customer that are rescheduling their pick-up decisions according to the storage charge introduced by the terminal operator. Thus, the rest of this section deals specifically with the pickup rescheduling of these customers.

Rescheduling of pick-up decisions for customers storing off-dock

Early pick-up of some containers to be stored off-dock will be delayed (due to imperfect coordination, queues, etc.), being stored temporarily in the yard—at least until the flat rate finishes. The delay will never exceed an upper limit t' such that, at delivery t, warehousing cost plus the tariff evaluated at t' will match the tariff (see Figure 6.4).

Then, the following relationship gives the upper limit as a function of the original delivery time:

$$\tau(t) = \tau(t') + c_0 + (t - t')c_1 \rightarrow t' = \begin{cases} 0 & t_p < t < t^* \\ t - \dfrac{c_0}{b - c_1} & t \geq t^* \end{cases} \qquad [6.5]$$

That is, customers with delivery time $t_p < t < t^*$ pick up the container immediately after unloading (they cannot afford delays) and those with $t \geq t^*$ suffer some delay. Next, t^* is given by:

$$\tau(t^*) = \tau(t_0) + c_0 + (t^* - t_0)c_1 \rightarrow t^* = \begin{cases} \dfrac{c_0}{b - c_1} + t_0 & a > c_1 t_0 \\ t_p & a \leq c_1 t_0 \end{cases} \qquad [6.6]$$

As can be seen in referring to equation [6.5], t^* is relevant only when larger than t_p (otherwise all customers with $t < t^*$ would remain at the yard until delivery), so:

$$t^* - t_p > 0 \rightarrow \frac{a - c_1 t_0}{b - c_1} \rightarrow a > c_1 t_0 \qquad [6.7]$$

provides the threshold in equation [6.6].

The following describes how customers willing to use off-dock warehouses before delivery (those with delivery time t_p or above) will reschedule container pick-up.

On the one hand, and as previously stated, customers with $t_p < t < t^*$ do not use the terminal yard at all, moving the container to the warehouse immediately. Depending on the fixed part of the yard tariff and the warehouse cost, this kind of customers may or may not exist, as equation [6.6] and equation [6.7] illustrate.

On the other hand, customers with delivery $t \geq t^*$ suffer some delay. We assume this delay to follow a uniform distribution between the end of the flat rate and the maximum delay given in equation [6.5]: $U(t_0, t')$.

As the point estimate of the rescheduled pick-up (t_τ) the expected value is used (as a function of the delivery time t, or pre-tariff pick-up):

$$t_\tau = E[U(t_0, t')] = \frac{(t_0 + t')}{2} = \frac{1}{2}\left(t - \frac{c_0}{b - c_1} + t_0\right) \qquad [6.8]$$

where equation [6.5] is plugged in. Uniform distribution is applied for simplicity and an empirical study of delay times could provide a better choice, although any symmetric distribution would lead to the same result (since the expected value is used). Rearranging equation [6.8] gives a transformation from each new pick-up time to the delivery (or pre-tariff pick-up):

$$t(t_\tau) = \frac{c_0}{b - c_1} + 2t_\tau - t_0 \qquad [6.9]$$

This transformation will be used in the next section as it allows for obtaining the position of a rescheduling customer (t_τ) in the original delivery distribution (*t*).

6.3.3 Timing of the cargo stored in the terminal

To analyze the costs and revenue sources of the terminal it is necessary to have an expression for the quantity of containers in the terminal yard at each time. If no storage tariff were to be charged, the occupation of the yard would be the sum of equation [6.4] for all shipments (see Figure 6.2): $\sum_{i=1}^{v} f^i(t)$.

When a tariff is introduced, each f^i decreases because some customers stop using the terminal, maybe moving to another one, and because of the alteration of pickup decisions.

The first can be thought of as a decline in shipment volume. Most studies on terminal yard tariffs assume container arrivals to be constant on the price while some authors consider them to be elastic (Holguin-Veras and Jara Díaz, 2006). Here the demand is assumed to be reduced when a tariff is introduced, but not drastically since the terminal operator has some market power.

The magnitude of the reduction depends on the tariff imposed relatively to the price of the total terminal operations *P*. An effective tariff is used: the tariff minus the off-dock warehouse variable cost (capturing the premium charged with respect to the warehouse cost). This effective tariff is evaluated at a representative value of f^i (the mean delivery time, $1/\lambda$, plus t_0) and divided by *P* (the price charged regardless of yard usage). Hence the demand for the terminal is reduced by a fraction:

$$\alpha(a, b, t_0) = \frac{\tau\left(\frac{1}{\lambda + t_0}\right) - c_1\left(\frac{1}{\lambda + t_0}\right)}{P} = \frac{a + (b - c_1)\left(\frac{1}{\lambda + t_0}\right)}{P} \qquad [6.10]$$

The second source of reduction arises when terminal customers change their pick-up decisions once a tariff is introduced (as discussed in section 6.3.2). In particular, those customers with delivery time $t \geq t^*$ get the pick-up distribution of equation [6.4] transformed by equation [6.9], obtaining their new pick-up distribution:

$$f^i(t) = \begin{cases} 0 & t < t^* \\ f^i\left(\frac{c_0}{b - c_1} - t_0 + 2t\right) & t > t^* \end{cases} \quad [6.11]$$

Thus, the after-tariff number of containers in the terminal yard is (see):

- Between unloading and the end of the flat rate (t_0): α times the distribution of containers not using the off-dock warehouse minus those picked up immediately;
- Between the end of the flat rate (t_0) and t_p: the remaining number of customers not using the off-dock warehouse, $\alpha\left(f^i(t) - f^i(t_p^i)\right)$; and the customers rescheduling, $\alpha f^i(t)$; and
- After t_p: the remaining containers of those customers rescheduling.

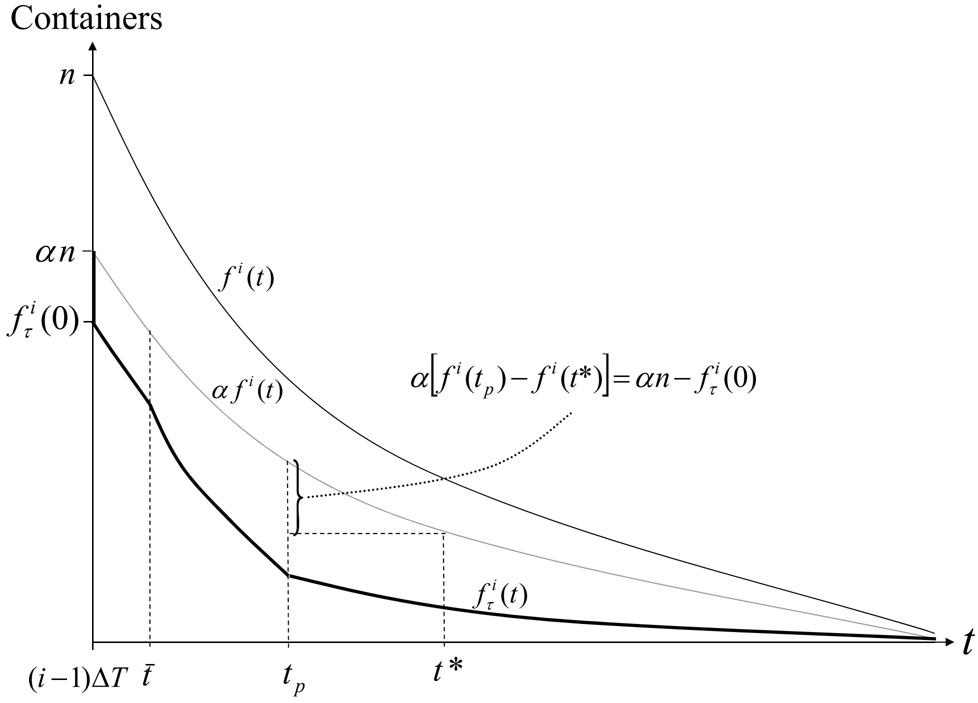


Figure 6.5: Cargo (from the ith unloading) stored in the terminal yard before (f) and after (f_τ) charging a tariff.

The after-tariff functional form is then:

$$f^i(t) = \begin{cases} \alpha\left(f^i(t) - f^i(t_p^i) + f^i(t^{*i})\right) & [i-1]\Delta T \le t \le t_0^i \\ \alpha\left(f^i(t) - f^i(t_p^i) + f^i(t)\right) & t_0^i < t \le t_p^i \\ \alpha \overline{f^i}(t) & t > t_p^i \end{cases} \quad [6.12]$$

where:

$t_0^i = t_0 + [i-1]\Delta T$

$t_p^i = t_p + [i-1]\Delta T$

$t^{*i} = t^* + [i-1]\Delta T$

Finally, the instantaneous number of containers being picked up is the derivative of equation [6.12]:

$$\frac{df^i(t)}{dt} = \begin{cases} \alpha \dfrac{df^i(t)}{dt} & [i-1]\Delta T \le t \le \mathrm{t}_0^{\mathrm{i}} \\ \alpha \left[\dfrac{df^i(t)}{dt} + \dfrac{d\overline{f^i}(t)}{dt}\right] & \mathrm{t}_0^{\mathrm{i}} < t \le \mathrm{t}_\mathrm{p}^{\mathrm{i}} \\ \alpha \dfrac{d\overline{f^i}(t)}{dt} & t > \mathrm{t}_\mathrm{p}^{\mathrm{i}} \end{cases} \qquad [6.13]$$

6.4 Objective function: maximizing terminal operator profit

In this section, the objective function used to determine the optimal value for the storage charge parameters is introduced.

However, before introducing the objective function it is required to define the cost and revenues functions, that is:

6.4.1 Simplified cost model for yard operations

The fixed cost is not quantified here, since the maximization of profit is independent from the fixed terms. The variable cost of the yard operations is essentially the cost of rehandling containers when picking-up. Kim and Kim (2007) take the variable cost as proportional to the expected time of rehandling and this as proportional to the average number of rehandles per pick-up. Kim (1997) estimated that the number of rehandles per pick-up is linear in the average height of stacks (number of containers divided by the number of ground slots), and thus linear in the number of containers in the yard.

But the storage variable cost is expected to soar when the cargo in the yard approaches its maximum capacity, and thus a linear function is no longer suitable (see Figure 6.6). This soaring cost near the maximum capacity is due to the increased number of rehandlings and also additional handling costs (damaged containers, delays, etc.).

A cost function such that the variable part of it will be approximately linear for low occupations and rise rapidly when reaching θ is to be chosen. An appropriate one is:

$$C(t) = C_f + C_v \left[\left(\theta - \sum_{i=1}^{v} f_\tau^i(t) \right)^{-1/2} - \theta^{-1/2} \right] \qquad [6.14]$$

where C_f and C_v are the fixed and the variable storage costs, respectively.

For low occupations, equation [6.14] approximates through a linear Taylor series to

$$C(t) \approx C_f + C_v \frac{\theta^{-3/2}}{2} \sum_{i=1}^{v} f_\tau^i(t) \qquad [6.15]$$

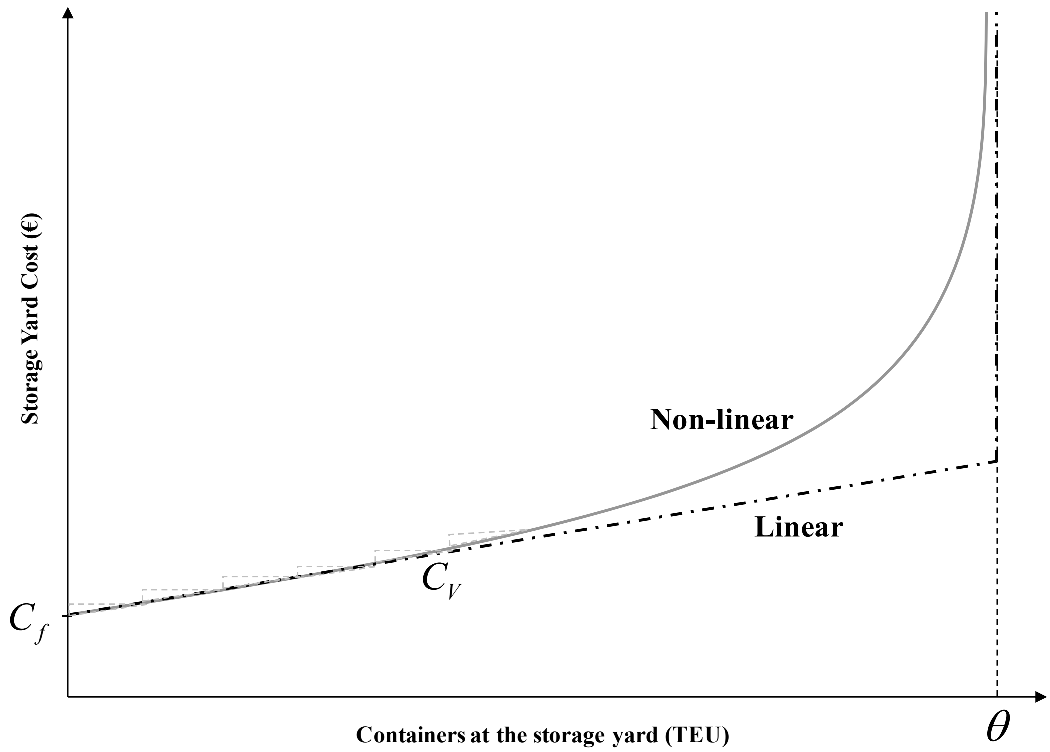


Figure 6.6: Functions for yard costs

And now C_v can be calibrated using the formulas in Kim and Kim (2007) and Kim(1997). The total cost is:

$$C(a,b,t_0) = C_f + C_v \int_0^{\infty} \left[\left(\theta - \sum_{i=1}^{v} f_\tau^i(t) \right)^{-1/2} - \theta^{-1/2} \right] dt \quad [6.16]$$

6.4.2 Revenues of terminal operator

The first source of revenue is the price for terminal operations. All containers shipped to the terminal are charged, so this stream accounts for vP times the volume of each unloading.

Terminal costs (excluding yard operations) are assumed to be linear in the number of containers: they are not affected by congestion. Denoting the variable cost (constant and equal to the marginal cost) by C_T, the profit for the terminal operations is:

$$D(a,b,t_0) = (P - C_T)(\alpha n V) = nv(P - C_T)\alpha(a,b,t_0) \quad [6.17]$$

Collecting the yard tariff is a second source of revenue. Since each T^i equals T^1 (all unloadings and delivery distributions are analogous to the first one) and the instantaneous number of containers leaving the yard is minus the derivative of the after-tariff distribution, the tariff revenue, R, amounts to:

$$R(a,b,t_0) = \sum_{i=1}^{v} R^i(a,b,t_0) = vR^1(a,b,t_0) = \quad [6.18]$$

$$= v\int_0^{\infty} -\frac{df_\tau^1(t;a,b,t_0)}{dt}\tau(t;a,b,t_0)dt =$$

$$= nv\alpha(a,b,t_0)\begin{cases} a + e^{-\lambda t}\left[\frac{b}{\lambda} + \left(a + \frac{b}{2\lambda}\right)e^{\frac{-\lambda c_0}{b-c_1}}\right] \\ -e^{-\lambda t_p(a,b,t_0)}\left[a + b\left(\frac{1}{\lambda} + t_p(a,b,t_0) - t_0\right)\right] \end{cases}$$

Finally, the maximization problem (profit minus fixed costs for the terminal operator) can now be easily obtained:

$$\underset{a,b,t_0}{Maximize}\, \Pi_T(a,b,t_0) = D(a,b,t_0) + R(a,b,t_0) - C(a,b,t_0) \qquad [6.19]$$

6.4.3 Solution procedure

Let $S(a) = [a_{min,}a_{max}]$, $S(b) = [b_{min,}b_{max}]$ and $S(t_0) = [t_{0_{min,}}t_{0_{max}}]$ be feasible ranges of the variables a, b and t_0, respectively. Then, for obtaining the optimal values all the combinations of the elements of $a \in S(a), b \in S(b)$ and $t_0 \in S(t_0)$ are enumerated and a shortlist of three parameters that maximizes equation [6.19] is selected as the optimal solution.

The enumerative procedure to obtain the solution is introduced as follows:

Step 1: $a = a_{min}$

Step 2: if $a > a_{max}$ then go to step 6; otherwise, $b = b_{min}$

Step 3: if $b > b_{max}$ then $a = a + x_a$, thus go to step 2; otherwise, $t_0 = t_{0\,min}$.

Step 4: if $t_0 > t_{0_{max}}$ then $b = b + x_b$, thus go to step 3; otherwise calculate $D(a,b,t_0)$, $R(a,b,t_0)$, and $C(a,b,t_0)$, defined in 6.4.1 and 6.4.2.

Step 5: $t_0 = t_0 + x_{t_0}$, thus go to step 4.

Step 6: Evaluate the objective function [6.19]. Then choose the set (a, b, t_0) that maximizes [6.19].

Here x_a, x_b and x_{t_0} are the stepwise of each parameter.

It should be remained that the variables a and b are price values and t_0 is the period of time whereas the flat rate is applied. Thus these three parameters belong to the zero or positive real numbers group. In addition by considering the restrictions regarding $a < c_0$ and $b > c_1$, the search space is defined: $S(a) = [0, c_0)$, $S(b) = (c_1, b_{max}]$ and $S(t_0) = [0, t_{0_{max}}]$.

6.5 Numerical case study

6.5.1 Baseline scenario

For the numerical case the model developed in this chapter is applied. In such case the input data is characterized by: v=5 unloadings, n=180 cont./unloading, ΔT=2 days, λ=1/6 days^{-1}, C_v=10 \$/cont.-day, θ=1.2nv cont., c_0=30 \$/cont., c_1=5 \$/cont.-day, P=95 \$/cont., C_T=75 \$/cont.

Table 6.2 shows the optimal values of the yard tariff (after a numerical optimization of the objective function) and Figure 6.7 the surface of the objective function. Note that fixed costs are not included.

Table 6.2: Optimal yard tariff and results for the numerical example

Optimal Price Schedule			Results		
a **(\$)**	***b*** **(\$/day)**	t_0 **(days)**	**Π(\$)**	**α (%)**	t_p **(days)**
10.4	8.7	0	12,160	65.6	5.3

The optimal t_0 is zero, not only for our specific parameters but also pretty consistently (see next section), as obtained in previous studies such as Kim and Kim (2007). However, the fixed part of the tariff (a) is found to be significantly greater than zero, contrary to the usual practice in most container terminals (see the introduction).

The composition of the profit, depicted in Figure 6.7, shows how costs and revenues behave when tariff parameters, a and b, change; using only the optimal (t_0=0).

When rates are low, costs soar (the less is charged for yard storage, the more congested it becomes) and terminal handling profit increases (unsurprisingly, since it is proportional to the terminal demand). The effect is reversed when a and b increase.

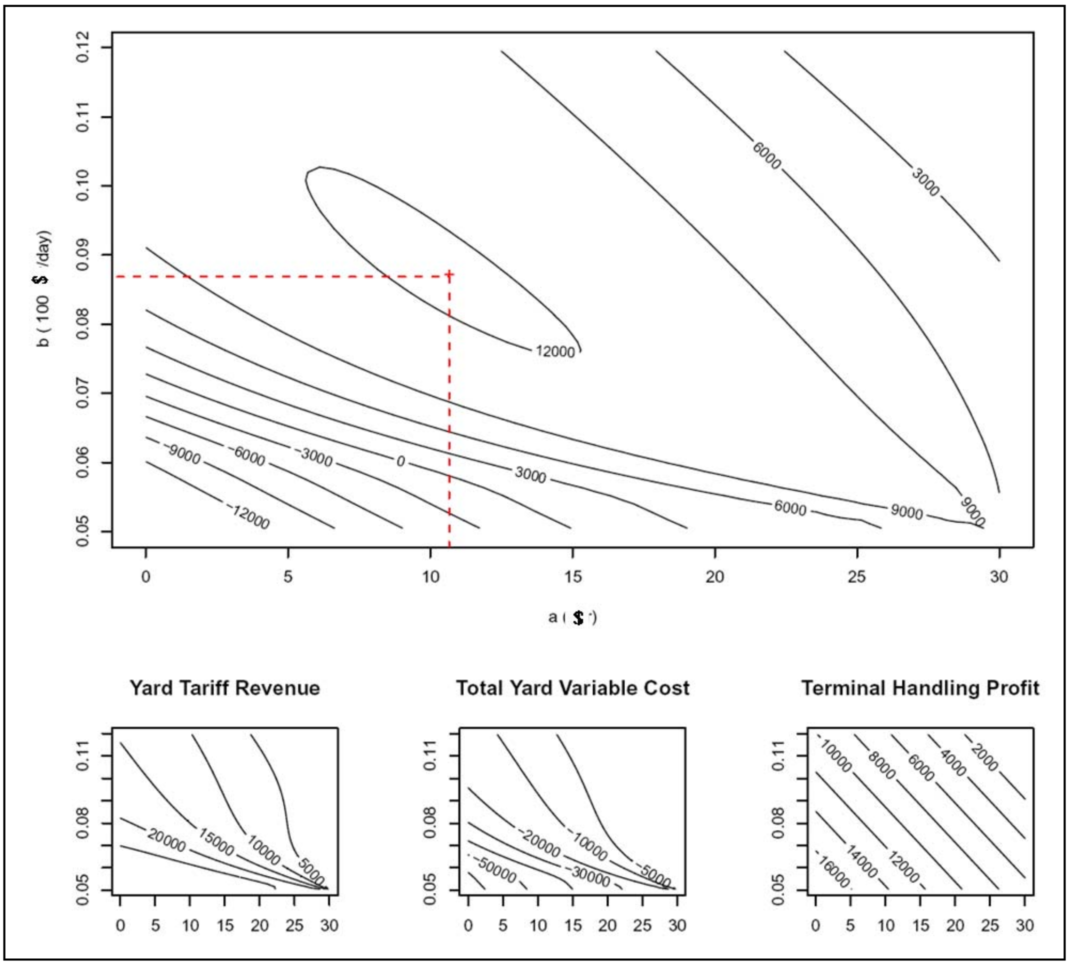


Figure 6.7: Profit minus fixed costs and its decomposition.

Yard tariff revenue, similarly to yard cost, grows inversely with the tariff parameters: there is a trade-off between collecting more money per container and attracting more containers.

6.5.2 Sensitivity analysis

To study how a terminal operator should respond to changes in the characteristics of the problem a sensitivity analysis is developed. Table 6.3 shows how the optimal values in alternative scenarios differ from the previous baseline example when, ceteris paribus, one of the basic model parameters is modified. The optimal flat-rate duration is always zero and thus not reported in Table 6.3.

- The inter-arrival time (ΔT) has little impact on profitability (as in our base scenario the terminal yard operates with low congestion) but in the expected direction: the more spanned vessel arrivals are, the lower costs will the yard apply. Delivery time from which customers decide to store off-dock (t_p) also reacts as expected: when T is reduced customers pick up earlier and vice versa.

Table 6.3: Percent deviation with regard to base scenario (ΔT_0=2, λ_0=1/6, C_{v0}=10, θ_0=1.2nv)

Scenario	***a***	***b***	**Profit**	**α**	t_p
$\Delta T = \Delta T_0/2$	–5.7	6.4	–0.8	–4.4	–10.4
$\Delta T = 1.5\Delta T_0$	0.0	–1.6	1.2	1.3	3.8
$1/\lambda = 0.66/\lambda_0$	–36.3	22.6	19.7	–12.9	–22.2
$1/\lambda = 1.33/\lambda_0$	47.5	–16.1	–14.1	5.6	20.3
$C_v = C_{v0}/2$	47.5	–38.8	69.2	24.7	740.0
$\theta = 0.6\ \theta_0$	18.1	–1.6	–3.4	–1.7	–6.1

- The rate of delivery (λ; the mean of delivery times being its inverse) appears to be a key driver of the model. With a lower mean (i.e., customers delivering earlier) the terminal slashes the fixed part of the tariff, a, and increases the variable part, b, obtaining more profit with both the relative demand (α) and t_p sharply reduced (as the terminal avoids congestion in the yard). An increasing mean has opposite effects.

- If operational costs in the yard were to be drastically cut (by half in our alternative scenario, due to mechanization or other sources of productivity), profit would soar: captured demand being close to the pre-tariff level and virtually no customer using off-dock warehousing.

- Reducing the yard capacity (θ), a sensible goal given the current pressure for saving terminal space, would have a rather small effect on profitability. A terminal operator should then increase the fixed part of the tariff, allowing to reduce yard occupation (by slightly lessening the demand and stimulating early pick-up) while maintaining similar revenues.

- The demand captured by the terminal is driven mostly by the variable yard tariff, b. The higher b is, the lower demand becomes-except if the change in b is parallel to an opposite drastic change in a.

6.6 Conclusions

Pricing schemes for inbound container yards were studied for first time in this chapter. The model built incorporates the reactions of the customers in two ways: a direct reduction of demand due to the introduction of a tariff and an indirect effect in the storage yard occupation due to migration to off-dock warehouses. The optimal tariff was, through numerical analysis, found to consist of a fixed part higher than zero and a variable part, with no period of flat rate.

General pricing guidelines for terminal operators were also obtained. The storage price per unit of time shall be increased when vessel inter-arrival time or the rate of delivery are lower. If yard costs are to be cut, the storage price per container shall be reduced proportionally. The fixed part of the tariff shall be increased when a reduction in yard cost or capacity occurs; or when the delivery rate increases.

Nonetheless, this first approach has some limitations since it is just a first approximation to solve the pricing storage problem in a generic way.

Demand behavior (responding to the yard tariff) could be inspected in greater depth; paying particular attention to the possibility that the demand from customers with different delivery rates may be differently affected.

Secondly, the model developed here does not include some important aspects affecting demand, such as functionality of the entire network. A particularly interesting line of further research to accommodate such aspects could be the inclusion of stochastic analysis, especially regarding vessel arrivals or network delays.

Finally, a deeper analysis with regard to the occupancy rate of the storage yard is required because in this chapter only one scenario has been considered. According to the results and sensitivity analysis is expected that different pricing schedules can be defined according to the yard congestion effects. That is why the analysis of the storage pricing problem is extended in chapter 7.

Chapter 7

Pricing storage strategies for improving storage yard performance: stochastic approach

7.1 Overview

Chapter 7 is organized as follows: first, in section 7.2, an analytical model based on the methodology introduced in chapter 3 but including the migration to an off-dock warehouse is presented. Then, in section 7.3, the storage pricing optimizing model to determine the optimal value for the tariff parameters is developed. In such section, a detailed cost model is included. In section 7.4 a numerical sample is addressed which is complemented with a sensitivity analysis. Afterwards a comparison between optimal results from chapter 6 and 7 is derived. Finally, some conclusions and contributions are stated. Additionally, the Appendix A presents detailed and explicit formulation for direct implementation in future works.

7.2 Analytical model to estimate import yard inventory when a storage pricing is introduced: stochastic approach

The purpose of the analytical model is to estimate the import yard inventory, in terms of number of containers, by considering the migration to an auxiliary remote warehouse when a storage pricing is introduced in the port container terminal.

7.2.1 Main assumptions

Similar to previous chapter, suppose v cargo vessels arrive with a defined inter-arrival time ΔT, at a container terminal which import storage capacity is θ containers. The number of unloaded containers per vessel is n, but instead of being constant in this chapter is considered as a random variable that follows a probability distribution function.

In this chapter, multiple vessels are also considered: deep-sea containerships that operate among a limited number of transshipment terminals (*hubs*) and smaller vessels (feeders) that link the hubs with the other ports (*spokes*).

Therefore, the probability distribution function will be defined for each type of vessels, as the average number of unloaded containers will differ. Then, we define $r, r = \{fs, ds\}$, be the variable that represents the type of vessel, in which *fs* represents a feeder service vessel and *ss* a deep-sea vessel.

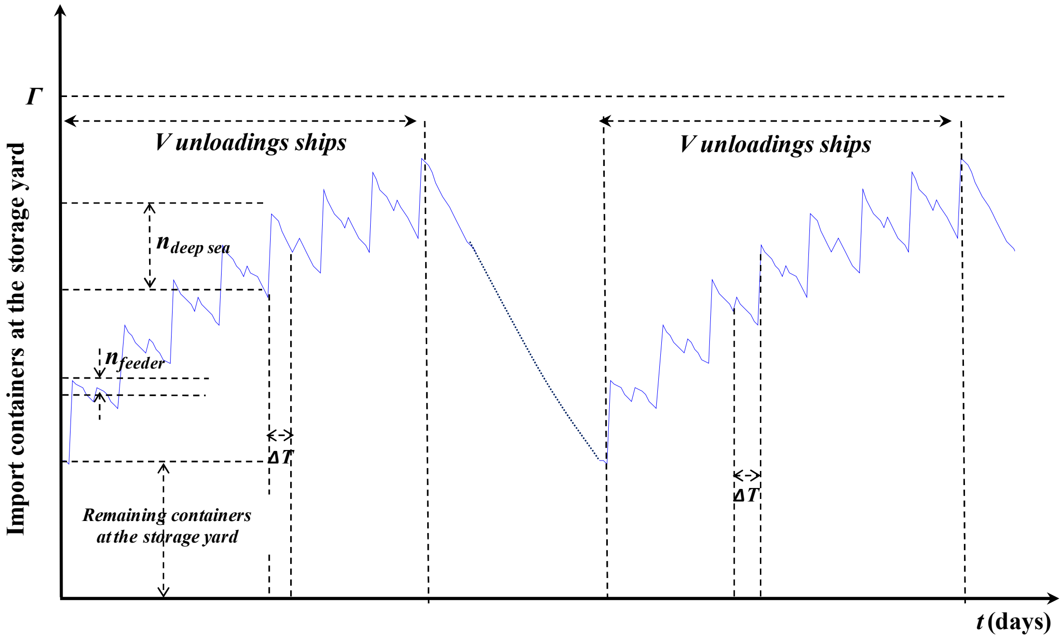


Figure 7.1: Inventory level of import containers at the storage yard and time-horizon planning

Other main assumptions of the model are as follows:

- The terminal operators' profit and the total cost of the system are maximized and minimized, respectively, for a cycle of *v* unloadings, based on time-horizon planning as introduced by Kim and Kim (1999).
- The terminal has full degree of market power (an oligopolistic scenario), so an inelastic terminal demand is considered. Then it is supposed that the inbound cargo flow of the container terminal is stable and independent of storage prices, as in De Castilho and Daganzo (1991), Holguin-Veras and Jara-Diaz (1999) and Lee and Yu (2012).
- It is assumed that customers' behavior is homogeneous regarding dwell time (Lee and Yu, 2012), that is, all containers behave according to the same delivery time distribution.
- Customers are seeking to minimize cost. If delivery time $t_s > t_p$, the container will leave the terminal immediately; otherwise, the customer will keep the container in the storage area until t_s (customers do not rearrange the length of dwell time because of the port storage charge).
- The dwell time of import containers is uncertain and is considered to be a stochastic variable. Watanabe (2001) and Zhang et al. (2003) suggested an exponential function for this approximation. To allow a more general delivery pattern a Weibull cumulative distribution is considered (of which the exponential distribution is a limiting case, k_{ts}=1), with parameters k_{ts} and λ_{ts}.

- The vessel headway (ΔT) is constant.
- The number of unloaded containers per vessel is considered a random variable (N_r). This variable is assumed to follow a Weibull distribution function ($N_r \sim Weibull\ (\lambda_r, k_r)$) according to empirical data from the Port of Barcelona (Spain). Its parameters are defined according to both types of vessels considered (λ_r, k_r) and N_r can adopt the following Z values,

  $N_r = \{n_r\} = \{n_{1r}, n_{2r}, n_{3r}, \ldots, n_{Zr}\}$.

To sum up, the problem analyzed in this chapter is characterized by a stochastic container arrival and departure process, since the number of unloaded containers per vessel is random and dependent of the type of vessel. On the other hand, the container departure process is defined by the import container dwell time, which is approximated to a Weibull (even an exponential) distribution function.

7.2.2 Number of inbound containers at the storage yard

The aim is to calculate the expected number of import containers stored at the yard at time *t*, considering the aforementioned assumptions. To obtain the expected number of containers stored at the yard, it is necessary to know the probability of having s containers, $s \in [0, n_r]$, at the terminal yard at a given time *t*, whereas the vessel discharged n_r containers.

Let us consider a hypothetical case in which a feeder vessel calls at the container terminal and discharges n_{fs} import containers. Let us also suppose, in this case, that n_{fs} is constant and deterministic, that dwell time (t_s) follows a Weibull distribution function and that the threshold time (t_p) is already known to the customers. Then, the probability of having s containers, $s \in [0, n_{fs}]$, at the terminal yard at a given time *t*, $P_{fs}^{s}(t)$, will be:

$$\begin{aligned} P_{fs}^{s}(t) &= \binom{n_{fs}}{n_{fs}-s}\left(\left[\mathrm{P}(t_s \le t)\mathrm{P}(t_s \le \mathrm{t_p}) + \mathrm{P}(t_s \ge \mathrm{t_p})\right]^{(n_{fs}-s)}\left[\mathrm{P}(t_s \ge t)\mathrm{P}(t_s \le \mathrm{t_p})\right]^{s}\right) \\ &= \binom{n_{fs}}{n_{fs}-s}\left[\mathrm{F(t)F(t_p)} + \mathrm{S(t_p)}\right]^{(n_{fs}-s)}\left[\mathrm{S(t)F(t_p)}\right]^{s} \end{aligned} \quad [7.1]$$

The function $F(t)$ indicates the probability that an individual container has already left the terminal at time *t*, $F(t) = P(t_s \le t)$, and the function $S(t)$ represents the probability that a container is still stored at the storage yard, that is, it has not left the terminal ($S(t) = P(t_s \ge t) = 1 - F(t)$).

Then, on one hand, the term $\left[F(t)F(t_p) + S(t_p)\right]^{n_{fs}-s}$ represents the probability that $(n_{fs} - s)$ containers have left the container terminal yard at time *t* and have gone directly to the off-dock warehouse because their delivery time, t_s is greater than the threshold $\mathrm{t_p}$. On the other hand, the term $[S(t)F(t_p)]^{s}$ indicates the probability that s containers are stored at the yard terminal due to $t < t_s < t_\mathrm{p}$.

The following step is to calculate the probability of having s containers, $s \in [0, n_r]$, at the terminal yard at a given time *t*, considering that n_r is a random variable that follows a probability distribution function ($G(n_r)$). Then, this variable is added to the formulation with the probability distribution function of the variable and the corresponding addition because n_r is a discrete random variable. Thus, the probability of s containers from the ship of type r being at the terminal will be:

$$P_r^s(t) = \sum_{n_r} \binom{n_r}{n_r - s} \left([\mathrm{F(t)F(t_p)} + \mathrm{S(t_p)}]^{(n_r - s)} [\mathrm{S(t)F(t_p)}]^s \right) P(n_r) \quad \forall t \geq 0 \qquad [7.2]$$

where $P(n_r)$ is the probability of discharging n_r containers from the vessel of type r. This value will depend on the assumption related to the probability distribution function, the parameters of which are calibrated according to historical data.

As previously assumed, the number of unloaded containers per vessel follows a continuous distribution function. So, it is necessary to make a correction for continuity to calculate the probability that a vessel unloaded exactly n_r containers (discrete variable). In this case, the following approximation is used:

$$P(n_r) = P[(n_r - 0.5) < N_r < (n_r + 0.5)] = G(n_r + 0.5) - G(n_r - 0.5) \qquad [7.3]$$

where $G(n_r)$ is the probability that a particular vessel unloaded n_r or less. For the particular in which $\mathrm{n_r}$ follows a Weibull distribution, $G(n_r) = 1 - e^{-\left(\frac{n_r}{\lambda_r}\right)^{k_r}}$, for $n_r > 0$, k_r and λ_r being the shape and the scale parameters, respectively.

Finally, if $t^i = (i - 1)\Delta T$ is the time when the ith vessel arrives and ΔT is the inter-arrival time between consecutive vessels, the probability of having s containers at the storage yard from the ith vessel, $i \in [0, N]$, of type r at time $t > t^i$, will be:

$$P_{ir}^s = \sum_{n_r} \binom{n_r}{n_r - s} \left([\mathrm{F}(t - t^i)\mathrm{F(t_p)} + \mathrm{S(t_p)}]^{(n_r - s)} \cdot [\mathrm{S}(t - t^i)\mathrm{F(t_p)}]^s \right) \cdot P(n_r) \qquad [7.4]$$

Then, the expected number of containers remaining at the storage yard from the i^{th} vessel, $i \in [0, N]$, of type r, $E_{ir}[Q(t)]$, is given by:

$$E_{ir}[Q(t)] = \begin{cases} \sum_{s=0}^{n_r} s \cdot P_{ir}^s(t) & t \geq t^i \\ 0 & t < t^i \end{cases} \qquad [7.5]$$

As an alternative, following the same procedure applied in chapter 3 (section 3.3.1) to simplify expression [7.5] and by considering the delivery time distributions of inbound containers, expression [7.6] is introduced:

$$E_{ir}[Q(t)] = \begin{cases} \sum_{n_r} n_r \, P(n_r) [\mathrm{S}(t - t^i)\mathrm{F(t_p)}] & t \geq t^i \\ 0 & t < t^i \end{cases} \qquad [7.6]$$

where $\sum_{n_r} n_r \, P(n_r) = E[n_r]$ is the expected number of unloaded containers from a vessel of type r.

The next step requires the inclusion of analytical expressions for inbound container dwell time in equation [7.6] which can be rewritten as:

$$E_{ir}[Q(t)] = \begin{cases} \lambda_r \Gamma\left(1+\frac{1}{k_r}\right)\left(\left(e^{-\left(\frac{t-t^i}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(1-e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\right) & t \geq t^i \\ 0 & t < t^i \end{cases} \quad [7.7]$$

Finally, it is required to calculate the expected total number of inbound containers at the storage yard during the cycle time, in which V containerships arrive at a constant rate ΔT. As mentioned above, two types of vessel are considered in this chapter (feeder and deep-sea), and thus $V = V_{fs} + V_{ds}$, where V_{fs} is the number of feeder vessels and V_{ds} the number of deep-sea vessels.

To calculate the total number of containers at the terminal at time *t*, the methodology defined in section 3.4 is applied.

Thus we consider the vector $\boldsymbol{V}$ which is defined in expression [3.17]. In such case let us assume that there are just two types of vessel, so the sum of both vectors will be the unity vector. The vector components indicate whether the i^{th} calling vessel is feeder or deep-sea, depending on whether there is a 0 or 1 in the corresponding position. The dimensions of both vectors will be V rows (corresponding to v vessels) and 1 column and its formulation was described in [3.20] and [3.21].

Then, the vector $E_r[Q(t)]$ is defined, whose v components specify the expected remaining number of containers being unloaded from each calling vessel of type r at the terminal during the cycle time considered at time $t > t^i$. Each vector component ($E_{ir}[Q(t)]$) is calculated according to expression [7.8], that is:

$$E_r[Q(t)]_{[1xv]} = (E_{1r}[Q(t)] \quad ,\dots, \quad E_{ir}[Q(t)] \quad ,\dots, \quad E_{vr}[Q(t)]) \quad [7.8]$$

Finally, deriving from expressions [3.17] and [7.8], the total expected number of containers at the terminal at time t ($E_T[Q(t)]$) will be:

$$E_T[Q(t)] = \sum_{r=\{fs,ds\}} E_r[Q(t)]_{[1xv]} \cdot V_{[vx1]} + E_T[Q(t_0)] = E_{fs}[Q(t)]_{[1xv]} \cdot V_{fs_{[vx1]}} + E_{ds}[Q(t)]_{[1xv]} \cdot V_{ds_{[vx1]}} + E_T[Q(t_0)] \quad [7.9]$$

where $E_T[Q(t_0)]$ is the expected number of containers remaining at the storage yard when the cycle time begins ($t_0 = 0$).

7.3 Storage pricing optimizing models

7.3.1 Cost model of the terminal operator

First of all it should be mentioned that the cost model developed in this section is an extended and detailed version of the one introduced in section 6.4.1. Differently from the simplified version in which constant values were used this model describes all cost components included in the analysis through comprehensive formulation.

The cost factors related to the terminal operator can be divided into fixed and variable costs. Generally, fixed costs include the construction costs for blocks and aisles and/or concession port fees that are paid to the corresponding port authority during the period of time in which the terminal is managed by the operator. Depending on the type of agreement, construction costs will be responsibility of the terminal operator or the port authority. Fixed costs also include the overheads for handling equipment (purchasing costs), which are related to the amount of equipment required for a specific throughput.

On the other hand, variable costs are related primarily to handling operating costs, i.e. direct labor, fuel and maintenance costs. In the particular case of YCs, direct costs relate to receiving containers from the vessel, storing and stacking in the yard, delivering to road trucks, and rehandling costs arising from multi-level stacking in the yard.

Operating costs are indirectly affected by the use of storage space. In standard working conditions, the elapsed time required for handling a container depends solely on the mechanical and kinetic characteristic of handling equipment, block and terminal layout, etc., but when the storage yard inventory approaches storage capacity limits, operational delays occur, and thus gross handling productivity decreases. This means that the operating time required for handling a container increases and therefore costs are also expected to rise.

In this chapter, it is assumed that a linear function is no longer appropriate to approximate the effects on operating costs when inventory levels are close to full storage capacity. In this situation, the storage variable cost is expected to soar as it approaches its maximum capacity. For this reason, it is assumed that operating costs will increase according to the pattern depicted in Figure 7.2, which can be formulated mathematically as follows:

$$\delta(t; a, b, t_0) = [\theta - E_T(Q(t))]^{-1/2} - \theta^{-1/2} \quad [7.10]$$

where θ is the storage capacity (in terms of TEU) and $E_T(Q(t))$ the storage space requirement at time t, formulated as in equation [7.9].

The equation [7.10] has been already used in this thesis, particularly in equation [6.14], in chapter 6.

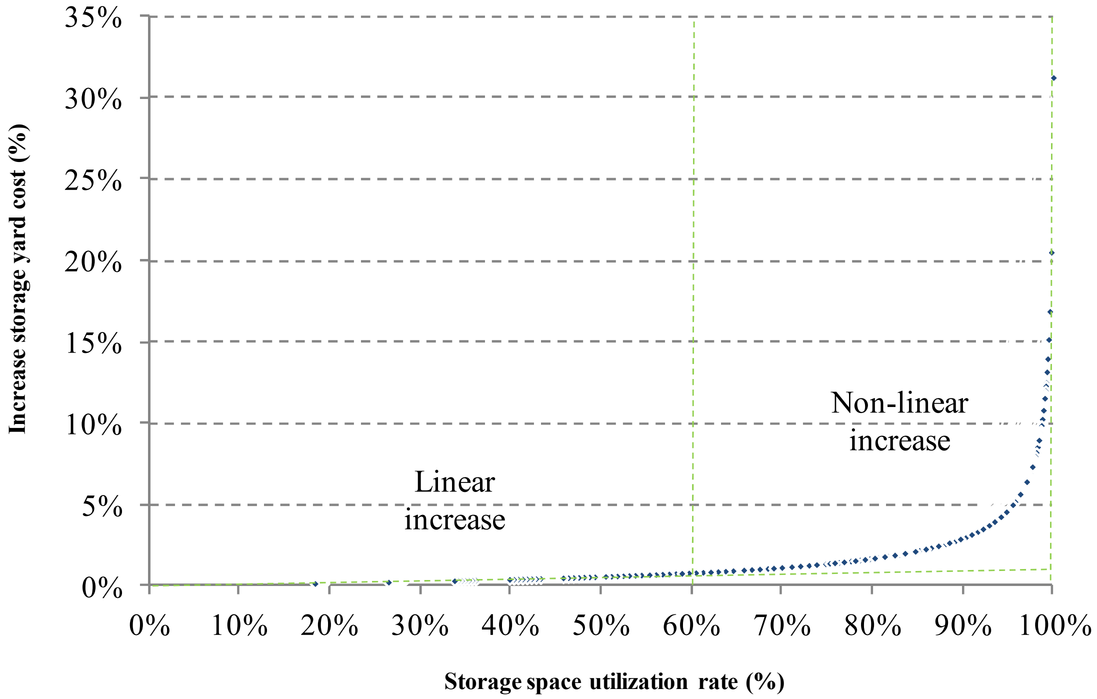


Figure 7.2: Increasing rate of variable costs due to congestion effects at the yard

As can be observed, the operating costs will be approximately linear for low occupation levels, in line with Kim (1997), and will rise rapidly when reaching storage yard capacity (θ). This soaring cost near the maximum capacity is due to the effects of congestion at the storage yard. These effects are produced predominantly by operating delays, the congestion of driving lines, increased waiting times, crane and vehicle interference, damaged containers, etc.

In addition, an increase in space utilization has a direct impact on stacking height as it becomes higher. Rehandling costs then also increase. Kim (1997) estimated that the number of rehandles per pick-up was: (1) proportional to the square of the average stacking height, and (2) linear to the remaining containers at the yard. In particular, the number of rehandles per pick-up was found to be $\rho = (\mathrm{h} - 1/4) + (\mathrm{h} + 2/16\mathrm{w})$, where h is the stacking height and w the number of containers per bay.

Finally, an additional cost resulting from congestion at the storage yard is related to the amount of equipment employed for handling processes. It is known that as the cycle time increases, the gross productivity of handling decreases and, as a result, the turnaround time of vessels and road trucks becomes longer. To offer a good quality of service, terminal operators are required to provide more equipment for handling operations to offer the same quality of service even when congestion effects arise.

In this chapter, only the variable costs arising from the effects of storage yard congestion are considered. To sum up, the following cost factors are considered:

1) The cost of rehandling containers when picking up.
2) Additional costs generated in operating processes due to the effects of congestion on terminal performance.

3) Additional costs related to the required amount of equipment (overhead costs) to maintain the same quality of service when handling productivity decreases.

Thus, the variable cost function depending on the utilization of the storage yard for the containers from the i^{th} vessel can be formulated as follows:

$$C_{ir} = C_{ir}^{reh} + C_{ir}^{op} + C_{ir}^{eq} \qquad [7.11]$$

The first term of expression [7.11] corresponds to the rehandling cost which is represented as:

$$C_{ir}^{reh} = \rho \cdot c_{YC}^{o,d} \cdot \int_{t^i}^{t_p+t^i} \left(-\frac{d}{dt} E_{ir}(Q(t))\right) dt \qquad [7.12]$$

where $c_{YC}^{o,d}$ is the YC operating cost per delivered container, the minus derivative function $(-\frac{d}{dt}E_{ir}(Q(t)))$ is the number of containers leaving the terminal, $E_T[Q(t)]|_{t=t_i}$ is the expected number of import container at the storage yard after unloading the containers from the i^{th} vessel and ρ is the average number of rehandles per pick-up.

The second term of expression [7.11] is the additional operating cost due to the impact of the space utilization on the terminal performance. This variable cost is formulated as follows:

$$C_{ir}^{op} = \left(c_{QC}^{o,u} + c_{YC}^{o,u} + c_{TR}^{o,u}\right) \cdot \left[E_{ir}(Q(z))\delta(z)\right]_{z=t^i} + c_{YC}^{o,d}(1+\rho)\int_{t^i}^{t_p+t^i} \left(-\frac{d}{dz} E_{ir}(Q(t))\right)\delta(t)dt \qquad [7.13]$$

where $c_{QC}^{o,u}$, $c_{YC}^{o,u}$ and $c_{TR}^{o,u}$ are the operating cost per container for QCs, YCs and transport vehicles (TR) during an unloading operation taking into account the expected cycle time for each type of equipment. In addition, $c_{YC}^{o,d}$ is the YC operating cost per delivered container. As can be seen from this expression, the effect of the space utilization on the operating cost is ruled by $\delta(t)$.

The third term of expression [7.11] represents additional costs related to the investment required to obtain extra equipment when congestion costs arise. This cost is defined as:

$$C_{ir}^{eq} = \left(c_{QC}^{F,u} + c_{YC}^{F,u} + c_{TR}^{F,u}\right) \cdot \left[E_{ir}(Q(z))\delta(z)\right]_{z=t^i} + c_{YC}^{F,d}(1+\rho)\int_{t^i}^{t_p+t^i} \left(-\frac{d}{dz} E_{ir}(Q(t))\right)\delta(t)dt \qquad [7.14]$$

where $c_{QC}^{F,u}$, $c_{YC}^{F,u}$ and $c_{TR}^{F,u}$ are the purchasing costs for QC, YC and TR per unloaded, taking into consideration the expected cycle time for each type of equipment, and $c_{YC}^{F,d}$ the corresponding purchasing cost per delivered container for a YC.

In Appendix A, the corresponding analytical expressions of the variable costs for the terminal operator are derived by including in the explicit functions related to the random variables of the problem.

Finally, the total variable cost for the terminal operator is:

$$C_T^{op} = \sum_{r=\{fs,ds\}} C_r \cdot V \qquad [7.15]$$

where $C_r = \{C_{1r} \quad ,\dots, \quad C_{ir} \quad ,\dots, \quad C_{Nr}\}$ in which C_{ir} is the total variable cost for the terminal operator (rehandling costs, additional operating costs and additional purchasing costs) and *V* is the vector defined in equation [3.17].

7.3.2 External cost of container terminals

To quantify the total costs of the system, the costs for road trucks and vessels served by the terminal operator are defined. The external costs for the container terminal operator are related to the value of the time that represents the opportunity costs of the turnaround time (average time elapsed between the arrival of road trucks or vessels at the terminal and departure). In essence, this value is the amount that a particular subject would be willing to pay to save time, or the amount they would accept as compensation for lost time.

Following the same criteria used for the operating costs of the terminal operator and assuming that when congestion problems are generated, delays in turnaround time occur, additional costs are derived.

The associated additional external costs for those road trucks ($C_{ir}^{e(ET)}$) that arrive at the terminal to pick up the containers unloaded from the i[th] vessel are expressed as follows:

$$C_{ir}^{e(ET)} = C_{ET} \int_{t^i}^{t_p+t^i} \left(-\frac{d}{dz} E_{ir}\big(Q(t)\big) \right) \delta(t) dt \qquad [7.16]$$

where C_{ET} is the cost per container related to the value of that time that a truck spends at the terminal to pick up a container. The cycle time of the road truck which is included in the unitary cost per retrieved container, is the sum of the travel time, waiting time and the service time required by the YC to retrieve a container from the yard and deliver it to the truck.

Complementarily, the associated additional external cost ($C_{ir}^{e(V)}$) for the i^{th} vessel served by the terminal is:

$$C_{ir}^{e(V)} = \frac{C_V}{g} \left[E_{ir}\big(Q(z)\big) \delta(z) \right]_{z=t^i} \qquad [7.17]$$

where C_V is the cost per container related to the value of the time that a vessel spends at the terminal for unloading a single container. The variable g represents the average number of QCs that operate simultaneously per vessel.

To sum up, the additional external costs associated with the i^{th} vessel are formulated as follows:

$$C_{ir}^{e} = C_{ET}\int_{t^i}^{t_p+t^i}\left(-\frac{d}{dz}E_{ir}\big(Q(t)\big)\right)\delta(t)dt + \frac{C_V}{g}\big[E_{ir}\big(Q(z)\big)\delta(z)\big]_{z=t^i} \qquad [7.18]$$

Similarly to the previous cost formulation, the corresponding analytical expressions regarding the external costs are developed in Appendix A.

Finally, the total amount of extra external costs due to congestion at the yard for a certain period of time will be:

$$\mathrm{C_T^e} = \sum_{\mathrm{r=\{fs,ds\}}} C_r^e \cdot V \qquad [7.19]$$

where $\mathrm{C_r^e} = \{\mathrm{C_{1r}^e}\ , \dots ,\ \mathrm{C_{ir}^e}\ , \dots ,\ \mathrm{C_{Nr}^e}\}$ the components of which are defined in [7.18] and V is defined in equation [3.17].

7.3.3 Customers' expenses to move containers to the off-dock warehouse

Customers that decide to move their containers to an off-dock warehouse have to pay a trucking company to move a container to an off-dock warehouse from the port and for storage for a period of time. The storage cost is defined according to equation [6.2] in which c_0 corresponds to the transport costs from the port terminal to the warehouse and c_1 is the variable storage cost per time at the off-dock warehouse.

Taking into consideration that the length of time of storage for customers who decide to move their containers to an auxiliary warehouse is longer than the threshold time, $\mathrm{t_p}$, the total payment amount can be formulated as:

$$C_{ir}^{c} = E[n_r]\int_{t_p+t^i}^{\infty}\left(-\frac{dS(t)}{dt}\right)c(t)dt =$$

$$= E[n_r]\left(c_0\left(\int_{t_p+t^i}^{\infty} -\frac{dS(t)}{dt}dt\right) + c_1\left(\int_{t_p+t^i}^{\infty} -\frac{dS(t)}{dt}t\,dt\right)\right) \qquad t > t^i \qquad [7.20]$$

where $c(t)$ is the storage cost at the off-dock warehouse.

As shown in Appendix A, expression [7.20] can be solved analytically when the delivery times are exponential. For the general Weibull distribution, no general closed form solution exists. The final analytical expression is also detailed in Appendix A.

Finally, the total payment for the users is:

$$\mathrm{C_T^c} = \sum_{\mathrm{r=\{fs,ds\}}} \mathrm{C_r^c} \cdot V \qquad [7.21]$$

where $\mathrm{C_r^c} = \{C_{1r}^c\ , \dots ,\ C_{ir}^c\ , \dots ,\ C_{Nr}^c\}$, in which each component corresponds to expression [7.20] and V is the vector defined in equation [3.17].

7.3.4 Revenues of the terminal operator

Terminal operators have different sources of revenue according to the services provided to customers. The most important source is the price for handling operations, that is: a tariff for loading/unloading containers to/from the vessel or receiving/delivering to road trucks or trains.

The second source of revenue is the storage charge collected from those customers who decide to stay at the container yard because the delivery time (t_s) is lower than the threshold time (t_p).

In this chapter, we only take into account those revenues directly related to the storage yard because storage pricing is introduced by terminal operators to mitigate variable costs generated by the higher utilization rates of storage space.

Therefore, the revenue of the terminal operator from the i^{th} calling vessel of type *r*, R_{ir}, will be determined by the following expression:

$$R_{ir} = \int_{t^i}^{t_p+t^i} \tau(t) \cdot \left(-\frac{d}{dz} E_{ir}(Q(t))\right) dt \qquad t > t^i \qquad [7.22]$$

where $\tau(t)$ is the storage pricing scheme at the container terminal and the minus derivative of the expected amount of containers in the yard $(-\frac{d}{dt} E_{ir}(Q(t)))$ is the number of container leaving the terminal at each time *t*, where $t \geq t^i$.

Expression [7.22] is solved analytically when the delivery times are exponential and its final expression is introduced in Appendix A.

Finally, the total revenues of the terminal operator are:

$$\mathrm{R_T} = \sum_{\mathrm{r=\{fs,ds\}}} \mathrm{R_r} \cdot \mathrm{V} \qquad [7.23]$$

where $\mathrm{R_r} = \{\mathrm{R_{1r}} \;, \dots, \; \mathrm{R_{ir}} \;, \dots, \; \mathrm{R_{Nr}}\}$ and *V* is the vector defined in equation [3.17].

7.3.5 Objective functions

This section formulates the objective functions for determining the optimal storage pricing for import containers, $\tau(t; a, b, t_0)$.

- **Maximization of the terminal operator profit**

  As in chapter 6, the first objective function maximizes the expected profit (Π_T) for the terminal operator, that is, it maximizes the difference between the expected revenues from the storage charge and the expected variable costs generated as a consequence of the increase of the use of the storage yard.

  Thus, the maximization of the expected profit derived by the terminal operator, which is the difference between expressions [7.23] and [7.11] is expressed as:

$$\underset{a,b,t_0}{Maximize}\; \Pi_T(a,b,t_0) = R_T(a,b,t_0) - \mathrm{C_T^{op}}(a,b,t_0) \qquad [7.24]$$

  where $a \in S(a), b \in S(b)$ and $t_0 \in S(t_0)$

- **Minimization of the terminal operator and customers' costs**

The second objective function minimizes the total integrated cost of the system: the operating costs for the terminal operator and the costs for customers within the system. The former cost includes the opportunity cost related to the value of the time that customers' containers spend at the terminal and the cost of using the off-dock warehouse, which includes the transportation cost to the remote warehouse and the expenses for storing containers there.

This function was also previously considered in Kim and Kim (2007), equivalized to maximize public welfare in the case that a port terminal was managed and operated by a public administration or government. Storage services at container terminals are usually required by customers. Therefore, in this case, the operator of the container terminal will prefer to offer a good quality of service to their clients, at the same time as minimizing its own costs.

Thus, the minimization objective can be written as:

$$\underset{a,b,t_0}{Minimize}\ \Phi_{\mathrm{T}}(a,b,t_0) = \mathrm{C}_{\mathrm{T}}^{\mathrm{op}}(a,b,t_0) + \mathrm{C}_{\mathrm{T}}^{\mathrm{e}}(a,b,t_0) + \mathrm{C}_{\mathrm{T}}^{\mathrm{c}}(a,b,t_0) \qquad [7.25]$$

where $a \in S(a), b \in S(b)$ and $t_0 \in S(t_0)$

The first term of expression [7.25] is the operating cost for the terminal operator; the second term corresponds to the external cost of the system, which corresponds to expression [7.19]; the last term corresponds to the customers' expenses for moving their containers to the off-dock warehouse operator, expressed in [7.21].

The problems defined in [7.24] and [7.25] optimize the storage pricing for import containers, by considering two different criteria, and consider the trade-off between the three decision parameters that characterize the tariff scheme: a, b and t_0. Thus:

- For the same values of b and t_0, as the value of the flat rate a decreases, durations of stay of import containers at the terminal storage yard become longer and thus operating and external costs increases because the average stacking height is greater and the storage utilization rate of the yard also increases. Revenues during the flat rate period (t_0) decrease because the marginal revenue per container is lower, but from t_0 onwards the total amount of revenues increase because the durations of stay are longer.
- For the same values of a and t_0, as the value of b increases, durations of stay at the port terminal become shorter. The limit case occurs when b tends to infinity, which means that the maximum duration of stay at the port terminal is t_0. In this case, the number of containers that stay at the port container terminal is lower because remaining there is only advantageous for containers with a short dwell time. Then the amount of revenue is expected to be reduced because of lower demand although the storage charge per day is higher. Fewer containers at the yard means a shorter stacking height and lower utilization rates; thus, it is expected that operating and external costs will not increase.

- Finally, for the same values of a and b, durations of stay become longer as t_0 increases. As a result, higher utilization rates of the storage space at the port are expected and the congestion and external costs will then soar. In addition, the number of rehandles increases. The total amount of revenue from the storage charge will be reduced because the flat-rate length of time is increased.

7.3.6 Solution procedure

The solution procedure is exactly the same that the one employed for solving the problem in chapter 6. Then, by rearranging the procedure to the particular properties of the above optimizing problems, the solution procedure is as follows:

Let $S(a) = [a_{min,}a_{max}]$, $S(b) = [b_{min,}b_{max}]$ and $S(t_0) = [t_{0_{min,}}t_{0_{max}}]$ be feasible ranges of the variables a, b and t_0, respectively. Then, to obtain the optimal values, all the combinations of the elements of $a \in \mathrm{S}(a), \mathrm{b} \in \mathrm{S(b)}$ and $\mathrm{t_0} \in \mathrm{S(t_0)}$ are enumerated and a shortlist of three parameters that maximizes [7.24] or minimizes [7.25] are selected as the optimal solution. The enumerative procedure to obtain the solution is introduced as follows:

Step 1: $a = a_{min}$

Step 2: if $a > a_{max}$ then go to step 6; otherwise, $b = b_{min}$

Step 3: if $b > b_{max}$ then $a = a + x_a$, thus go to step 2; otherwise, $t_0 = t_{0\,min}$.

Step 4: if $\mathrm{t_0} > \mathrm{t_{0_{max}}}$ then $\mathrm{b} = \mathrm{b} + \mathrm{x_b}$, thus go to step 3; otherwise calculate $\mathrm{R_T}$, $\mathrm{C_T^{op}}$, $\mathrm{C_T^c}$ and $\mathrm{C_T^e}$, defined in sections 7.3.1 to 7.3.5.

Step 5: $\mathrm{t_0} = \mathrm{t_0} + \mathrm{x_{t_0}}$, thus go to step 4.

Step 6: Evaluate the objective functions [7.24] and [7.25]. Then choose the set $(a, \mathrm{b}, \mathrm{t_0})$ that maximizes [7.24] and the set $(a, \mathrm{b}, \mathrm{t_0})$ that minimizes [7.25], separately.

Here x_a, x_b and x_{t_0} are the stepwise of each parameter.

It should be noted that the variables a and b are price values and $\mathrm{t_0}$ is the period of time in which the flat rate is applied. Thus, these three parameters are in the zero or positive real numbers group. In addition by considering the restrictions regarding $a < \mathrm{c_0}$ and $\mathrm{b} > \mathrm{c_1}$, the search space is defined as follows: $\mathrm{S}(a) = [0_{,}\mathrm{c_0})$ $\mathrm{S(b)} = (\mathrm{c_1}, \mathrm{b_{max}}]$ and $\mathrm{S(t_0)} = [0_{,}\mathrm{t_{0_{max}}}]$.

7.4 Numerical experiments

In this section, numerical experiments are carried out to address the objective functions. It is supposed that the container terminal is operated by RMG cranes and the block layout is characterized by w=6 and $H_m \in [4,6]$. It is assumed that every day a vessel arrives at the terminal (ΔT=1day) and the time-horizon planning is 20 days. The average import dwell time is approximately 3.5 days, which is equivalent to k_{ts}=1.5 and λ_{ts}=3.5. The average numbers of unloaded containers, according to historical data from the Port of Barcelona (Spain), are $E[n_{fs}]$=530TEU and $E[n_{ds}]$=1,180 TEU, the distribution parameters of which are: (k_{fs}=2, λ_{fs}=600) and (k_{ds}=4, λ_{ds}=1,200).

It was also considered that c_0 =30$/TEU, c_1 =5$/TEU-day, $c_{QC}^{F,u}$=6.90$/TEU,$c_{QC}^{o,u}$=3.30$/TEU,$c_{YC}^{F,d}$=2.15$/TEU , $c_{YC}^{F,u}$=1.31$/TEU,$c_{YC}^{o,d}$=2.01$/TEU,$c_{YC}^{o,u}$=1.68 $/TEU, $c_{TR}^{F,u}$ =0.24$/TEU, $c_{TR}^{o,u}$ =1.92$/TEU, C_{ET} =9.70$/TEU and C_V =18.97$/TEU. The specification of the expecting operating and investment costs was obtained from a currently working container terminal.

The capacity of the storage yard (θ) is variable within the range [3,000-10,000] to analyze the effect of space utilization on the definition of the optimal tariff parameters.

In the sample it is assumed that two types of vessels arrive at the terminal in random order and thus yard inventory fluctuations are expected. This scenario could reflect the real circumstances of terminals that receive large numbers of containers from deep-sea liner vessels and at the same time operate several feeder lines with neighbor ports.

For the different experiments, $S(a)$, $S(b)$ and $S(t_0)$ consist of real values from 0 onwards but the search space is reduced according to a <30 and b>5. Thus, $S(a) = [0,30)$, $S(b) = (5,100]$ and $S(t_0) = [0,100]$.

7.4.1 Results and sensitivity analysis

Table 7.1 shows the results for the problems aimed at maximizing the expected profits for the terminal operator and minimizing total expected integrated costs for a container terminal with a storage yard occupancy of over 75% (θ=3,500 slots).

Table 7.1: Optimal parameters, expected profits and total expected integrated costs when θ=3,500 and space utilization is approximately 75%.

Block stacking height (H_m)	**Storage capacity (θ)**	**Maximize terminal operator profits**		**Minimize total integrated costs**	
		$(a,b,t_0)^*$	$\Pi_T^*(a,b,t_0)$	$(a,b,t_0)^*$	$\Phi_T^*(a,b,t_0)$
4	3500	(29,6,2)	299,553$	(14,13,7)	33,584$
6	3500	(29,6,2)	295,536$	(23,14,8)	37,858$

As can be seen, the optimal storage pricing parameters for the maximization model are a^*=29$, b^*=6$/day and t_0^*=2 days for both cases regarding the stacking height of storage blocks. However, the expected profits are 2% lower for the 6-tiers high case because operating costs are higher.

In this case, Figure 7.3 depicts the change in the expected profit with respect to the threshold time (t_p) which determines the final choice of customers and therefore the number of import container that are stored in the port terminal. The optimal threshold time to maximize the expected profits of the terminal operator is at or around 12 days, which means that those import containers stored for greater lengths of stay are sent to remote warehousing because it is the cheaper alternative. Specifically, for this time period, 7.5% of unloaded containers are moved to an off-dock warehouse.

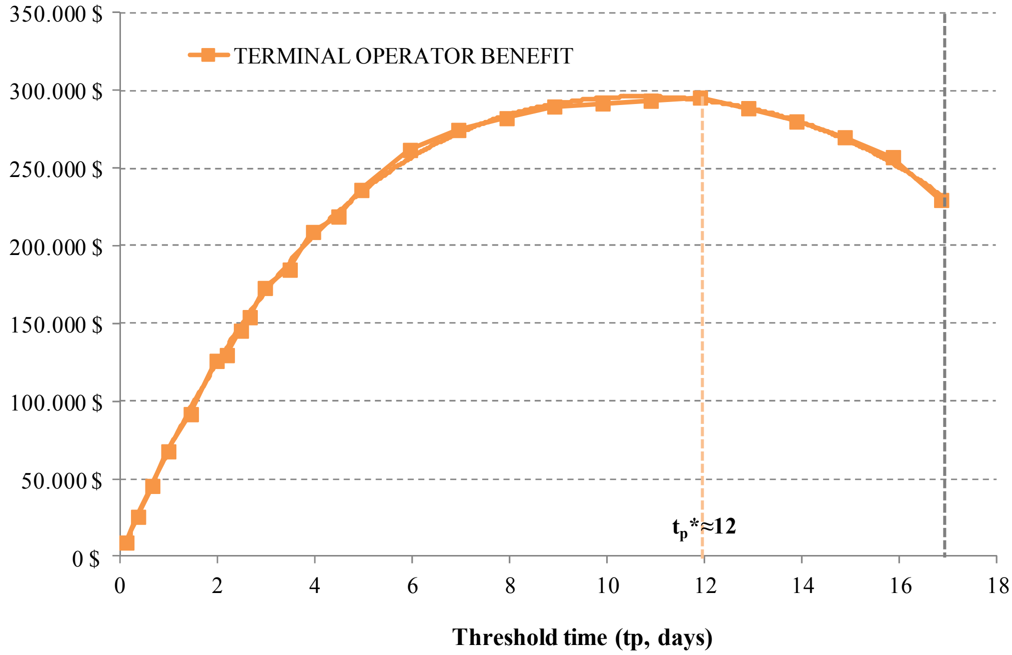


Figure 7.3: Maximum expected profits regarding the threshold time ($\mathbf{t_p}$)

The higher the threshold time the higher the number of containers that customers will opt to store at the port container terminal. The revenues and variable costs for the terminal operator will also be higher, but the variable costs will increase rapidly as the occupancy rate reaches the maximum storage capacity, as can be observed from the curve depicted in Figure 4. Next, for t_p values higher than optimal, the marginal variable cost is higher than marginal revenues, and thus the expected profits are lower. Finally, it was found that for t_p values of greater than 16.5 days, the variable costs increase drastically because the storage yard becomes full and congestion affects terminal performance as a whole. In such cases, the expected profits are negative.

On the other hand, in terms of minimizing the total costs of the system, the optimal solution is a^*=14\$, b^*=13\$/day and t_0^*=7 days and a^*=23\$, b^*=14\$/day and t_0^*=8 days for 4-tiers high stacking and 6-tiers high stacking, respectively. In both cases, the threshold time is approximately 13 days, but slightly higher in the first case in which the stacking height is four tiers. This difference is justified because the expected rehandling costs are lower, and thus more import containers are allowed to be stored in the yard.

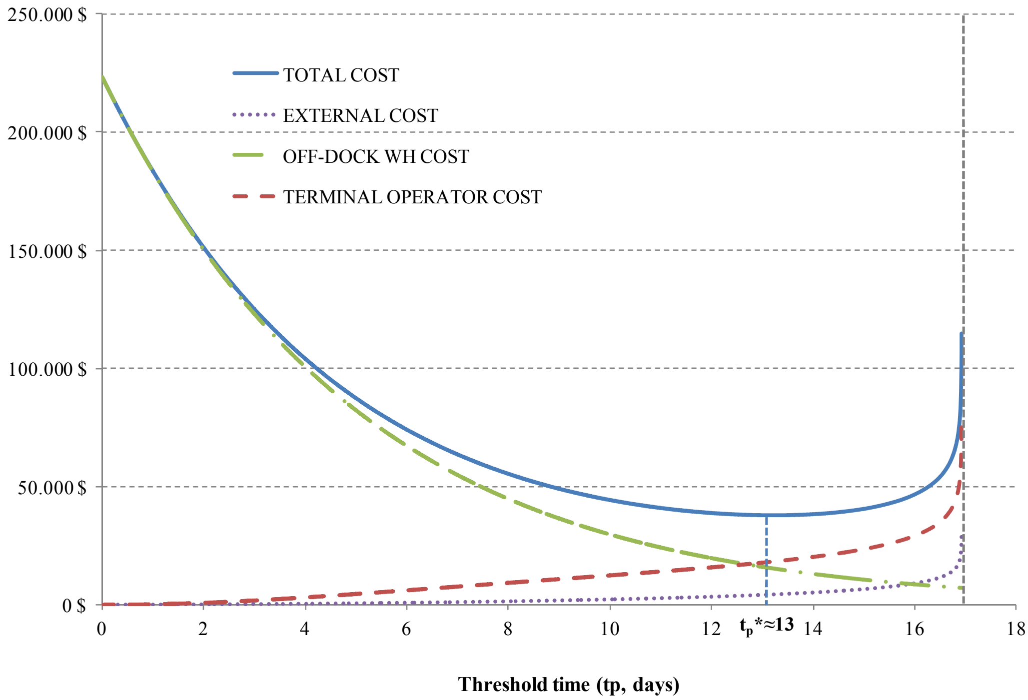


Figure 7.4: Expected total costs regarding the threshold time (t_p)

Figure 7.4 shows changes in the costs involved in the minimizing model. The operating costs and external costs increase in line with the threshold time because the number of import containers stored and its corresponding length of time in the port container terminal is greater. In contrast, as the threshold time increases, the amount of payment from those customers moving their containers to remote warehousing will be lower. Thus, the optimal solution in relation to minimization is a threshold of approximately 13 days, as can be observed.

Similarly to the statements related to the maximization problem, the storage yard at the port terminal becomes congested when t_p is higher than 16.5 days, which is why a vertical asymptote is derived from the calculations.

In addition, various numerical experiments were performed to analyze the effect of the main input parameters and variables of the problem on the optimal solution for both objective models.

Figure 7.5 shows changes in the optimal solution for various rates of storage space utilization, that is, the relationship between the average number of import containers at the storage yard and the storage capacity (θ). It can be observed that as the use of space increases, the optimal value for parameter a decreases and that for parameter b increases slightly in relation to maximizing the expected profit, reducing the value of the threshold time (t_p). This means that the length of stay at the yard is shorter and no congested situations are expected to occur.

To minimize cost, as the use of storage space decreases, the trend is to increase the threshold time because space is not scarce and any congestion effect is derived from the terminal performance. However, when congestion problems arise (higher occupancy rates), it is preferable that the number of containers at the yard is reduced. Then, the optimal storage pricing is merely a flat rate characterized by a and t_0, as it can be seen in the right part of Figure 7.5.

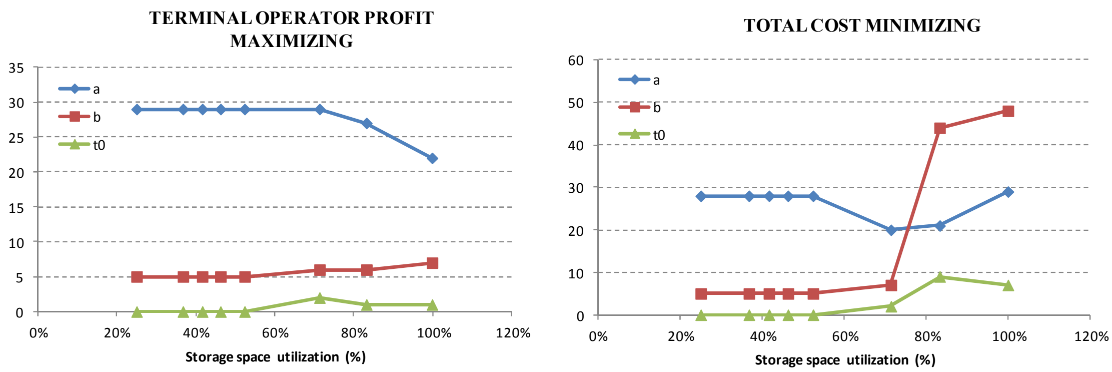


Figure 7.5: Change in the decision variables (a, b, t_0) in relation to the problem with respect to the storage space utilization (%)

Figure 7.6 shows how the optimal values changes with regard to the relationship between the outgoing flow (with regard to the import container dwell time) and the incoming flow (related to the inter-arrival time) at the container terminal yard.

The trend in maximizing expected profit as the average dwell time increases is to cut the number of incoming containers to the storage yard to reduce the variable operating costs of the terminal operator as expected length of stay is longer. The longer the dwell time the lower the profitability of the storage space and the higher the variable costs. Thus, when the duration of stay is long, the optimal pricing storage schedule is characterized by a zero flat-rate (t_0=0) and parameters a and b with positive values, as depicted in Figure 7.6.

To minimize the total cost, the system responds to a dwell time increase in the same way as for the maximization of operator profits, that is, by reducing the number of incoming containers to the yard to avoid congestion situations. However, the threshold time t_p is higher than the optimal threshold time for maximizing terminal profit because reducing the hypothetical amount of customers' expenses for moving their containers to off-dock warehouse operators is more advantageous. In this case, the optimal tariff schedule has a flat rate duration followed by a storage charge based on time.

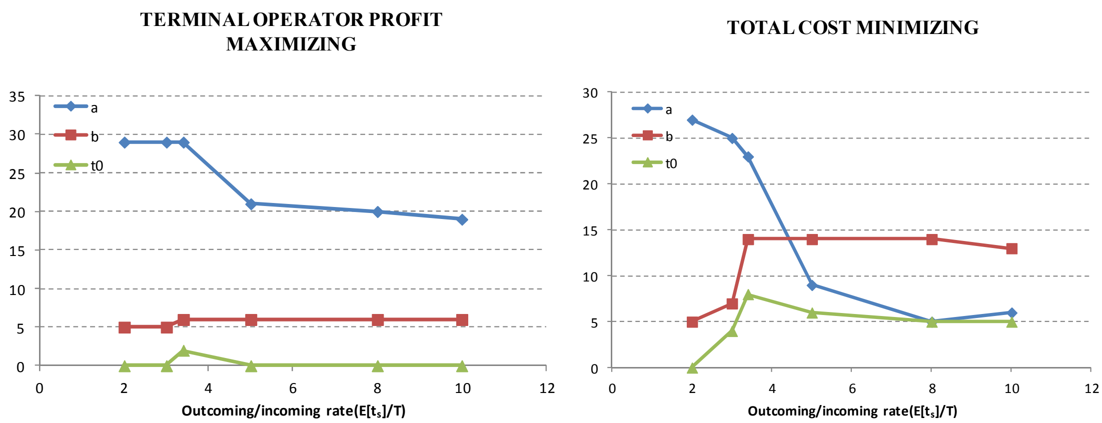


Figure 7.6: Changes in the decision variables (a, b, t_0) of the problem concerning the relationship between the outcoming and incoming rate

Finally, Figure 7.7 shows that as the cost of transporting containers from the port to the remote warehouse increases, the optimal value of parameter a increases proportionally in terms of maximizing the profits of terminal operators; in this case, parameters b and t_0 are not sensitive to the transportation costs (c_0).

On the other hand, to minimize the total costs of the system, the trend is to reduce the value of parameters b and t_0 as the transportation cost increases to maintain the same value of threshold time (t_p), which guarantee the minimum cost of the system. For the different combinations depicted in Figure 7.7, the optimal threshold time value is close to 12 days.

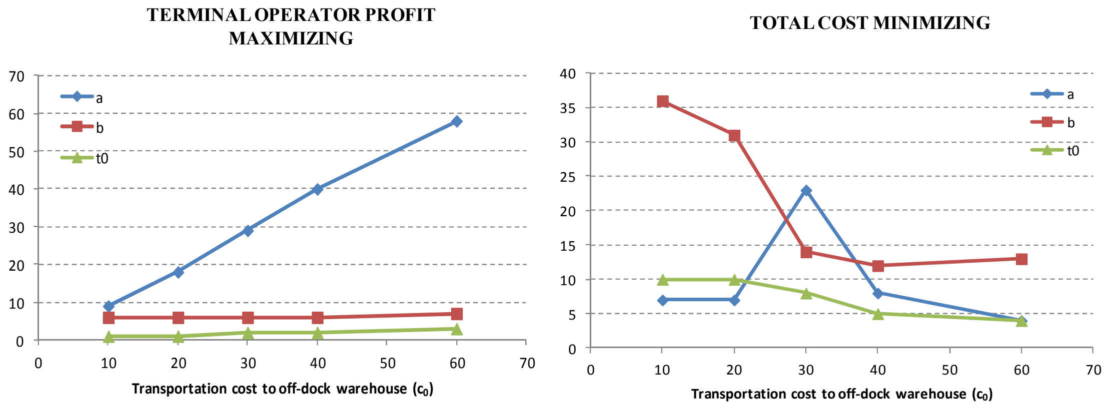


Figure 7.7: Changes in the decision variables $(\mathrm{a}, \mathrm{b}, \mathrm{t}_0)$ for the problem regarding the transportation costs from the port terminal to the off-dock warehouse

To sum up, the following statements are presented:

- First, to maximize the expected profit for the terminal operator and when the storage yard capacity is not a limiting factor (maximum occupancy rate is below 70%) the optimal pricing schedule is characterized by a linear increase function in relation to the storage time and t_0=0, that is $\tau(t; a, b)$. In this case, terminal operators should introduce a storage charge similar to, but slightly cheaper than, the remote warehouse costs to attract potential demand.

  The optimal storage pricing scheme for minimizing the total cost of the system is similar, because the purpose is to minimize the amount of payment to the off-dock warehouse as the operating and external costs are already reduced because the storage yard is not congested.

- Second, for container terminals with capacity problems (average occupancy rate higher than 70%), the optimal storage pricing consists of a flat rate greater than zero until t_0 and then a linear increase rate per storage time greater than the corresponding cost at the remote warehouse ($\tau(t; a, b, t_0)$). The purpose of this structure is to avoid the terminal yard becoming congested by reducing the average length of stay of those containers that are stored at the terminal yard.

- The results demonstrate that current practical storage pricing schedules (see Table 6.1) are not optimal, as some free time is considered at almost all the container terminals. However, these results are in accord with the main contributions on storage pricing at port terminals, i.e., those of Kim and Kim (2007) and Lee and Yu (2012), which also argue that actual practice differs from optimal schemes. In addition, results from chapter 6 are in accordance with results just obtained in this chapter.

7.5 Discussions and comparison between the deterministic and the stochastic approach

In this section, we undertake a comparative analysis of the deterministic and the stochastic scenarios regarding container arrival at the terminal. It merely consists of quantifying the deviation in profit and cost between both cases and how the optimal parameters change for different variability rates.

It should be recalled that the higher the variability of the random variables the lower will be the corresponding expected value, and the more deviation is expected with respect to the deterministic case and even the hypothetical real cases, as demonstrated in chapter 3.

Next, additional numerical experiments are carried out to compare the optimal results from the deterministic model analyzed in chapter 6 and the stochastic model in this chapter. Table 7.2 presents the optimal values for the parameters and the optimal expected profits and cost deviations with regard to the deterministic case.

Table 7.2: Comparison between the optimal results obtained for deterministic and stochastic scenarios. The symbol "+++" indicates the highest variability and "0" the deterministic case.

Scenario	Covariance (n_{fs},n_{ds})	Maximize terminal operator profits		Minimize total integrated costs	
		(a,b,t_0)*	$\Pi_T{}^*$	(a,b,t_0)*	$\Phi_T{}^*$
Deterministic	0	(27,6,1)	305,372$	(5,19,5)	39,271$
Stochastic	+	(29,6,2)	295,536$	(23,14,8)	37,858$
	+++	(29,7,3)	241,445$	(7,17,5)	29,816$

From the results, it can be stated that the optimal expected profits are approximately 3.5% and 21% lower than in the deterministic case with low and high variability, respectively; the higher the variability the lower the expected profits.

Regarding the expected total costs, the optimal values are approximately 3.6% and 24% lower with low and high variability, respectively. Moreover, the optimal parameters for storage pricing and the optimal threshold time are also different because the expected number of containers arriving at the terminal differs, and the threshold time (t_p), which determines the optimal demand for the container yard terminal is also modified.

7.6 Conclusions

This chapter addresses the pricing storage problem for import containers taking into consideration the stochastic behavior of the storage yard and a generic price schedule, characterized by a flat rate and a storage time charge.

An analytical model based on a statistical and probabilistic approach is formulated to forecast the expected number of containers stored at the storage yard. This model also considers the potential migration to a remote warehouse depending on the storage price schedule, introduced by the terminal operator to reduce the average length of stay. The optimal solutions have been found by evaluating the following two objective functions: maximizing the expected terminal operator profit and minimizing the total expected cost of the system, which involves the terminal operator and the terminal customers.

The optimal solutions from numerical experiments are obtained by defining an appropriate search space and by enumerating the different combinations of the three parameters that characterize the pricing schedule. Data from actual container terminals were used to obtain the results. It is found that the optimal solution depends primarily on the average yard occupancy rate which is related to the storage capacity and/or the relationship between the average length of stay at the yard and the arrival container flow, that is, the outgoing/incoming rate.

The main contributions of this study to the literature are:

1) Differently from previous studies on container terminals, the analytical model developed considers the stochastic behavior of the storage yard by defining the input and output container flows as random variables. More specifically, this chapter assumes multiple vessels (feeder or deepsea) that arrive randomly and separately at the terminal with an uncertain number of unloaded containers.
2) Based on the results, two potential statements for terminal operators can be derived:
   - When the storage yard capacity is not a limiting factor (the occupancy rate is lower than 70% of the capacity, according to the numerical case), the optimal pricing schedule to maximize the expected profit is a function that increases with the storage time from the outset, that is, without a flat rate period. In other words, the terminal operator should define a pricing schedule similar to that of off-dock warehousing but slightly cheaper to attract the entire potential demand.
   - On the other hand, when the storage capacity is scarce and congestion problems arise, the optimal price schedule has a flat rate period and afterwards a storage charge based on time. The optimal value of the parameters will depend on the space utilization rate, transportation cost to a remote warehouse, storage charge per time of the alternative, and the relationship between the input and output container flows.
3) Finally, from the comparison of the deterministic and stochastic approaches it is apparent that the deviation in optimal results depends on the variability of the input variables. From the numerical examples, it can be seen that the deviation in optimal profits and costs with respect to the deterministic case ranges from 3.5% to 24.0%, for lower and higher variability, respectively.

Chapter 8

Conclusions and future research

8.1 Overview

In daily operations at container terminals, terminal operators are facing many decisions in an attempt to run handling processes efficiently and to increase terminal productivity. In such a context, the objective of this thesis was to provide efficient solutions and optimization techniques to improve the efficiency and productivity of yard handling processes, to increase the profitability of storage space and to reduce operating costs due to congestion effects, by using both operational and economic approaches.

In order to attain the general objective, this thesis addressed the following particular issues:

1) The yard planning and design problem, in which storage space utilization is determined;
2) The allocation problem for import containers in order to reduce rehandling movements; and
3) The storage pricing problem for import containers to encourage customers to pick up their containers earlier.

In addition, this thesis also includes two analytical models, based on a statistical and probabilistic approach. The first one aims to forecast storage yard inventory over a period of time by taking into account the yard stochastic behavior and, the second one, is developed to estimate the average number of rehandling moves, when containers with different departure probabilities are mixed in the same stack.

The structure of the thesis was organized according to the abovementioned issues in which specific objectives were reached separately. Thus, the main findings and conclusions of this research were obtained by combining the detailed conclusions and contributions of each chapter. These are described in the following section.

8.2 Main findings and conclusions

This section summarizes the most important conclusions derived from the different chapters in this thesis. In addition, more detailed results and particular conclusions can be found in the last part of each chapter.

Chapter 3, entitled *"An analytical model to forecast yard inventory in container terminals"*, proposes a mathematical formulation based on a probabilistic and statistical approach for the **estimation of yard inventory** in container terminals.

Differently from previous studies the mathematical model considers, on one hand, multiple vessels and, on the other hand, that the container dwell time (i.e. the time containers spend within the terminal) and number of (un)loaded containers per vessel are random variables. By making these assumptions, the stochastic behavior of the storage yard is included (first contribution of the thesis).

Moreover, this chapter also includes an analysis of extreme inventory values which is useful to predict the likelihood that a peak may occur during a period of time through the Generalized Pareto Distribution. Both analyses let terminal operators and planners acquire complete knowledge of the regular and extreme behavior of storage space requirements and guarantee an appropriate risk analysis, for instance, in the terminal planning and design stages.

The yard inventory results from the analytical model showed, first, that there exists an imbalance in the short-term (fluctuations between short periods of time) because of the dissipation and accumulation pattern of inbound, outbound and transshipment containers. Secondly, it was found that in the long-term, yard inventory behavior could be approximated to a sinusoidal function, which can then be used to determine the minimum capacity requirement of the yard. Finally, it can be observed that there is an imbalance between peaks and average behavior. This gap is interesting for the decision-making process with regard to storage space capacity since yard operating costs will depend on it, as shown in this thesis.

Lastly, in chapter 3 it was also demonstrated that the expected results from the model developed are close to the hypothetical real yard inventory values. In particular, it was found that the MAE between the analytical results and simulated results was lower than 8.4% and the RMSE was lower than 15.3%. Therefore, it can be confirmed that the mathematical model developed is reliable and valid for forecasting yard inventory series as it deal properly with the stochastic properties of the container yard system.

Next, chapter 4 addresses the **yard planning and design problem** in which optimal space utilization is determined by taking into consideration the container yard inventory (space requirements), which is the output from the model introduced in chapter 3.

In order to determine how much space should be provided for the storage area in terms of number of slots, chapter 4 proposes an optimization model that aims to minimize the total integrated cost (terminal operator costs and external costs related to road trucks and vessels). The cost optimization model considers the effect of space utilization on terminal performance in such a way that when yard inventory levels are close to capacity, operating delays occur and operating costs increase. Moreover, a mixed strategy was considered in which private and rental storage space was combined in the cost model.

The optimization model was applied to two different yard layouts (parallel and perpendicular) and separately for the import storage area and export and transshipment storage area because operating processes and design requirements differ. From the numerical samples in chapter 4 it was found that:

- Optimal storage space utilization for the export and transshipment area was higher than that for the import area. In addition, the optimal space utilization for the parallel layout was higher than that for the perpendicular layout because YC operating costs are higher.

  From the results and corresponding sensitivity analysis it was derived that the optimal space utilization for the parallel layout rates range from [52-70%] and [55-80%] for the import area and for the export and transshipment area, respectively. Next, for the perpendicular layout, the optimal space utilization are within the range [45-60%] and [51-68%] for import area and export and transshipment area, respectively. Mainly, the optimal space utilization is lower for the perpendicular layout because YC operating costs are higher.

- With regards to the comparison between the parallel and perpendicular layout it was found that the space required for the perpendicular layout was 10% higher than for the parallel layout although the total cost was 6% lower. This is because the fact that for the parallel layout construction cost, transporter vehicles operating cost and cost related to external trucks in the terminal are higher because longer travel distance are required.

As regards to the **allocation problem for import containers**, chapter 5 analyzed the yard performance of new storage strategies aiming to reduce the number of unproductive moves during retrieval operations. First, with the aim of evaluating the performance of storage strategies, chapter 5 presented a method to estimate the expected amount of rehandles when import containers from different vessels and with different departure probabilities are mixed in the same stack. This approach differs from previous studies, which have assumed that all containers have the same departing probability. Thus, it represents a potential contribution of this thesis.

Furthermore, as previously mentioned, three new storage strategies were proposed for inbound containers. These complement the two previous general storage strategies introduced by De Castilho and Daganzo (1993) known as segregation and non-segregation strategies.

The numerical experiments demonstrated that the suitability of each strategy depends directly on the state of terminal congestion and indirectly on the average stacking height as well as on the relationship between vessel headway and container dwell time.

Overall, the following statements were derived:

- Strategies S_1 and S_2, which are comparable to the non-segregation strategy, are recommended for terminals with a short average stacking height and a ship headway-to-container dwell time ratio less than 0.5, or when container dwell time is high. Thus, these strategies are more appropriate for terminals that are not congested.

- On the contrary, for terminals with a small storage area and high traffic volume (when storage capacity must increase by way of higher container stacking), strategy S_3, which is characterized by reallocating the remaining containers to other parts of the storage block and segregating new from old containers, becomes preferable for inbound yard management. This strategy requires fewer rehandling moves and thus demonstrating the advantage of dynamic strategies in these situations.

The last part of this thesis focused on the **storage pricing problem** for import containers. Two different approaches were considered with regard to the arrival of import containers in the storage yard: a deterministic scenario in which the number of incoming containers per vessel was constant (chapter 6) and a stochastic scenario within multiple vessels where a random variable was assumed to define the number of incoming containers (chapter 7).

The model used for estimating the amount of import containers in the storage yard when a storage pricing schedule is introduced was founded on the model introduced in chapter 3. The main difference between them was that the migration to an off-dock warehouse was included. Further, chapter 6 considered an additional reaction of customers, namely migration to another container terminal since it is operating in a competitive environment.

This thesis assumed a generic storage charge proportional to the length of storage time beyond the flat-rate time limit that includes the zero as well. The proposed pricing scheduled is different from those in previous studies and current practices in container terminals; however since it adopts a generic schedule, the previous ones are included. Then, to determine the optimal values for the three parameters that define the pricing schedule, two objective functions were considered: 1) maximization of the terminal operator's profits and 2) minimization of the total integrated cost of the system (this problem was considered in chapter 7).

From the results, two statements for terminal operators were obtained:

- When storage yard capacity is not a limiting factor (occupancy rate is lower than 70% of capacity, according to the numerical case), the optimal pricing schedule for maximizing the expected profit is an increasing function with storage time from the beginning, that is, without a flat rate. This result was also confirmed in chapter 6.

  In other words, the terminal operator should define a price schedule similar to the off-dock warehouse but slightly cheaper in order to attract all potential demand.

- On the contrary, when storage capacity is scarce and congestion problems arise the optimal price schedule has a flat rate period and afterwards a storage price charge per time. The optimal value of the parameters will depend on the space utilization rate, transportation cost to the off-dock warehouse, storage charge per time of the alternative and on the relationship between the input and output container flows.

Finally, a comparison was made of both deterministic and stochastic approaches with regard to the expected maximum profit and minimum expected total costs. The results from the comparative analyses showed that the deviation between the optimal results depends on the variability of the input variables. From the numerical samples, it was observed that optimal profit and cost deviation with respect to the deterministic case ranges from 3.5% to 24.0%, for lower and higher variability, respectively.

8.2.1 Summary

To sum up, this thesis provided three analytical models that offer potential contributions to research on container terminals.

1) The utility of the first model is forecasting the storage yard inventory under the assumptions that incoming and outgoing container flows are uncertain and that multiple vessels call at the terminal. The main characteristic of this model is the stochastic approach through mathematical formulations, which will allow future users and researchers to deal with inventory fluctuations and seasonal variations by employing explicit equations.
2) The second model estimates the expected number of rehandling movements when import containers with different leaving probabilities are mixed in the same stack. The mathematical expressions are based on probabilistic distribution functions according to the assumptions related to container dwell time.
3) The third analytical model estimates the demand of the storage yard when a storage pricing schedule is introduced by the terminal operator. This model, which derived from the first one, includes the import container migration to an off-dock warehouse since long-term storage costs are cheaper than staying in the yard terminal.

Furthermore, this thesis also presented potential improvements and solutions for planners in the initial design stages and for terminal operators that face capacity shortages. According to the numerical experiments, optimal storage space utilization for minimizing costs was demonstrated to be around 63% and 57% on average (total storage area) for the parallel and perpendicular layout, respectively. Nonetheless, although useful for determining storage capacity in the initial stages for newly built container terminals, these criteria are unsuitable for terminals currently operating.

On the other hand, because increasing volumes of containers are expected to be stored in ports as container trade increases continuously, storage space is becoming a scarce resource. Thus, terminal operators are required to make efforts to improve operations efficiency and reduce operating costs, even in congested situations.

In such a context, this thesis provided two potential solutions for import storage yards. Furthermore, these include different alternatives according to the yard occupancy rate. In short, these solutions are:

- Three new allocating storage strategies that define the policy on where to stack import containers at the yard to reduce rehandling movements and thus, operating costs.
- Two different storage pricing schedules, depending on the storage yard occupancy rate, in order to reduce the average length of stay in the terminal. As a consequence, terminal performance and handling productivity will be improved.

8.3 Future research

The following lines of future research are suggested:

- From the stochastic analysis regarding extreme value theory addressed in chapter 3, enlarging the study by developing an accurate risk assessment analysis for determining storage capacity and the amount of handling and transportation equipment is proposed. Similar to other engineering fields such as hydraulics, structures and seismology this issue could be appealing for predicting yard inventory for dimensioning container terminals.
- Including additional criteria in the definition of the allocating strategies for import containers. For instance, the inclusion of energy consumption in rehandling movements would be interesting to improve terminal efficiency. In such a way, the consideration of container weight, hoisting/lowering distance, trolley travel movement and so on would be required to determine the final location of containers.
- Extending the storage pricing problem for export containers. Some container terminals, for instance that in the Port of Busan (South Korea), face capacity constraints and delays on vessel operations due to the inefficient organization of storage space. Thus, this measure could be studied in future works in order to provide optimal solutions.

Appendix A: Formulation

This appendix is focused on the development of the generic formulation which appears alongside chapter 7 by introducing explicit formulas according to the problem assumptions.

a) Number of inbound containers at the storage yard

From equation [8] and assuming that the import container dwell time follows a Weibull distribution function (k_{ts}, λ_{ts}) and the number of unloaded containers is a random variable also approximated to a Weibull distribution (k_r, λ_r) which mean value can be expressed as $E[n_r] = \lambda_r \Gamma\left(1+\frac{1}{k_r}\right)$ in which the Gamma function is defined as: $\Gamma(n) = (n-1)!$.

Then, the analytical expression can be formulated as:

$$E_{ir}[Q(t)] = \begin{cases} \lambda_r \Gamma\left(1+\dfrac{1}{k_r}\right)\left(\left(e^{-\left(\frac{t-t_i}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(1-e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\right) & t \geq t_i \\ 0 & t < t_i \end{cases} \qquad \text{[A1]}$$

and its minus derivative, which is the instantaneous number of containers leaving the terminal, is expressed as:

$$-\frac{d}{dt}E_{ir}[Q(t)] = -\lambda_r \Gamma\left(1+\frac{1}{k_r}\right)\left[\left(\frac{k_{ts}}{\lambda_{ts}}\left(\frac{(t-t_i}{\lambda_{ts}}\right)^{k_{ts}-1} e^{-\left(\frac{t-t_i}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(1+e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\right] \quad t \geq t_i \qquad \text{[A2]}$$

b) Costs of the terminal operator

-Rehandling costs

From equation (16) and using [A1] and [A2], the analytical formulation of the rehandling cost for the terminal operator becomes:

$$C_{ir}^{reh} = \rho \cdot c_{YC}^{o,d} \cdot \lambda_r \Gamma\left(1+\frac{1}{k_r}\right) \cdot \left[\left(1-e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)^2\right] \qquad \text{[A3]}$$

where:

$$\rho = \left(\frac{\{E_T[Q(t)]|_{t=t_i}\}\frac{H_m}{\theta} - 1}{4}\right) + \left(\frac{\{E_T[Q(t)]|_{t=t_i}\}\frac{H_m}{\theta} + 2}{16w}\right) \qquad [A4]$$

where H_m is the maximum stacking height of the bay.

-Additional operating equipment costs

From the generic expression (18) and introducing explicit functions, the additional operating equipment costs related to the amount of containers unloaded from the i[th] vessel is:

$$\begin{aligned} C_{ir}^{op} &= \left(c_{QC}^{o,u} + c_{YC}^{o,u} + c_{TR}^{o,u}\right) \cdot \lambda_r \Gamma\left(1 + \frac{1}{k_r}\right) \\ &\quad \cdot \left(\left(1 - e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(\left(\theta - \{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2} - \theta^{-1/2}\right)\right) \\ &\quad + c_{YC}^{o,d}(1+\rho)\int_{t_i}^{t_p+t_i} -\frac{d}{dz}E_{ir}(Q(t)) \\ &\quad \cdot \left(\left(\theta - \{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2} - \theta^{-1/2}\right) dt \end{aligned} \qquad [A5]$$

where ρ is detailed in expression [A4] and θ the yard storage capacity

-Additional purchasing equipment costs

Similarly than the previous case, the analytical expression of the additional purchasing equipment cost related to the unloaded containers from the i[th] vessel is:

$$\begin{aligned} C_{ir}^{eq} &= \left(c_{QC}^{F,u} + c_{YC}^{F,u} + c_{TR}^{F,u}\right) \cdot \lambda_r \Gamma\left(1 + \frac{1}{k_r}\right) \\ &\quad \cdot \left(\left(1 - e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(\left(\theta - \{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2} - \theta^{-1/2}\right)\right) \\ &\quad + c_{YC}^{F,d}(1+\rho)\int_{t_i}^{t_p+t_i} -\frac{d}{dz}E_{ir}(Q(t)) \\ &\quad \cdot \left(\left(\theta - \{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2} - \theta^{-1/2}\right) dt \end{aligned} \qquad [A6]$$

c) External costs related to the value of time of road trucks and vessels

The additional external cost associated to the i[th] vessel is:

$$C_{ir}^{e} = C_{ET}\int_{t_i}^{t_p+t_i}\left(-\frac{d}{dz}E_{ir}(Q(t))\right)\delta(t)dz + \frac{C_V}{g}\left[E_{ir}(Q(t))\delta(t)\right]_{t=t_i} \qquad t \geq t_i \qquad [A7]$$

Then, by including expressions [A2] and rearranging the above expression, the final analytical formulation for the external costs becomes:

$$C_{ir}^{e} = C_{ET}\int_{t_i}^{t_p+t_i}\left(-\frac{d}{dz}E_{ir}\big(Q(t)\big)\right)\left(\left(\theta-\{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2}-\theta^{-1/2}\right)dt \;+\frac{C_V}{g}\lambda_r\Gamma\left(1+\frac{1}{k_r}\right) \cdot\left(\left(1-e^{-\left(\frac{t_p}{\lambda_{ts}}\right)^{k_{ts}}}\right)\left(\left(\theta-\{E_T[Q(t)]|_{t=t_i}\}\right)^{-1/2}-\theta^{-1/2}\right)\right) \qquad t\geq t_i \qquad [A8]$$

d) Customers' expenses to move containers to the off-dock warehouse

The total expenses from customers to move containers unloaded from the i^{th} vessel to the off-dock warehouse is defined according to next equation:

$$C_{ir}^{c} = E[n_r]\int_{t_p+t_i}^{\infty}\left(-\frac{dS(t)}{dt}\right)c(t)dt \qquad t>t_i \qquad [A9]$$

Considering that $c(t) = c_0 + c_1 t$ and rearranging [A7], above expression derives as that:

$$C_{ir}^{c} = E[n_r]\left(c_0\left(\int_{t_p+t_i}^{\infty}-\frac{dS(t)}{dt}dt\right)+c_1\left(\int_{t_p+t_i}^{\infty}-\frac{dS(t)}{dt}t\,dt\right)\right) \qquad t>t_i \qquad [A10]$$

The last integral term of expression (A8) ($\int_{t_p}^{\infty}-\frac{dS(t)}{dt}t\,dt$) can just be solved analytically for k_{ts}=1 (for the Exponential distribution which is a particular case of the Weibull distribution). On the other hand, the minus derivative of the survival function is:

$$\frac{dS(t)}{dt}=\frac{d}{dt}\left(e^{-\left(\frac{t-t_i}{\lambda_{ts}}\right)^{k_{ts}}}\right)=\frac{k_{ts}}{\lambda_{ts}^{\;2}}(t^{k_{ts}-1})e^{-\left(\frac{t-t_i}{\lambda_{ts}}\right)^{k_{ts}}} \qquad t\geq t_i \qquad [A11]$$

Then the final analytical expression by introducing (A9) for k_{ts}=1 becomes:

$$C_{ir}^{c} = \lambda_r\Gamma\left(1+\frac{1}{k_r}\right)\left(c_0e^{\left(-\frac{t_p}{\lambda_{ts}}\right)}+c_1e^{\left(-\frac{t_p}{\lambda_{ts}}\right)}\left(1+\frac{t_p}{\lambda_{ts}}\right)\right) \qquad [A12]$$

e) Revenues of the terminal operator

The revenues from the storage pricing are defined in equation (26) which is:

$$R_{ir} = \int_{t_i}^{t_p+t_i}\tau(z)\cdot\left(-\frac{d}{dz}E_{ir}(Q(z))\right)dz \qquad [A13]$$

Using expression [A2] and rearranging it, [A13] becomes:

$$R_{ir} = \int_{t_i}^{t_0+t_i}\tau(t)\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt+\int_{t_0+t_i}^{t_p+t_i}\tau(t)\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt =$$

$$=\int_{t_i}^{t_0+t_i}a\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt + \int_{t_0+t_i}^{t_p+t_i}(a+b((t-t_i)-t_0))\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt = \qquad [A14]$$

$$= a\int_{t_i}^{t_0+t_i}\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt + (a-b\mathrm{t}_0)\int_{t_0+t_i}^{t_p+t_i}\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt + b\int_{t_0+t_i}^{t_p+t_i}\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)\cdot(t-t_i\,)dt$$

Once again, the last term of expression [A14] can just be solved analytically for k_{ts}=1 (for the Exponential distribution which is a particular case of the Weibull distribution). In such case, the above expression becomes:

$$R_{ir} = a\int_{t_i}^{t_0+t_i}\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt + (a-bt_0)\int_{t_0+t_i}^{t_p+t_i}\left(-\frac{d}{dt}E_{ir}\big(Q(t)\big)\right)dt + b\left\{-E_{ir}\big(Q(t)\big)(t-t_i)\Big|_{t_0+t_i}^{t_p+t_i} + \int_{t_0+t_i}^{t_p+t_i}E_{ir}\big(Q(t)\big)\,dt\right\} \quad [A15]$$

Next, by plugging in explicit expressions developed in chapter 7 in [A15], total revenues associated to a bunch of containers from the i[th] vessel are:

$$R_{ir} = \lambda_r\Gamma\left(1+\frac{1}{k_r}\right)\left(1-e^{-\frac{\mathrm{t}_p}{\lambda_{ts}}}\right)\left\{a\left(1-e^{-\frac{\mathrm{t}_0}{\lambda_{ts}}}\right) + (a-bt_0)\left(e^{-\frac{\mathrm{t}_0}{\lambda_{ts}}} - e^{-\frac{\mathrm{t}_p}{\lambda_{ts}}}\right) + b\left(t_0e^{-\frac{\mathrm{t}_0}{\lambda_{ts}}} - t_pe^{-\frac{\mathrm{t}_p}{\lambda_{ts}}}\right) + b\lambda_{ts}\left(e^{-\frac{\mathrm{t}_0}{\lambda_{ts}}} - e^{-\frac{\mathrm{t}_p}{\lambda_{ts}}}\right)\right\} \quad [A16]$$

in which: $t_p = \frac{c_0+bt_0-a}{b-c_1}$

Appendix B: Abbreviations

NB: This section is designed to clarify and demystify many of the more common abbreviations and acronyms used in the shipping business. Most, but not all, of these appear in the text. Readers may consult this section quite independently.

AGV	Automated Guided Vehicles
AM	Annual Maxima
AS/RS	Automated Storage/Retrieval System
ASC	Automated Stacking Crane
CDF	Cumulative Distribution Function
CT	Cycle Time
CTO	Container Terminal Operator
ET	External Truck
GA	Genetic Algorithm
GEV	Generalized Extreme Value
GPD	Generalized Pareto Distribution
MAE	Mean Average Error
OHBC	Over-Head Bridge Cranes
OR	Operations Research
PoT	Peaks over Threshold
QC	Quay Crane
RMG	Rail Mounted Gantry
RMSE	Root Mean Squared Error
RTG	Rail Tired Gantry
SC	Straddle Carrier
SSAP	Storage Space Allocation Problem
TEU	Twenty-foot Equivalent Unit
TP	Transfer Point
TR	Transport vehicle
UNCTAD	United Nations Conference on Trade and Development
YC	Yard Crane

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