Container Handling and Layout Optimization in Empty Container Depots

by

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Abstract

In this dissertation, we explore shipping container depot layout with particular emphasis on empty container depots with material handling provided by top-lifters. Top lifters are the most common handling equipment used in container depots and the port yards of many countries. We consider both rectangular and non-rectangular yard layouts and we estimate the relocation and cycle times of top-lifters as well as other common container handling equipment, the overhead crane, and the reach stacker.

The first research topic, "*Relocations in container depots for different handling equipment types: Markov models,*" proposes a family of Markov models to analytically characterize the distribution of the number of relocations per retrieval in a container depot. In this study, we generalize the few models available in the literature by 1) relaxing the assumed material handling equipment type (we consider the three vehicles mentioned above) and 2) allowing for container arrivals during the retrieval process.

The second research topic is "*Retrieval and placement times estimation for top-lifters.*" This addresses the estimation of retrieval and placement times using the Markov model of the first study. Along with the estimations of handling, we use regression models based on a time study directed in a real container depot in Chile.

The third research topic is "*An analytical model for the design of top-lifter operated container yard layouts"* and this focuses on constructing alternative layouts for a container depot operated by top-lifters that have access to the top edge of a bay. In this study, we propose an analytical model that evaluates the expected cycle time of a top-lifter to find the optimal yard block design. We optimize the number of driving lanes, both vertical and horizontal, as well as block depth,

height, and length of a bay design. We generalize the approach to be applicable for both rectangular and non-rectangular yard designs.

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1. Introduction

Sea transportation has been used since the Minoans who established the first European civilization in 2200 B.C. on the island of Crete in today's Greece. The Minoans used longships for good transportation between Egypt and the other eastern Mediterranean neighbor countries. Sea travel has figured in most ancient stories in the Western tradition, including Homer's Odyssey (Petering, 2007).

The use of sea trade and transportation is still common in today's global market. There are statistics regarding the importance and usage of maritime shipping compared to other transportation. According to the Review of Maritime Transport 2015 report, around 80 percent of global trade by volume and over 70 percent of global trade by value is carried by sea and handled by ports worldwide. These shares can be higher in most developing countries (UNCTAD, 2015). In terms of weight, over 90% of all international cargo is carried by sea at some point on its way. Additionally, the ton-miles of cargo carried by water are more than twice the total ton-miles carried by road, railway, and air combined (Petering, 2007). According to the Review of Maritime Transport 2015 report, the world fleet grew by 3.5 percent during the 12 months up to January 1st, 2015 which is the lowest annual growth rate in over a decade. In total, at the beginning of 2015, the world's commercial fleet had 89,464 vessels, with a total tonnage of 1.75 billion deadweights (carrying capacity) tonnage (UNCTAD, 2015).

More than fifty years ago, a trucker from North Carolina, Malcolm McLean, invented today's marine containers to make his trucking company shipping cost lower (Levinson, 2006). The container shipping industry has been dominant in international trade because it is the most cost-effective transportation compared to others. According to the World Shipping Council, there were almost 5,000 container ships in the global fleet with almost 17 million twenty-foot equivalent unit

(TEU) in July 2013, most of which are operated by members of the World Shipping Council, and there were 445 new container ships on order (World Shipping Council, 2017b). Container ships' capacities have increased from 1,500 TEU in 1976 to excess of 19,000 TEU today, with some ships on order being able to carry 22,000 TEU. Besides being able to carry more goods, today's ships are also more fuel-efficient (World Shipping Council, 2017a). In terms of the fuel efficiency per ton-mile of goods shipped, ships use 2.2 times less fuel than trains and 9.7 times less fuel than trucks (Petering, 2007). Considering fuel efficiency and the recent increase in the international trade of finished products with globalization, it is inevitable that the container shipping industry is placed at the very center of the global economy. Most overseas goods such as furniture, toys, footwear, clothing, auto parts, bananas, electronic components, and computers are shipped by containers. There are two different types of containers commonly used, dry and refrigerated (reefer) containers. Dry containers are the most common type of containers. They are convenient to carry most types of goods, including those packed in boxes, cartons, cases, bags, pallets etc. Reefer containers are equipped with an electrical appliance to cool or heat the air in the container. These containers are used to carry frozen and fresh goods. Historically about 93 % of the fleet is made up of dry containers and reefers make up approximately 6.25% of the global fleet. The remaining 0.75 % is tanks (World Shipping Council, 2017c). Even though the number of dry containers fleet is higher than the number of reefer containers, the amount of fruit, vegetables, fish, meat, and general food stuffs shipped in reefer containers has been increasing in recent years.

1.1. Global Container Shipping

Since container transportation makes cargo loading, unloading, and stacking easier between different transportation modes such as ship, rail, and truck, it increases the efficiency of international transportation. Because of that, the standard size container invention in the 1950s was an important factor in international trade. Efficient loading and unloading of the containers from one transportation mode to another provide reliable and efficient transportation over a long distance. Containerization has become universal in international cargo transportation and has helped remarkably in globalization.

We can define the global container shipping industry as a combination of three elements: the shippers, the shipping lines, and the terminal operators. Shippers are the companies who need to transport their goods from one location to another. In other words, the shippers are exporters or importers such as Adidas, Samsung, etc.

Shipping lines, also called carriers, are the companies that have vessels and are paid by shippers to carry their cargos. Shipping lines services are not only to transport cargo overseas but also to receive containers from the origin point and deliver to the destination point. In other words, the fee paid to shipping lines includes all required transportation to transfer containers from origin to destination. If inland transportation is required, then the shipping line needs to provide rail or truck transportation before and/or after maritime transportation. Park (2017) states that "The five biggest container lines control about 60 percent of the global market, according to the data provider Alphaliner". The world's largest shipping line is known as A.P. Moller - Maersk Line and operates 580 container vessels with a total of 2.8 million TEU as of September 2014 (Duddu, 2015).

Terminal operators are the ones who provide service for shipping lines. They provide loading and unloading of container ships and temporary storage for containers such as container terminals and stevedoring companies. These companies have their own container handling equipment such as quay cranes, yard trucks, and yard cranes and usually lease their land from municipalities. Typically, long-term agreements are made with shipping lines including the fee for the provided service and the service criteria. These agreements include aspects such as a certain number of the shipping line's vessels per week and the fees of service and storage. The focus of this dissertation is the terminal operator who provides the service for empty containers.

Container terminals are critical in the global supply chain because they are the places that connect maritime transportation and other transportation. In addition to that, container terminals are also among the most complicated facilities because of the volume and the variability of operations. Container terminal management is one of the big businesses in countries that have access to the sea or ocean. One of the world's largest container terminal operators, PSA International, had revenues of 3.68 billion of Singapore dollars and profits of 1.17 billion of Singapore dollars in 2016 with around 30,000 employees handling 67.6 million TEUs of containers (PSA International Pte Annual Report 2016, 2017).

Container terminals are known bottlenecks of global supply chains. Thus, considering these billion-dollar businesses, if there is a tiny improvement to container terminals operations, it makes significant impacts and benefits of all related businesses such as shippers and shipping lines. The improvement of container terminal operations benefits not only the revenues but also the environmental issues of businesses around the world. The main environmental impacts of container terminal operations are emissions and noise from cargo handling and transportation. Thus, any improvement in container terminal operations can improve these environmental issues.

1.1. Empty Container Logistics

As we can see from the common usage of shipping containers, marine containers are very efficient to transport goods. Since shipping containers can be reused and eliminate much handling, its usage has been increasing day by day. However, because of the inconstancy in trade, the number of container transfer varies from time to time and place to place. As a result, the number of container flows can be higher or lower than the number of container flows in the opposite direction, which is termed an imbalance of trade lanes. Thus, the number of cargo containers must be matched with empty containers. Because of the unpredictability of demand, this causes an unbalanced flow between empty containers and cargo which makes containers stay in some ports or depots empty.

Inbound and outbound laden container movement has been increasing in the last few decades with increased globalization in the world. Depending on the industry, a country or port can have cargo surplus or deficit caused by the difference between export and import volume. While cargo surplus areas need more empty containers for cargo shipments, cargo deficit areas have more empty containers than needed. This results in an unbalanced empty container movement. This unbalanced container movement causes the biggest hidden cost to the container shipping industry since an empty container does not add any value to their service (Lee, 2014).

Inbound and outbound cargo transportation can be shown as diagrammed in Figure 1.1. For inbound transportation, the loaded container (cargo) from the main container terminal is retrieved and is carried to the destination (consignee) by means of inbound transportation such as trucking or railway. After unloading the container, the empty container is returned by the trucking company to the carrier's main container terminal or empty container depot close to the main container terminal. A similar process is followed for the outbound cargo. The empty container is picked up from the main container terminal or the empty container depot by the trucking company and brought to the exporting company or warehouse. After loading the container, the trucking company transports the loaded container to the main container terminal. There is also another empty container shipment type from the empty container depot to the main container terminal. This shipment type usually occurs as a "massive shipment". Here, many empty containers are transferred to another container terminal by ship in bulk to balance the empty container need in different ports. As we can see from the diagram (Figure 1.1), most of the truck trips have empty container movements, either for empty container pickup or return.

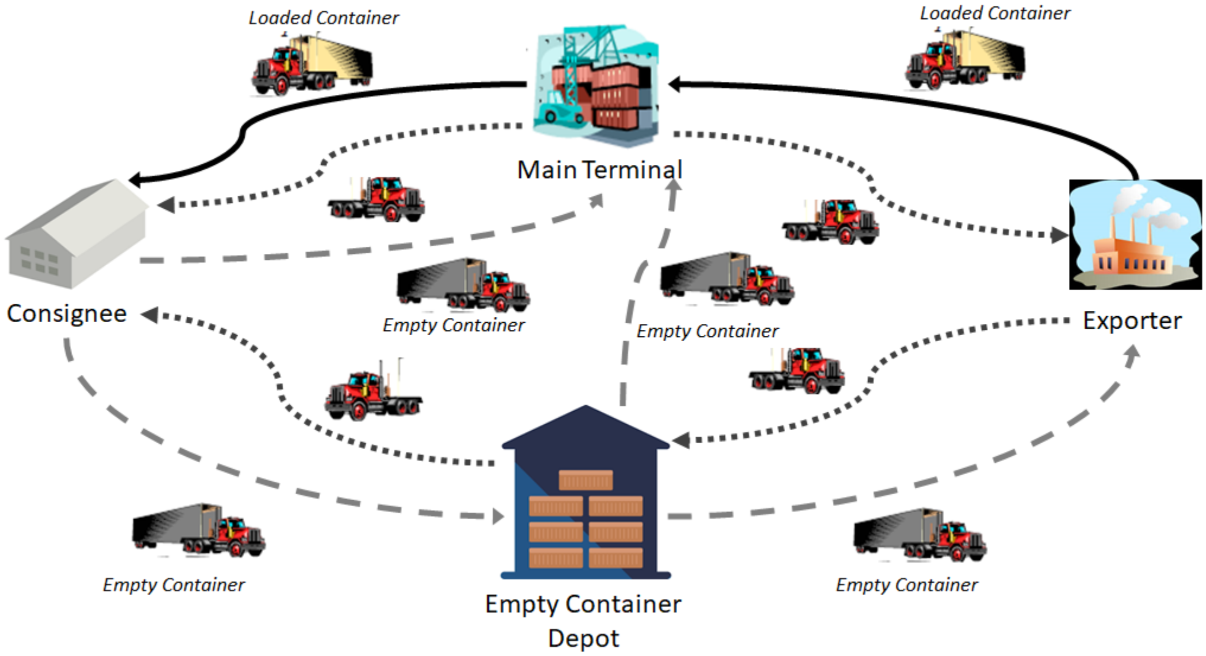


Figure 1.1. Cycle of container handling (Hanh, 2003)

The fundamental reason of the accumulation of empty containers in depots or container yards is known to be imbalanced overseas trade between individual markets or import oriented and export-oriented economies. For instance, there are so many empty containers that are shipped to Asia to be laden with electronics, shoes, or exotic foods for Europe. In the webpage Shipping Watch, according to Kristiansen (2012), the largest ocean carrier Maersk Line spends around $1 billion on the transportation of around four million empty containers in a year and the major reason is the trade imbalance between Asia and Europe.

Even though import and export trades are balanced in developed countries, they can still face imbalanced empty container demand because of the imbalanced container types. Usually, the import of final products is done in 40' standard containers whereas the export of raw materials and semi-raw materials is done in 20' standard containers. In addition to the overall trade and container type imbalance, seasonal imbalances between markets also cause “surplus” or empty container accumulation on one side and “shortage” or excessive demand for empty containers on the other side.

Because of globalization, the number of containers and the sizes of the ships have been increasing. The growth of container transportation makes container transportation operations more complicated, so the global players seek to make their operations more efficient and decrease their cost. One of the ways they do this is by improving their empty container transportation since empty container transportation does not add any explicit value to their service.

Laden container logistics starts with a booking confirmation. After the booking confirmation, an empty container is shipped from the carrier’s place of origin depot to the next cargo loading point (shipper’s location) to be filled with cargo. The origin depot can be either a third party empty container depot or the carrier’s own place such as a maritime terminal or a warehouse. After the container is filled with cargo, the laden container is shipped to the port to be placed on a carrier’s ocean vessel. Upon completion of the maritime transfer to the destination port, the laden container is unloaded from the ocean vessel to be shipped to the consignee’s premises. Note that there may be multiple port transfers during the maritime transfer. The container is transported to the consignee premise by either the consignee or a truck company for cargo unloading.

After the cargo is unloaded from the container, the empty container is shipped to the carrier’s depot or designated location by truck. The empty container either can then be used for the next shipment booking or shipped to an empty container deficit location. If the empty container needs to be shipped to another location, the empty container logistics cycle starts with empty container transportation from the origin location to the shipment port by truck. According to the carrier’s berthing schedule, the empty container is loaded onto the ocean vessel and shipped to the destination port. When the empty container is shipped to the destination port, the empty container can be transferred either directly to the shipper's warehouse or it can be transferred to the carrier's empty container depot. General empty container flow can be seen in Figure 1.2. Note that cargo loading and unloading sometimes can be made in the container freight stations.

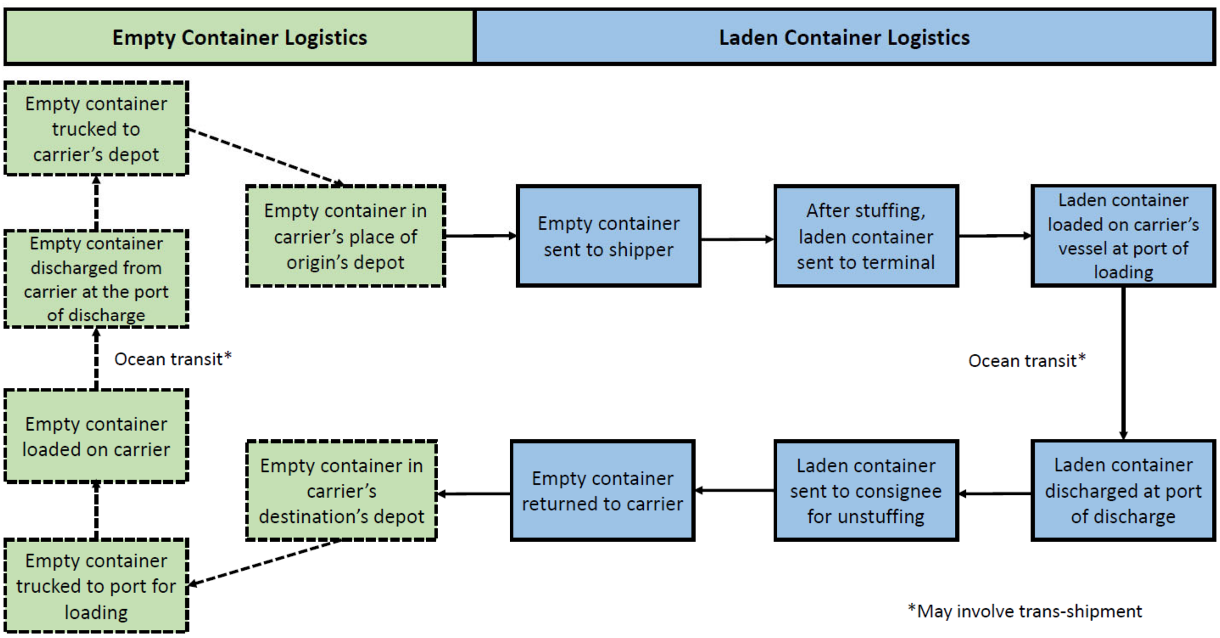


Figure 1.2. General empty container logistics flow (Lee, 2014)

However, after the laden container is emptied, it can be either directly transported to its next loading point or any transfer location. This transfer location can be the carrier's container yard, a third party empty container depot, a shipper (exporter) warehouse, a container leasing company depot, or a container rail yard. Each of these locations creates a different flow pattern in the empty container movement cycle (Figure 1.3).

The management of empty container movement is crucial to container shipping. The main goal of all parties involved in the container business is to provide efficient, practical, and economic empty container movement. This main goal gets more attention especially from ocean carriers who usually own most of the containers involved in their operations. Empty container movement involves two different movement areas: local or regional movement and international movement. While international movement such as empty container repositioning directly affects ocean carriers, local movement such as transportation of the container from the port to its destination is undertaken by customers.

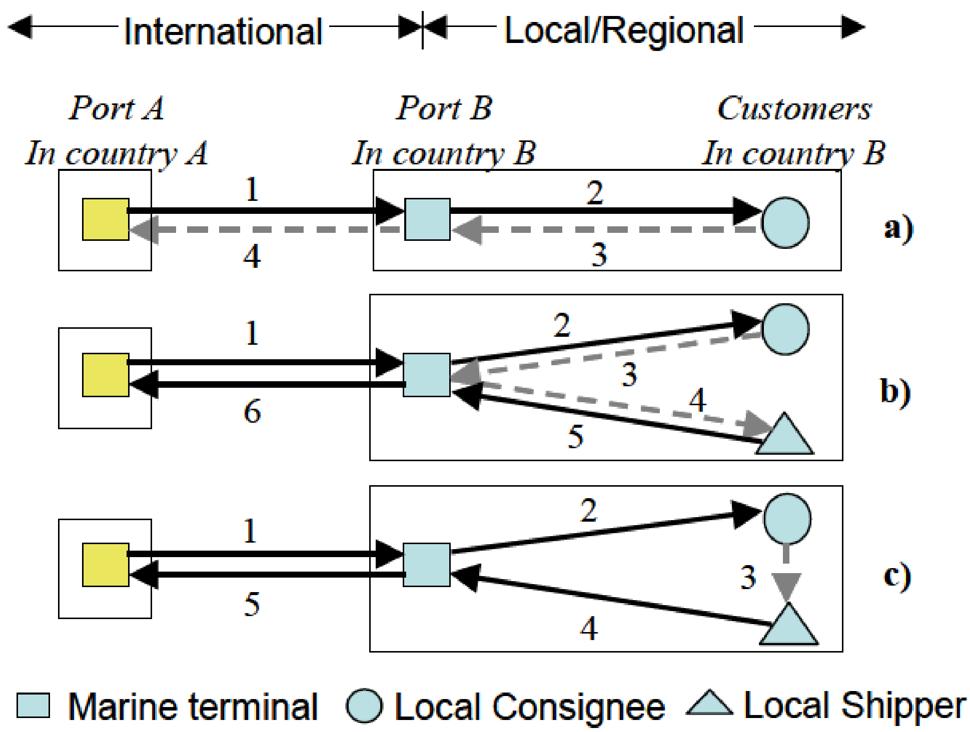


Figure 1.3. Possible movement patterns of an ocean international container (Hanh, 2003)

In Figure 1.3, general container movement is shown for both empty and laden containers, even though different alternative movement patterns may occur. In Figure 1.3a, Figure 1.3b, and Figure 1.3c, three different flow patterns are shown. In Figure 1.3a, loaded import containers are first transported to another port terminal (movement 1) by an ocean carrier based on an order from the shipper who is the importer. Then, the loaded container in the port terminal is transported by truck or railway, or both, to the consignee's warehouse (movement 2) to be unloaded. After unloading in the consignee's warehouse, the empty container is transported back to the marine terminal (movement 3) from where it will be shipped to the original location or another empty container shortage (or demand) location for the next cycle (movement 4). This flow pattern of empty container movement requires both local/regional (movement 3) and international (movement 4) participation. This movement flow pattern is often called the "repositioning" of empty containers while the movement patterns in Figure 1.3b and Figure 1.3c are often called "match-back" strategies. The main characteristic of the match-back strategy is that different carriers try to match their empty container needs from available empty containers instead of repositioning the empty containers back to their original location. The difference between Figure 1.3b and Figure 1.3c is the flow pattern of the inland movement of empty containers. In Figure 1.3c, the empty container is sent directly to the identified shipper (exporter) who needs the empty container for export instead of sending it to the marine terminal first. After the container is loaded with the product, the container is transported to the marine terminal for shipment to its destination. The movement pattern in Figure 1.3c is called "triangulation" or "street-turn". This pattern provides the movement of empty containers from a local surplus point to a demand point without transporting it back to the marine terminal. This movement either can be with or without the exchange of the ownership of the empty container from one owner/operator to another.

The "match-back" strategy, shown in Figure 1.3b and Figure 1.3c, is very efficient and a preferred approach since repositioning costs can be eliminated. However, the "triangulation" or "street turn" pattern impacts local and regional movement since only this pattern provides direct reuse of empty containers without shipment to the main marine terminal. Thus, this pattern reduces the total truck miles traveled (Hanh, 2003).

Visser (2011) mentions that around 300,000 to 400,000 empty containers are waiting to be filled or relocated in the United States. New York State alone keeps about 100,000 empty containers owned by leasing companies and 50,000 empty containers owned by shipping lines waiting in different depots and terminals. The same issue occurs in Europe as well. The port of Rotterdam had 2.3 million TEU empty containers out of total throughput of 10.7 million TEU in 2008 (Visser, 2011). As a result of this accumulated throughput, these empty containers must be stored as well as transported, either to a depot or to a client to be filled with goods (Visser, 2011). This generates a total cost of around 25 billion euros annually and creates a negative impact on the environment through harmful emissions (4FOLD - The Innovative Foldable Shipping Container, 2016).

1.2. Container Ownership

Even though usually container shipping lines have the ownership of containers and store containers in their depots, they can either own containers or lease containers from leasing companies like Triton Container (Manaadiar, 2013). Unlike the early times of containerization, shipping lines have been trying to decrease their owned portion of containers to lower their total cost, but most shipping lines still own the most part of the containers used in their operations. However, owning containers creates the expense of owning the equipment, maintenance, and repair, relocation, etc. Because of that, container inventory management is significant. Since there is a trade-off between having enough containers and sustaining low inventory costs, container inventory management is a challenge for shipping lines' daily operations. From a logistics viewpoint, this task becomes more challenging when surplus and deficit locations are at different parts of the world serviced by different carriers.

An Equipment Interchange Report (EIR) is a document to be used by the participants to ensure container quality conditions when the containers are transferred from one location to another. Inspection is necessary when a container is being transferred and routed for distribution. Inspection is usually done by terminal and depot operators (on behalf of shipping lines) at terminal and depot gates when they are picked up or returned. Based on the EIR, payments are made to shipping lines (or leasing companies if the container is leased) by the responsible element for any damage or loss (Hanh, 2003).

When containers are transported (by ship, train, lorry, river barge, or truck) or stored in any port or inland terminal, they can be either full (cargo shipping for import or export or transit) or empty. While the global full container throughput was about 493 million TEU in 2012, the total world throughput (container handled at ports; which includes the ports of origin, destination, and transshipment) was 620 million of TEU in the same year (Rodrigue et al., 2017) (Figure 1.4).

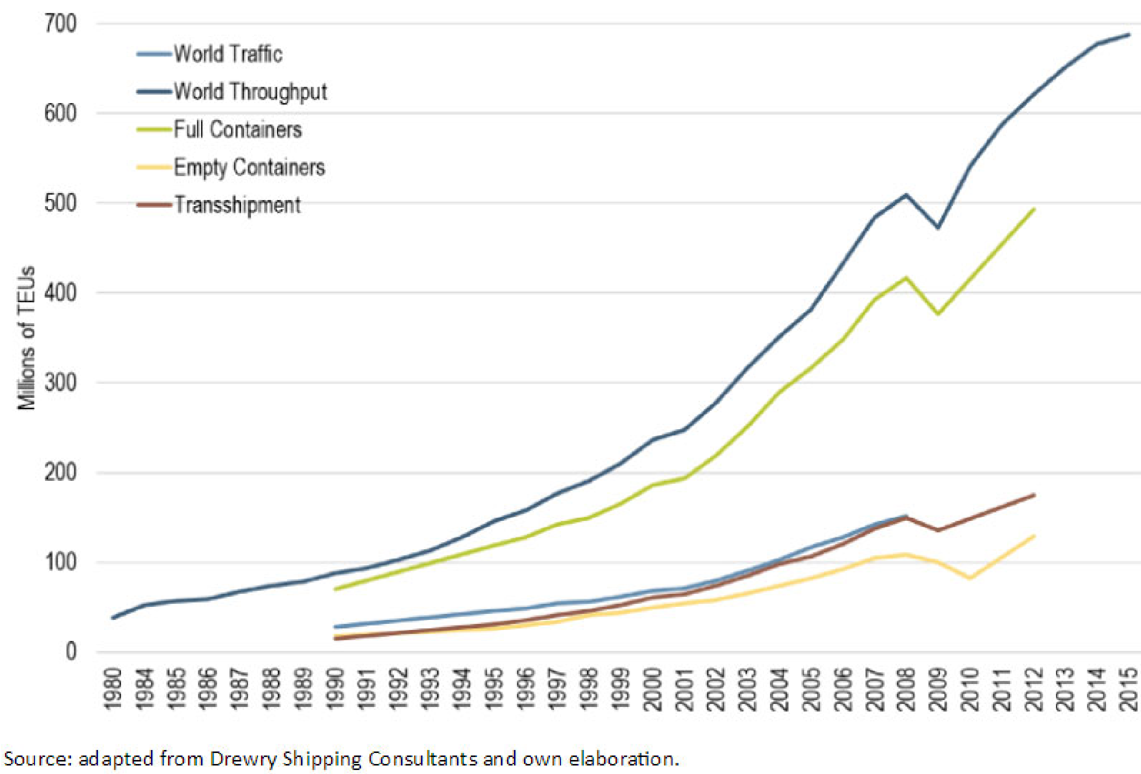


Figure 1.4. World container traffic, 1980-2015 (millions of TEU) (Rodrigue et al., 2017)

The containers in the market somehow need to be relocated either as full or empty. According to Rodrigue et al. (2017), containers spend about 56% of their 10 to 15 years lifespan idle or being repositioned as empty without generating any income but creating a cost that is part of the shipping rates. Containers take the same amount of space and time whether they are transferred or stored as full or empty. It is unlikely to observe a balanced number of full and empty containers in any location because of unbalanced production and consumption. Thus, that is inevitable to store and transport empty containers between different locations. There are about 2.5 million TEUs of empty containers stored in yards and depots around the world. This volume represents about 20% of the total volume carried by maritime shipping lines (Rodrigue et al., 2017).

Empty container repositioning costs include the inland transport charges by trucking companies, storage and handling fees by terminals, and shipping fees by shipping lines to transport from accumulated empty container locations to deficit empty container locations.

As problems caused by empty container transportation increase, the importance of empty container logistics has been increasing. This issue is important to all parties-from ocean carriers and shippers to trucking companies and local and regional governments (Hanh, 2003).

1.3. Problem Statement

According to the Boston Consulting Group, $15-20 billion each year is spent on empty container repositioning within the shipping industry. This amount makes up to 8% of a shipping line's operating costs (Whiteman, 2016).

Because of the mismatches in time and location, storing and relocating empty shipping containers are inevitable. On the other hand, carriers do not want to spend time and money on empty container accumulation because the handling and storage costs lower their profitability. In addition to that, empty containers make profitable port spaces unusable. Moreover, the accumulation of empty containers creates an obstacle for fast and cost-effective operations in ports or terminals. Then the question arises: "What to do with empty containers or how can we improve the efficiency of the empty container storage?".

For this reason, the search for a better model that would make either transportation or handling operations more efficient has been an interest of operators, leasing companies, port authorities, terminal operators, city administrations, and container depot authorities. Empty container logistics has also become a significant and complex conversation that scholars are engaging in.

Since empty container logistics is one of the main significant costs in the container logistics industry and it does not add value to cargo transportation, economic savings can be reached with efficient empty container logistics. In this industry, usually, inefficiency can be seen in the movement of empty containers. Because of this situation, shippers prefer to use inland depots for the storage of empty containers near the market of receivers/shippers in the hinterland to reduce the traveling distance. In our study, the main goal is to improve operations by increasing handling operation and layout efficiency.

The objective of the dissertation is to develop a decision support model to improve the operations and identify superior depot layouts for empty container depots. We use analytical models to model container handling and enumerative optimization to establish superior layouts for empty container depots.

1.4. Major Contributions

This research examines the influence of layout and material handling type in empty container depots. More specifically, the goal is to develop an effective decision support model and method for solving realistic empty container depot layout and optimization questions. A goal is to make operations more efficient and decrease truck turnaround time in the depot. Truck turnaround times are important because they influence ship berthing time and congestion in and near the depot. Empty container depots have not been studied as much in the literature as have port-side terminals but empty container depots are numerous and their importance is growing.

The research is divided into two main parts:

1. Modeling the number of relocations using Markov chains for three common handling equipment considering both container retrievals and arrivals for various bay designs to find the expected number of relocations along with other statistics e.g. standard deviation.

2. Proposing different depot layouts to provide the minimum expected handling time for the dominant handling equipment, the top-lifter, for both rectangular and non-rectangular container yards.

This research contributes to the literature by:

- Developing model(s) that reflect realistic container handling operations considering both retrievals and arrivals of containers to estimate the number of relocations along with other descriptive statistics. The proposed model is applied to three different common handling equipment used in both port yards and empty container depots. To the best of our knowledge, this is the first such study that considers handling equipment other than the yard crane and arrivals during retrieval operations.
- Optimizing the layout of empty container depot by taking into consideration the required capacity along with a fixed perimeter for both rectangular and non-rectangular shaped container yards. To the best of our knowledge, this is the first study that considers the top-lifter as the handling equipment to propose a layout optimization model. Because of the lower investment cost of top-lifters compared to the more expensive yard cranes, most port yards use top-lifters in developing countries such as Chile. Moreover, top-lifters are the most common handling vehicle in empty container depots.
- Providing operational statistics to evaluate the various layout designs, which can help container yard managers in tactical level decisions to compare the performance of various management policies and in establishing appropriate levels of resources and personnel.

1.5. Organization of Dissertation Proposal

The organization of the proposal is as follows. In Chapter 2, an extensive literature review on maritime logistics and container terminal is provided. Chapter 3 introduces the methodology that is proposed to calculate the number of relocations using a Markov chain model for various container handling equipment. It should be noted that this paper has been submitted to *Computers & Industrial Engineering* and is currently under review. Chapter 4 describes the methodology for the expected time calculation of container retrieval and placement for various bay designs in container yards operated by top-lifters. In Chapter 5, a methodology is developed to identify superior layouts for rectangular and non-rectangular shaped container yards operated by top-lifters. Finally, Chapter 6 contains the conclusions and future research directions of the dissertation.

2. Literature Review

Global container traffic has grown from 28.7M TEU to 152.0M TEU between 1990 and 2008. This corresponds to the average annual compound growth of 9.5%. In the same period, container throughput went from 88M TEU to 530M TEU, with an average increase of 10.5% annually (Hall et al., 2016; Metalla & Koxhaj, 2013; Salido et al., 2012).

Over 20 million containers are circulating among thousands of factories, warehouses, distribution centers, retail centers, seaports, highways, logistics centers, railways, and transit depots around the world (Budgetshippingcontainers.co.uk, 2016; www.btocloud.eu, 2017). Berman (2018) stated that estimated fleet capacity growth was around 4%-5% in 2018 up from 2017's 3.3%. The total capacity of new container-ships delivered in 2018 was expected to be around 1.3 million TEU. It was expected 30% of this capacity would be from mega-ships of 18,000-25,000 TEU (Berman, 2018). As expected, because of the high number of containers and ships circulating around the world, the container shipping industry has become more complicated, thereby creating more issues such as overcapacity problems. These issues are not only of interest to parties in the industry but also to other parties such as those who have an interest in urbanization and environmental awareness (Ascencio et al., 2014). Scholars are also interested in examining potential solutions to these issues by researching new information systems, digitalization, and blockchain technology to make shipping lines operations efficient.

Container terminals are complex because of their large volumes and stochastic movements. To handle the problems occurring in container logistics, container terminals have been looking for innovative ways to improve their logistics processes with other parties such as shipping lines and shippers. Some of those innovative approaches are truck appointment systems, foldable containers, etc. ("4FOLD - The Innovative Foldable Shipping Container," 2016; "4FOLD Foldable

Container," n.d.; Guerra-Olivares et al., 2016). Adding innovative ways to complex container terminals, the process of container terminals is more complicated prompting researchers to become more interested over the last decade.

To our best knowledge, empty container depot operations and layout design have never been addressed together in the literature. Thus, in this chapter, we present a general summary of the state of the art models, methodologies, strategies, and contributions of previous studies regarding the optimization of the container terminal operations. We propose models and solutions based on the reviewed studies in this chapter.

This chapter contains the relevant literature and is divided into three sections. First, we review container terminal operations. Next, the literature about terminal design and planning is given in three subparts. Next, simulation use in maritime logistics problems is covered. In the simulation part, the literature about terminal and port operation studies using simulation is given. Last, in the conclusion, the motivations of this dissertation are explained briefly.

2.1. Container Terminal Operations

Using the keyword of "container terminal", there are a lot of articles in the academic literature considering container terminal operations. The most well-known articles surveying the research on container terminal operations have been done by Bierwirth & Meisel, 2010, 2015, Carlo, Vis, & Roodbergen, 2013, 2014a, 2014b, Meersmans & Dekker, 2001, Stahlbock & Voß, 2008, Steenken et al., 2004, Vis & De Koster, 2003.

A good overview of container terminal operations is given by Günther & Kim (2006). They defined the container terminal as a complex system which is a combination of different handling, transportation, and storage units that are highly interactive with each other and experience uncertainty. They also classified planning and control problems into the three categories of terminal design, operative planning, and real-time planning (Figure 2.1). Even though this classification is based on container terminals in ports, it can be implemented in empty container terminals as well.

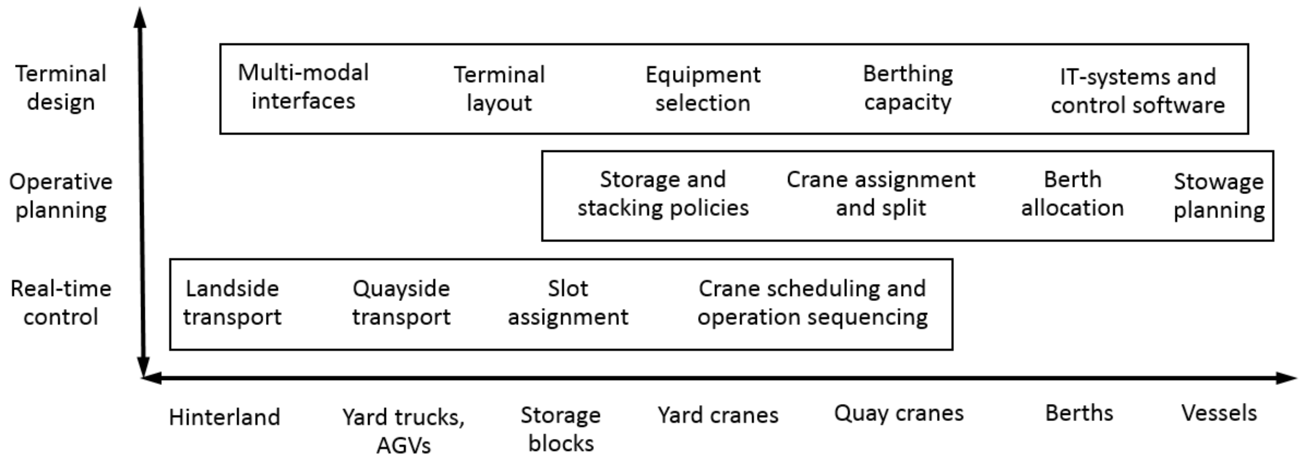


Figure 2.1. Logistics planning and control issues in port container terminals (Günther & Kim, 2006)

Murty et al. (2005) summarized the various operational decisions made in container terminals. The authors described these decisions in detail and discussed the strategies being used to design a computerized decision support system to make some of these decisions efficiently. In this study, the authors state that storage yards in terminals are a combination of adjacent blocks that are sequenced with each other. However, in some studies, a block is called a bay. The position of a container inside a block is identified by row, bay, and tier. A typical block has four to eight rows of spaces. In addition to bay and row, tier is used which refers to the height of the container stacks. In each stack, containers are stored one on top of another. The placing of a container in a stack, or its retrieval from the stack, is made by cranes called yard cranes. Yard crane is a type of handling tool used in port container terminal for loading and unloading containers of railcars and road trucks as well as stacking operations in yards. Authors also mention that the most commonly used yard cranes are Rubber Tired Gantry Cranes (RTGs) that move on rubber tires.

Other handling tools are used in small and medium-sized container terminals such as reach-stackers and top-lifters (called container forklift trucks or dedicated container handlers). Although these types of handling tools can be used for functions the same as yard cranes, they are usually used in small and medium-size container yards. They are also used for container transportation in yards. The main difference between reach-stackers and top-lifters is reaching the rows behind the first row. Reach-stackers are not limited to first-row access, but top-lifters can reach only the first-row containers. The choice between using these two handling tools depends on the selectivity of a given container. Selectivity is the number of containers on top or in front of a container that need to be removed to access the target container. The aim is to decrease the number of restacking (dead-lifts) ("Container handler or reach stacker? Three things to consider" 2016). Some applications such as empty container operations require frequent handling. For faster handling, top-lifters can be a better decision (Hendriks, 2014). The depot we consider uses top-lifters for handling.

In the literature, there are several studies discussing container yard operations (Carlo et al., 2014b). However, most of those studies consider loaded container yards since loaded container logistics add more value to the parties in the logistics chain than empty containers do. Nevertheless, because of the unbalanced volume of import and export, empty containers will cost more and more to container logistics parties. Consequently, there is a need to study and solve problems related to empty container logistics.

Some studies considered container processing in railway yards. Boysen et al. (2012) reviewed container processing in railway yards from an operations research perspective and analyzed basic decision problems for the two most important yard types: conventional rail–road and modern rail–rail transshipment yards. They also classified the related literature by the problem treated and the methodology used.

In literature, there are a limited number of studies that consider empty container management optimization problems. Those studies analyze problems concerning the benefits of the shipping lines since they have authority over empty container logistics management. Theofanis & Boile (2009) and Braekers et al. (2011) conducted detailed literature reviews on empty container management. Theofanis & Boile (2009) surveyed the key factors affecting empty container logistics management and the strategies implemented by ocean carriers and other stakeholders. Braekers et al. (2011) described the decisions to be taken at each planning level (strategic, tactical, and operational) and surveyed the models proposed in the literature for each planning level. While Theofanis & Boile (2009) examined and analyzed empty container management problems at global, interregional, regional, and local levels, Braekers et al. (2011) analyzed the problem at a regional level. However, studies are limited in the case of empty container management.

There are some studies considering the decision-making problem of repositioning of empty containers from an algorithmic viewpoint (Braekers et al., 2013; Di Francesco et al., 2013; Epstein et al., 2012; Erera et al., 2009; Hajeeh & Weam, 2011; Lai, 2013). Some literature extended the mathematical models and algorithms to beyond empty container repositioning to integrate the distribution of empty and full containers for a given time horizon (Bandeira et al., 2009). Choong, et al. (2002) analyzed the effect of planning horizon length on empty container management to minimize total costs, subject to meeting requirements for moving loaded containers. As mentioned by Braekers et al. (2011), as future research opportunities, Xie et al. (2017) and Zheng et al. (2015) extended the empty container allocation problem considering the coordination among liner carriers or intermodal transport firms to lower repositioning costs.

Karmelić et al. (2012) focused on the analysis of data considering global container capacities and the reasons for empty container imbalances, aiming to show the importance of empty container management and the need for empty container planning. The authors pointed out that the empty container logistics are complex systems involving many subjects such as owners or operators, leasing companies, port authorities, terminal operators, and local public authorities.

Some research contributions of the above literature are summarized in Table 2.1 from several aspects such as the category of the study, the research content, and the research method applied.

Table 2.1. Some research contributions to the container terminal operations literature

References	**Category of study**	**Idea of content**	**Method Applied**
Bierwirth & Meisel, 2010	Berth allocation and quay crane scheduling	A review to provide support in modeling problem characteristics and suggesting applicable algorithms.	Survey
Bierwirth & Meisel, 2015	Berth allocation, quay crane assignment, and quay crane scheduling	Extends a previous work by Bierwirth & Meisel (2010).	Survey
Carlo, Vis, & Roodbergen, 2013	Transport operations in container terminals	A review of transport operations and the material handling equipment used. Highlights current industry trends and developments and proposes a new classification scheme.	Survey
Carlo, Vis, & Roodbergen, 2014a	Seaside operations in container terminals	Reviews seaside operations at container terminals and highlights current trends and developments.	Survey
Carlo, Vis, & Roodbergen, 2014b	Storage yard operations in container terminals	Reviews storage yard operations, including the material handling equipment used and highlights current industry trends and developments.	Survey
Meersmans & Dekker, 2001	Design and operation of container terminals	A review of the relevant decision problems at strategic, tactical, and operational levels.	Survey
Stahlbock & Voß, 2008	Operations research at container terminals	Extends a previous survey by Steenken et al. (2004) and provides the current state of the art in container terminal operations and operations research.	Survey
Steenken et al., 2004	Container terminal operation and operations research	Descrives and classifies the main logistics processes and operations in container terminals and presents a survey of methods for their optimization.	Survey
Vis & De Koster, 2003	Transshipment of containers at a container terminal	A classification of the decision problems that arise at container terminals. Discusses quantitative models trying to solve the related problems.	Survey
Günther & Kim, 2006	Container terminals and terminal operations	Reflects recent developments and examines research issues concerned with quantitative analysis and decision support for container terminal logistics.	Survey
Murty et al., 2005	Decision support system for a container terminal	Describes the daily operations of a container terminal and discusses the strategies being used to design decision support systems for these operations.	Survey
Boysen et al., 2012	Railway yard operations	Reviews container processing in railway yards from an operations research perspective and analyzes basic decision problems.	Survey
Theofanis & Boile, 2009	Empty container management	Surveys the key factors affecting empty container logistics management and the strategies implemented by ocean carriers.	Survey

Table 2.1. continued

References	Category of study	Idea of content	Method Applied
Braekers et al., 2011	Empty container management	Describes the decisions to be taken at each planning level: strategic, tactical and operational, and surveys the models proposed in the literature for each planning level.	Survey
Braekers et al., 2013	Integration of loaded and empty container movements	Proposes algorithms to solve a full truckload vehicle routing problem for transporting loaded and empty containers in drayage operations.	Modeling and optimization
Di Francesco et al., 2013	Empty container repositioning	Proposes a stochastic programming approach for the empty container repositioning problem, in which different scenarios are included in a multi-scenario optimization model.	Modeling and optimization
Epstein et al., 2012	Empty container repositioning	Presents a system to support one of the largest shipping company's decisions for repositioning and stocking empty containers.	Modeling and optimization
Erera et al., 2009	Empty container repositioning	Develops a robust optimization framework for dynamic empty repositioning problems using time-space networks.	Modeling and optimization
Hajeeh & Weam, 2011	Empty container repositioning	Formulates a mathematical model with the objective of finding an optimal sequence of ships movement among ports to satisfy demand at the ports with minimum total cost.	Modeling and optimization
Choong, et al., 2002	Empty container management	Presents a computational analysis of the effect of planning horizon length on empty container management for intermodal transportation networks.	Modeling and optimization
Xie et al., 2017	Empty container repositioning	Studies the empty container inventory sharing and coordination problem in intermodal transport and proposes alternative policies for inventory management.	Modeling and optimization
Zheng et al., 2015	Empty container repositioning	Proposes a two-stage optimization method for the empty container allocation problem considering coordination among liner carriers.	Modeling and optimization

From the studies we reviewed about container terminals, the following research gaps can be observed. Even though it is obvious that research on container terminal operations is abundant, there are few studies considering empty containers. The research about empty containers in the literature focuses on relocating empty containers which is much different than the interest of our study. Empty container relocation problems focus on balancing empty containers from surplus locations to deficit locations where the relocations are done as massive shipments. Other studies focus on port terminal operations which consider container terminals in ports. Operations of container terminals in ports are different than empty container depots even though there are some similarities between them. Because of that, we propose analytical methods to make operations more efficient in empty container depots different than the ones in literature proposed for container terminals in ports.

2.2. Container Terminal Design and Planning

In this section, the container terminal design and planning literature is discussed since there is no study considering empty container depot layout or stacking problems to the best of our knowledge. This literature can be reviewed in three sub-areas: yard layout design, storage space allocation problems, and container stacking operations (Luo et al. 2011).

2.2.1. Container Yard Layout Design

The main parts of any container terminal are container yard, transfer roads, and quays. For further discussion, "terminal" will refer to "container terminal" and "yard" will refer to "container yard" to avoid repeating "container" and distinguish between each other. Terminal's performance is related to its capacity and structural configuration. Although terminals have the same system arrangements, they can be different than each other in terms of size, function, and geometric layout.

Yards consist of blocks which are also called stacks. A block can be considered the basic unit of storage in yards (Lee & Kim, 2010b). Each block consists of bays (length) and rows (width) (Figure 2.2). In some yards, there are special areas allocated for reefer containers since they need electric plugs. In our study, we only focus on dry containers, although the empty container depot considered in this study has reefer containers area in the yard.

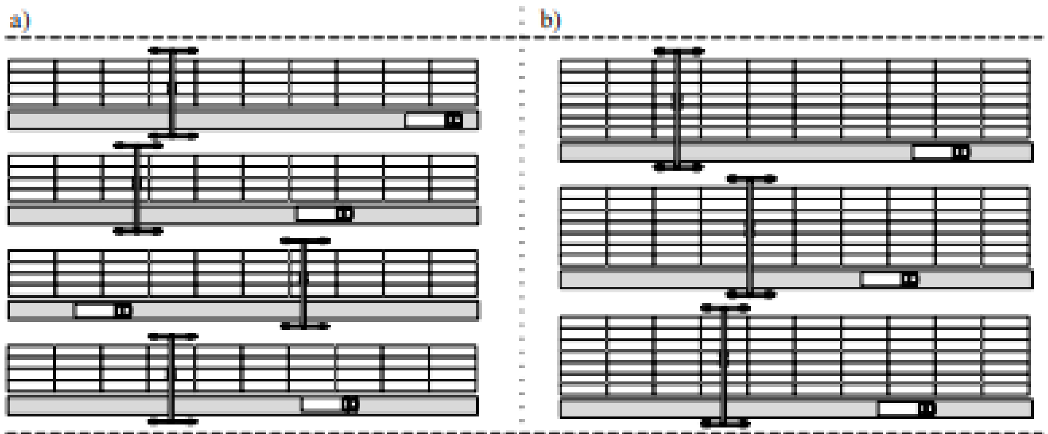


Figure 2.2. Yard layout with four rows (a) and with seven rows per block (b) (Wiese, 2009)

In the literature, there are two main terminal layouts defined in terms of block positioning: parallel and perpendicular. The layout of the terminal is planned considering different parameters in the terminal such as throughput, physical shape, and handling and transportation equipment used in the terminal.

In a parallel terminal layout, storage blocks (stacks) are positioned parallel to the quay. In this layout type, yard cranes can move from one block to another. Since driving lanes are designed beside blocks, internal and external trucks can move straight to aisles. Inbound and outbound containers are stored in different storage blocks. Thus, there are no mixed blocks in this layout type.

In a perpendicular terminal layout, storage blocks are perpendicularly positioned to the quay. Unlike in parallel layout, yard cranes cannot move from one block to another. Thus, each block has a fixed number of yard cranes. In this layout type, there are transfer points at the edge of each block for containers to pick up from and deliver to trucks. For that, internal and external trucks cannot move between blocks. Since the blocks are positioned perpendicular to the quay, generally inbound containers are located close to the landside, and outbound containers are located close to the quay in the same block. That is why inbound and outbound containers are stored in the same block.

One factor affecting container terminal productivity and operating systems is yard design and layout. Yard design and layout are also affected by other factors such as capacity and the type of handling equipment used in the yard (Wiese et al., 2011).

Carlo et al. (2014b) divided the layout design literature into two parts: (1) overall yard layout design including determining the number of blocks, and (2) block yard layout design. In this perspective, there are several existing container terminal design studies in the literature. Some of these studies compare parallel terminal layouts versus perpendicular terminal layouts using simulation methods (Liu et al., 2004). They focused on the impact of automation and terminal layout on terminal performance.

Kim et al. (2008) proposed a method to determine the yard layout design where transfer cranes and yard trucks are used considering the truck travel cost and the relocation cost of transfer cranes as objective factors. They also showed that the parallel layout design outperforms the perpendicular layout design for that type of terminals.

Wiese et al. (2010) considered the problem of designing yards where rubber-tired gantry cranes are used as stacking equipment. They proposed an integer linear program that was restricted to rectangular shaped yards. They showed that the model can be formulated as a special resource constrained shortest path problem for rectangular shaped yards. To solve instances for non-rectangular shaped yards, a variable neighborhood descent heuristic was proposed.

Wiese et al. (2011) proposed a procedure to determine the configuration of the yard with automated rail-mounted gantry-cranes (RMGs) in a perpendicular layout and showed how to obtain non-dominant solutions. They showed that smaller block widths lead to better yard performance, but also higher cost. Later, Wiese et al. (2013) proposed a model to estimate cycle times of the straddle carriers considering both parallel and perpendicular layouts.

Lee & Kim (2013) used an optimization model to determine the optimal layout of an entire container terminal. They compared the results with real-world layouts under constraints of a maximum allowable turnaround time of trucks for receiving and delivering a container. They also compared the maximum allowable system times of transporters for loading and unloading a container. However, their results showed that the width of blocks needs to be increased to achieve better performance and lower cost for both parallel and perpendicular layouts.

Other studies related to the storage block design are Petering (2009), and Petering & Murty (2009). These authors analyzed how the width and length of the blocks affect terminal performance using a simulation model of a parallel layout of transshipment container terminals. They concluded that block widths from 6 to 12 rows and the block lengths from 56 to 72 bays are the optimal values which result in the highest quay crane work rate and greatest yard crane mobility depending on the number and characteristics of the handling equipment used in the terminal. However, in real yards, the common number of rows is between 6 and 9 and a typical block is about 40 bays long (Alcalde, 2014). Alcalde (2014) mentioned that the common usage of tiers ranges from 3 to 6 high. However, in the case study considered in our study, containers can be stacked up to 7 tiers. There are a couple of factors in determining the maximum tier number such as handling tools used in the yard and the expected number of relocations. The main reason that the maximum tier number of 7 in the empty container depot (ECD) considered is the handling equipment used in the depot. In general, in ECDs, depot layout and handling equipment are different from seaside container yards. A top-lifter is used in empty container depots as the handling equipment which is different than the straddle carriers and quay cranes used in terminal yards, in terms of the lifting weight and movement direction capacity.

Lee & Kim (2010b) proposed four optimization models to determine the block size in a container terminal using four objective functions with constraints as follows: (1) minimizing the weighted expected yard crane cycle time for various operations subject to a provided minimum block storage capacity, (2) maximizing the storage capacity subject to a maximum expected cycle time of a yard crane, (3) minimizing the weighted expected truck waiting time for various operations subject to a provided minimum block storage capacity, and (4) maximizing the storage capacity subject to a maximum expected truck waiting time. This study also provided detailed formulas for the expected cycle times and variances of all yard crane operations which depend on the block layout. However, the same authors in a different study proposed a more detailed expression to estimate the yard crane cycle time for different placement of transfer points. They placed transfer points beside each bay and block, and at both ends of the blocks. They used simulation to validate the cycle-time estimations (Lee & Kim, 2010a).

Kim & Kim (2002) developed a cost model to determine the optimal size of the yard and the number of transfer cranes to handle import containers. The cost model consists of the cost of space, the cost of transfer cranes, and the cost of outside trucks. Two different types of cost objectives were analyzed; one considered total cost only in the terminal and the other considered total cost taking into account both terminal and customer perspectives.

Kemme (2012) analyzed the effects of crane systems and yard block layout decisions on the long-run performance of RMGs storage yards using a simulation model analyzing four different RMG systems and 385-yard blocks layouts. The author concluded that there was a strong relationship between the storage capacity of a yard block and the corresponding mean waiting time of straddle carriers for quayside retrieval operations in all crane systems.

Taner et al. (2014) developed a simulation model to investigate the effects of different layout formats of artificial terminals built by filling in the coasts in shallow seas. The authors analyzed these terminal layout formats using different transporter dispatching rules and resource allocation strategies in terms of total annual handling number. According to their analysis, terminal operation performance is significantly affected by terminal layout design under different transporter dispatching rules and allocation strategies, and each layout format requires a unique combination of transporter request rule and intersection rule. Intersection rules are used to avoid traffic congestion or accidents at intersections during automated guided vehicles (AGVs) travel.

Tang & Tang (2013) proposed an integer programming model to determine the length and layout of each block to maximize yard truck transport efficiency between blocks, and storage capacity of the yard where block lengths are not necessarily equal. Zhou et al. (2016) presented a two-stage stochastic programming model supported by a simulation model. The goal of the study was to obtain a cost-effective and reliable design solution to the layout and equipment deployment strategy of a yard in mega container terminals. The considered container yard type was a parallel yard layout with transfer lanes. They applied their methodology to a terminal at the Shanghai Yangshan Port Area in China.

The literature about container yard layouts is summarized in Table 2.2.

Table 2.2. Some research contributions to container yard layout design

References	Idea of content	Method Applied
Lee & Kim, 2010b	Proposes two methods for optimizing the block size by considering the throughput requirements of yard cranes and the block storage requirements.	Modeling and optimization
Liu et al., 2004	Demonstrates the impact of automation and terminal layout on terminal performance.	Simulation
Kim et al., 2008	Suggests a method to determine the layout type, the outline of the yard, and the numbers of vertical and horizontal aisles.	Mathematical model
Wiese et al., 2010	Introduces an integer linear program for planning the layout of container yards with transfer lanes.	Integer linear program
Wiese et al., 2011	Proposes a procedure for finding a promising storage yard configuration for a layout that is typical for the use of automated rail-mounted gantry cranes.	Modeling and optimization
Lee & Kim, 2013	Proposes a method for optimal layout of container yards considering storage space requirements and throughput capacities of yard cranes and transporters.	Mathematical model
Petering, 2009	Evaluates block widths ranging from two to fifteen rows in a marine container terminal.	Discrete event simulation
Petering & Murty, 2009	Evaluates several different block lengths and yard crane deployment systems.	Discrete event simulation
Lee & Kim, 2010a	Analyzes two different types of block layout.	Modeling and simulation
Kim & Kim, 2002	Proposes a method of determining the optimal amount of storage space and the optimal number of transfer cranes for handling import containers.	Mathematical model
Kemme, 2012	Investigates the strategic design of rail-mounted-gantry-crane systems differing in block length, width, and height.	Simulation
Taner et al., 2014	Investigates transporter dispatching rules and resource allocation strategies in terms of total annual handling number in artificial container terminals.	Simulation
Tang & Tang, 2013	Optimizes the layout design of blocks in a new container yard considering unequal block lengths.	Integer programming
Zhou et al., 2016	Obtains a cost-effective and reliable design solution to the physical layout and equipment deployment strategy of the yard at a mega container terminal.	Mathematical modeling and discrete-event simulation

Kim et al. (2008) and Wiese et al. (2010) proposed methods to find the optimal yard layout for container yards where transfer cranes are the primary handling equipment. However, both studies considered the case that driving lanes between bays are allowed for internal truck moves. In our study, the container stacks are placed differently than those container yards because different handling equipment top-lifter is used and driving lanes are bi-directional.

To sum up, considering the literature discussed above, many authors have considered the storage yard design problem. Those studies analyzed the problems using simulation or mathematical models, but none of them considered using different handling tools other than the common port terminal yard cranes. However, in our study, the handling tools, top-lifters, are much different than the considered ones in literature because top-lifters have only access to containers in the first row of blocks and they cannot reach any container behind the first row of blocks. Besides, in these studies, usually the incoming and outgoing container schedules are known in advance. For that, operators can assign locations based on the outgoing schedule when containers arrive in the yard. However, in empty container depots, all incoming container arrival times are not known in advance. As with incoming containers, outgoing container request times are not known in advance except for massive shipment containers since their request time is based on the ships' arrivals to ports.

2.2.2. Storage Space Allocation Problems

The storage space allocation problem addresses assigning the best location for a container in a yard. Although many researchers have addressed the yard design and planning problem through simulation or optimization models, none has attempted to analytically determine storage space requirements by considering the stochastic properties of the yard until a study was done by Taleb-Ibrahimi et al. (1993). The authors attempted to find the minimal storage space needed to implement a proposed handling and storage strategy given a certain traffic level. Before this, most researchers had assumed a predetermined space utilization estimated from historical data.

Kim & Park (2003) formulated the storage allocation problem for incoming export containers as a mixed-integer linear program. The authors proposed two heuristic algorithms and compared them with each other. One algorithm is built based on the container's duration of stay and the other one is based on a sub-gradient optimization method.

Zhang et al. (2003) developed a rolling-horizon approach and formulated a mathematical programming model to determine the total number of containers to be placed in each storage block at each period to balance the workload among blocks. Their model also determines the number of containers associated with each vessel that makes up the total number of allocated containers to each block at each period, to minimize the total traveled distance of internal trucks. Later, Bazzazi et al. (2009) proposed a genetic algorithm to solve the extended version of the problem formulated by Zhang et al. (2003) in which the type of container affects the allocation decision.

Murty et al. (2005) suggested three stages for the storage space allocation problem: (1) block assignment, (2) dispatching policy, and (3) storage position assignment. In the first stage, only the total number of incoming outbound and inbound containers to be stored in each block during each period is determined. In stage two, the dispatching policy of incoming trucks is determined. Based on the dispatching policy determined here, terminal gate operators send trucks to the assigned blocks. The goal of stage two is that each block gets an equal number of containers assigned in stage one by the end of the period while minimizing congestion within the blocks and on the roads. In the last stage, the optimal available position in the block is determined for storing the containers to minimize the number of relocations.

However, there have been few studies that analyzed the problem considering two steps simultaneously. One of these studies was done by Chen & Lu (2012). In this study, the authors first formulated a mixed-integer programming model to allocate the yard bays and the amount of space in each yard bay for outbound containers for each period of the planning horizon. In the second stage, they proposed a hybrid sequence stacking algorithm to determine the final storage location for the next arriving container considering an efficient loading sequence to the ship.

Nishimura et al. (2009) analyzed the storage problem which deals with transshipment containers from a mega-container ship to feeder ships by using a heuristic based on Lagrangian relaxation. Different than the studies mentioned above, the study by Woo & Kim (2011) assumed that the amounts of space allocation were not given. Instead of a given amount of space, they proposed and compared methods to determine space reservations for the outbound containers based on four policies used in practice. They also analyzed the impact of the size of space reservations on the efficiency of loading operations. In addition to that, they proposed a method for determining the total space requirement of the outbound containers yard by considering the fluctuation in container inventory level.

Lee et al. (2012) developed an integer program integrating two decision problems; the terminal allocation problem for vessels and the yard allocation problem for transshipment container movements. The authors also developed a 2-level heuristic to solve the integrated problem efficiently.

The summary of the literature about storage space allocation problems is given in Table 2.3.

Table 2.3. Some research contributions to storage space allocation problems

References	Idea of content	Method Applied
Taleb-Ibrahimi et al., 1993	Explores storage space requirements for export containers at port terminals using yard cranes.	Algorithm
Murty et al., 2005	Develops a decision support system to minimize the berthing time of vessels, the resources needed for handling, the waiting time of trucks and congestion, and to make the best use of the storage space.	Algorithm
Chen & Lu, 2012	Proposes a two-stage approach for solving the storage location assignment problem for outbound containers.	Mixed-integer programming
Zhang et al., 2003	Proposes a rolling-horizon approach to solving a space allocation model.	Mathematical model
Bazzazi et al., 2009	Proposes a genetic algorithm to solve an extended storage space allocation problem that considers the type of container to choose the allocation of containers to the blocks.	Mathematical model and heuristic
Nishimura et al., 2009	Proposes an optimization model to investigate the flow of containers from the mega-containership to feeder ships and a heuristic based on Lagrangian relaxation to solve the model.	Mathematical model and heuristic
Woo & Kim, 2011	Proposes a method for allocating storage space to groups of outbound containers in port container terminals.	Mathematical model and algorithm

Since storage space allocation is done traditionally in the empty container depot considered in this study, a space allocation method similar to the method proposed by Chen & Lu (2012) could be implemented at the depot. They developed a two-stage solution method. The first stage concerns the reservation of storage space for outbound containers bound for each ship. The second stage concerns the decision to store a container at a particular location in the assigned bay. The objectives of the first stage are to reduce the time required for the yard trucks to transfer the containers from the yard to the berth for loading onto ships, and to balance the workload of each yard bay. We can implement the first stage in our problem to reduce the queue of trucks in front of the gate when there is a massive shipment. Since all containers of the massive shipment should be retrieved from the depot during the ship berthing, truck congestion in front of and within the depot occurs during the massive shipment. Since gate locations are fixed in the depot, container storage areas can be assigned resulting in the total travel distance of trucks so that the time in the system and the number in the queue of trucks can decrease after implementing the first stage mixed integer programming method proposed by Chen & Lu (2012). We can implement some extra constraints such as 20 feet containers need to be stored in the blocks located along the back streets of the depot. However, we will not need some constraints such as the constraint defining the workload in each container block in their proposed method. The workload in each container block is evaluated by the total number of containers handled in the planning horizon.

2.2.3. Container Stacking Problems

According to Gharehgozli et al. (2017), the stacking operations literature can be classified into two groups: (1) stacking containers and (2) handling tool scheduling. Since this study focuses on stacking containers, the stacking containers literature is discussed briefly in this part.

The container handling process in maritime terminals can be divided into three phases. In the first phase, incoming containers are assigned to stacks. In the second phase, containers are stored in a terminal before being transferred to another location. In the final phase, containers are retrieved for shipment. In all of these phases, the main goal is retrieving containers with minimum relocation. In the literature, all stacking problems can be categorized with three focuses: (1) container storage loading, (2) container storage unloading or relocating during retrieval, and (3) pre-marshaling problems (Caserta et al., 2011; Gharehgozli et al., 2017; Lehnfeld & Knust, 2014). However, this classification can be different in some review papers. For example, Carlo et al. (2014b) review the container stacking literature in four categories. They consider another class called "re-marshaling" (e.g., Choe et al., 2011; Lee et al., 2012). If the pre-marshaling operation is done by moving the containers to a place different than prepositioning the containers in the same place from which they are removed, it is called re-marshaling. We use these two terms interchangeably in our study.

However, all three categories of container stacking problems aim to minimize the expected number of relocation movements during or before the retrieval process. Relocation is an unproductive move performed to reach the target container that is blocked by other containers (Carlo et al., 2014b). Relocation is also called “re-handling”, “reshuffling”, or “shuffling”.

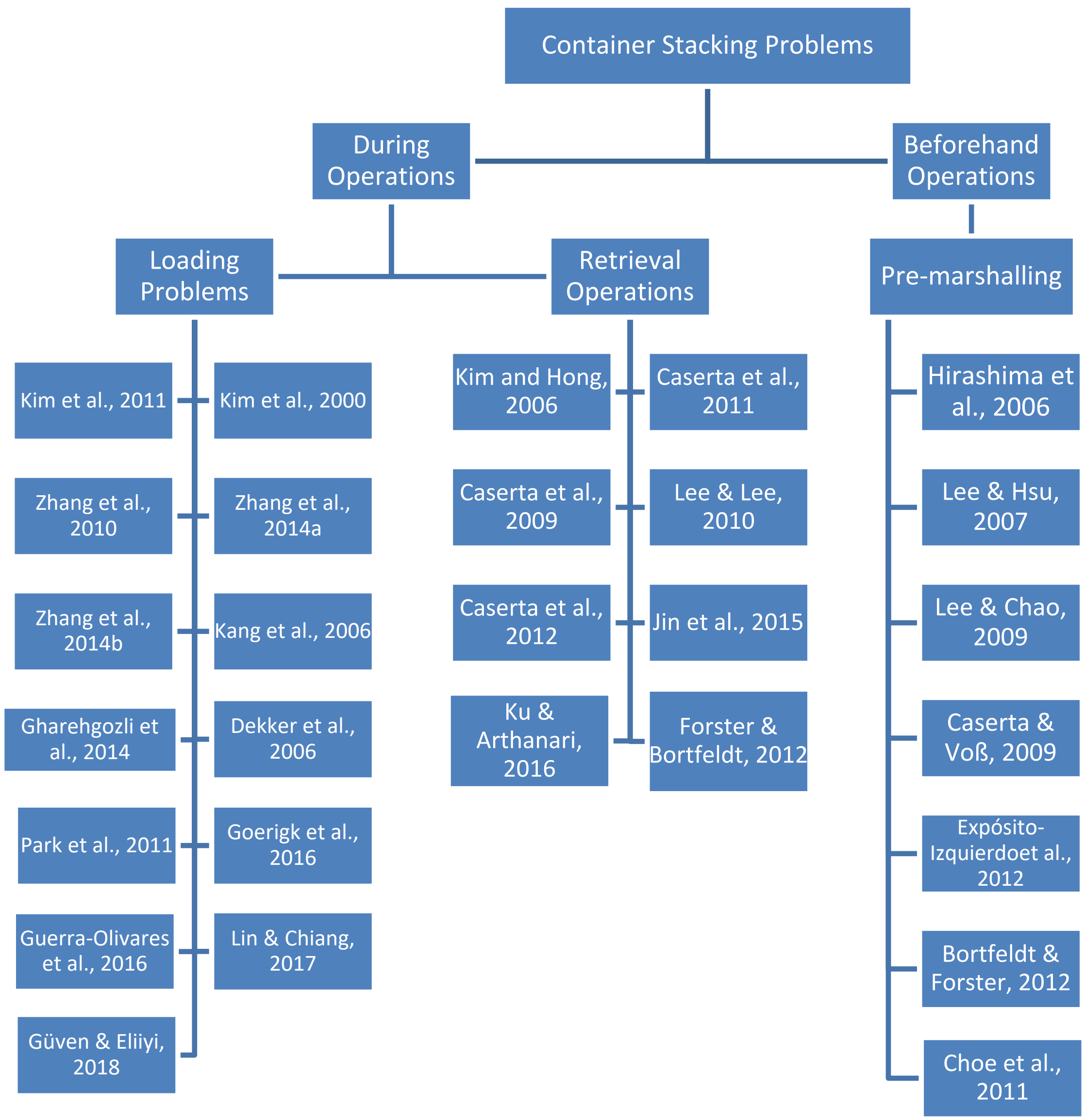


Figure 2.3. Overview of research in container stacking operations

2.2.3.1. Container Storage Loading Problems

Even though pre-marshaling and relocating policies help to minimize the number of reshuffles during retrieval, efficient stacking policies significantly decrease the relocation effort later. Some studies in the literature focus on how to locate incoming containers properly to make the retrieval process efficient. These problems are called “container storage loading problems”. However, these problems are also relevant to other industries such as steel manufacturing and wood plate manufacturing. For example, Kim et al. (2011) proposed several mixed-integer programming models to make a storage plan for incoming thick steel plates to minimize the number of reshuffles during the delivery stage. Their models can find optimal solutions for small problems and lower bounds for large problem instances. They also proposed a randomized iterative heuristic approach to solve large problem instances.

The container stacking literature can be reviewed into two categories: allocation of storage space and determination of stacking position. In this section, we only review the determination of stacking position literature which considers the handling of containers instead of storage space allocation.

Container storage loading problems mainly deal with the storage of incoming containers. This category of problems aims to find a feasible location for each incoming container in a depot, yard, or, sometimes ship stowage. These problems study how to stack incoming containers in a block aiming to minimize the expected number of reshuffles. Even though these problems can be combined with unloading problems or re-marshaling problems, pure loading problems assume that there is no outgoing container from the container yard during the loading operations.

Most loading problems in the literature consider weight-related constraints to assign a stacking position for an incoming container. The first weight-related loading problem was considered by

Kim et al. (2000). The authors proposed a dynamic programming model to determine a storage location for incoming export containers in a container yard considering its weight. The objective is minimizing the number of relocation movements during the loading operations of a ship considering the configuration of the container stack and the weight distribution of containers in the yard. The authors also developed decision trees to avoid the impractical computational time of dynamic programming for real-time decisions. The optimal solutions set from dynamic programming are used to build a decision tree. However, Zhang et al. (2010) showed that the equations in the dynamic programming model proposed by Kim et al. (2000) are not valid. The authors analyzed a transformation from the original model and corrected the invalid equations to make the other parts of the original paper valid.

Zhang et al. (2014a) extended the work of Kim et al. (2000) and Zhang et al. (2010). The authors proposed two new allocation models. The difference between them is a punishment coefficient for placing a lighter container onto the top of a stack loaded with heavier containers. Previous work neglected the stack height and the existing weight groups in each stack information to interpret the punishment parameter. In addition to that, the authors proposed an approximate dynamic programming algorithm to overcome the computational difficulty of the previous dynamic programming algorithm for large-scale problems.

Zhang et al. (2014b) also extended the previous work of Kim et al. (2000) and Zhang et al. (2010) with a different perspective. Kim et al. (2000) and Zhang et al. (2010) assumed that the proportion of the remaining arriving containers in each weight group remains the same during the container arriving stage. Even though this assumption makes the state size smaller so that the problem is easier to solve, this assumption is not applicable in practice. Zhang et al. (2014b) proposed two new dynamic programming models considering an adjusted proportion of the remaining containers' weight groups based on the containers' proportions in a yard. The proposed models were compared from two perspectives: state size and stacking quality. The authors also proposed a two-stage heuristic to solve large-scale instances in a reasonable computational time.

Kang et al. (2006) proposed a simulated annealing search algorithm to find a stacking location for an incoming export container considering uncertain weight information which different than other related studies (e.g., Kim et al., 2000; Zhang et al., 2010; Zhang et al., 2014b). The expected number of relocations is calculated based on the probability distribution of each estimated weight group which can be obtained from historical data statistics. The containers are classified into weight-groups as 'light', 'medium', and 'heavy' which are common groups in most container terminals. They compared their method with a traditional same-weight-group stacking method using simulation and they showed that their method is more effective than the traditional method based on the number of relocations.

Goerigk et al. (2016) considered two constraint types; stacking and payload. Stacking constraints refer to items that can be stacked onto each other. These constraints can be used to provide practical requirements such as item departure times or incompatible item dimensions. Payload constraints ensure that more weight is not stacked on top of an item than the stability of this item allows. However, as item weights are uncertain, the authors proposed strict and adjustable optimization models for finite and interval-based uncertainties. Furthermore, exact decomposition and heuristic solution algorithms were developed to solve these problems.

Gharehgozli et al. (2014) developed a decision-tree heuristic algorithm to find near-optimal solutions for large-scale loading problems. The objective of their algorithm is how to stack incoming containers in a container block to minimize the expected number of reshuffles. Their algorithm uses the results of a stochastic dynamic programming (DP) model developed by Kim et al. (2000). However, their method uses the DP results in a different way than Kim et al. (2000) use in their method. Kim et al. (2000) use “machine learning logic” which produces the branches of the decision trees one by one based on the amount of information each branch provides for making the decision on where to locate an incoming container. However, Gharehgozli et al. (2014) maps all states of DP solutions in decision trees as nodes and branches and then simplifies and generalizes them.

Dekker et al. (2006) investigated different stacking policies in an automated stacking container terminal using simulation. They developed a simulation using the “MUST” language. They developed two separate programs: generator and evaluator. The generator program creates entry and departure times of 175,000 containers over a period of 15 weeks of operation. The evaluator program performs a deterministic simulation based on experimental setting using the stochastic output of the generator program. They use a random stacking policy as a benchmark case considering only the container size as a matching condition.

Park et al. (2011) proposed an online search algorithm called dynamic policy adjustment for an automated container terminal. The proposed algorithm dynamically adapts and optimizes a stacking policy with the change of the stacking environment such as incoming container type and dwell time. The authors argue that their proposed algorithm can easily adapt to a changing environment since the proposed algorithm continuously generates variants of stacking policies.

Guerra-Olivares et al. (2016) proposed a heuristic to stack incoming export containers into a container terminal. They estimated the upper bound of the expected number of reshuffles during the retrieval process to measure the performance of the proposed heuristic. In the case the authors considered, the terminal had a specific area for export containers where the containers stay around 72 hours prior to the arrival of a ship.

Lin & Chiang (2017) proposed a heuristic algorithm to solve real-size storage space allocation problems in a second. The authors implemented their heuristic algorithm at the Port of Kaohsiung, Taiwan. However, their method relies on detailed container arrival information, and the retrieval order of containers are known in advance.

Güven & Eliiyi (2018) considered the stacking problem for all incoming types of containers (transit, export, import, or empty) in a container terminal. They proposed a binary mathematical model to assign each incoming container to a stacking position considering the category of an incoming container. The category of a container is defined by its destined vessel, its receiver or its owner, and the arrival/departure time based on the trade type of container. The authors used simulation to compare three different stacking policies. They used the data from the Port of Izmir for simulation.

2.2.3.2. Container Storage Unloading or Relocating Methods During Retrieval

Container storage unloading problems focus on container retrievals from a storage area. Pure container unloading problems assume that there are no incoming containers to an area during the retrieval process. The container storage unloading problem is also termed the block relocation problem (BRP) (Caserta et al., 2011; Kim & Hong, 2006) or the container relocation problem (CRP) (Forster & Bortfeldt, 2012) in the literature (Ku & Arthanari, 2016; Lehnfeld & Knust, 2014). We use the container relocation problem (CRP) to refer to these kinds of problems. The CRP aims to minimize the number of relocation moves for removing blocking containers when containers are retrieved from stacks based on a given retrieval order.

To the best of our knowledge, Kim and Hong (2006) first studied the CRP. They assumed that containers are categorized into different groups and the same category containers can be retrieved interchangeably to minimize the number of reshuffles. The authors suggested two methods for determining the locations of relocated blocks. They provided a branch-and-bound algorithm and a heuristic rule by estimating the expected number of additional relocations for a stack. They assumed that there is no pre-marshaling allowed. The performance of the branch-and-bound algorithm is compared to that of the heuristic rule. They presented numerical results on problems with a maximum of six stacks and four tiers.

Caserta et al. (2011) proposed a corridor method that solved the CRP through a dynamic programming model. They also imposed two additional constraints to reduce the number of states that need to be considered. They also generated a set of instances for various sizes of stacks and tiers to test their method's efficiency.

Caserta et al. (2009) developed a binary encoding of a stacking area where homogeneous blocks are stored in stacks. They implemented a binary encoding within a look-ahead heuristic. The binary encoding allows fast access to information related to the current status of the stacking area and fast transformation into neighbor solutions to develop metaheuristic search strategies. They compared their results with those from the literature and showed that their binary encoding implementation outperformed the best-known approaches in terms of solution quality and computational time.

Lee & Lee (2010) developed a three-phase heuristic for a multiple-bay scenario CRP to obtain a movement sequence for the crane to retrieve all containers in a specified order. The multiple-bay scenario CRP objective is minimizing the total number of container relocations from multiple bays combined with the minimization of the crane's working time. The crane working time includes the bay changing time and intra-bay time. In the first phase of the algorithm, a feasible retrieval sequence is determined by a greedy approach. This sequence is improved in the second phase while maintaining feasibility. In the last phase, the working time for the crane is reduced using a mixed-integer program.

Caserta et al. (2012) proved that BRP is an NP-hard problem. They also presented a binary linear programming model for BRP to overcome some limitations of existing models in the literature by introducing some realistic assumptions which reduced the problem size or search space. Even though the proposed approach is reasonably fast for medium-sized instances, they proposed a simple heuristic based on a set of relocation rules to obtain real-time solutions for practical problems. Their proposed method benefits from a set of relocation rules for shifting containers located on top of the one to be retrieved. They showed that their proposed heuristic is effective compared to optimal solutions obtained using a state-of-the-art commercial solver.

Jin et al. (2015) proposed a greedy look-ahead heuristic for the CRP. They applied their heuristic method on four data sets. They showed that their heuristic algorithm provided better solutions for most existing instances, especially for large-scale instances in less computational time compared to the other approaches in the literature. However, it cannot guarantee optimality even in infinite runtime.

Ku & Arthanari (2016) proposed a search-space reduction technique called the abstraction method to reduce the search space for CRP since it is an NP-hard problem. They also proposed a bi-directional search method using the abstraction method. They showed that their proposed approach allows practical size problem instances to be solved optimally within reasonable computational time.

Forster & Bortfeldt (2012) proposed a tree search algorithm for CRP. The algorithm is based on a natural classification of possible moves and it applies a branching scheme using move sequences of promising single moves so that it only explores a partial solution space. They tested their algorithm against all other former algorithms in the literature using existing instances and newly created random instances by the authors. They concluded that their proposed algorithm is a competitive solution method that can be applied to larger size CRP instances.

2.2.3.3. Pre-marshaling Problems

The pre-marshaling problem (PMP) can be considered a restrictive version of CRP. In the PMP, the initial configuration of containers is sorted based on a given retrieval order such that the retrieval process can be done with no, or few, relocations during the retrieval process. The PMP can be defined as finding a final container stack configuration that needs no, or few, relocation movements during the retrieval process while minimizing the number of relocations to reach that final configuration. The main difference between CRP and PMP is that the initial existing containers stay after the pre-marshaling whereas containers leave stacks in CRP (Bortfeldt & Forster, 2012; da Silva et al., 2018; Gharehgozli et al., 2017; Lehnfeld & Knust, 2014).

Hirashima et al. (2006) proposed a Q-learning algorithm for PMP. In the proposed method, each container has several preferred final positions in the buffer area. The authors extended the learning algorithm to obtain several desirable layouts in the buffer area. The authors used computer simulations to show the proposed method efficiency. The proposed method found better results for both small and large-scale problems as compared to the conventional ones.

Lee & Hsu (2007) proposed an integer programming for a PMP. The proposed model is based on a multi-commodity network model and the objective of the model is to minimize the number of container movements during pre-marshaling. The authors also showed possible extensions of the model modifying some of the constraints. However, they assumed that relocations may only take place within a bay and the model can only be applied to small-scale problems. Some simplifications of the model are discussed to make the model more computationally efficient. They proposed a heuristic to solve large size problem instances. They showed results for 37 examples.

Lee & Chao (2009) extended the work by Lee & Hsu (2007). They also defined the objective function value as the weighted sum of the length of the sequence and the mis-overlay index of the corresponding final layout. A movement sequence is an ordered list of container movements showing what containers to move, how to move, and the order of moving. A mis-overlay is a situation when a container with a lower priority is stacked on top of one with a higher priority, i.e., a container that needs to leave later is stacked on top of one that needs to leave sooner. A mis-overlay index refers the maximum depth of mis-overlays in a bay. In other words, their objective addresses the number of relocations during the retrieval phase and the number of movements to get the final stack configuration. The authors also developed a heuristic that improves the initial movement sequence iteratively. The proposed heuristic consists of a neighborhood search process, an integer programming model, and three minor subroutines. Neighborhood search improves the mis-overlay index in the final bay configuration. An integer programming model reduces the length of the movement sequence (the number of relocations) while keeping the corresponding final bay configuration. The three minor subroutines work as follows: The first one generates movements which completely empty a randomly selected stack to make the search space larger for neighborhood search. The second one reduces the length of the current movement sequence based on a simple rule. The last one reduces the mis-overlay index of the final bay configuration.

Caserta & Voß (2009) proposed a metaheuristic for PMP for a single bay based on a corridor method algorithm. The algorithm consists of four iteratively repeated phases; corridor definition/selection, neighborhood search, move evaluation and selection, and local search improvement. The algorithm is stochastic in nature and uses a set of greedy rules. The algorithm was tested on the problem from the container terminal logistic domain.

Expósito-Izquierdo et al. (2012) proposed a heuristic to solve PMP and developed an instance generator for PMP. The main proposed heuristic, Lowest Priority First Heuristic (LPFH), states if the lower priority containers are at the bottom of the stack then they do not need to be relocated in the future. The authors compared their results with the ones by Caserta & Voß (2009) and optimal solutions obtained by an A* search algorithm. The developed instance generator creates instances based on different degrees of difficulty. The difficulty level is determined based on the occupancy rate of a bay and the percentage of containers with high priority containers located below low priority containers. The authors stated that computational experiments showed good performance of their proposed heuristic and instance generator. The developed instance generator is available online.

Bortfeldt & Forster (2012) proposed a tree-search heuristic based on a natural classification of possible moves to solve PMP. In the tree search algorithm, the nodes of the tree represent the different configurations of the stacks. The initial configuration is represented by the root node and a final possible configuration is represented by leaf a node. The proposed methodology was compared with all former solution approaches for PMP and it showed that the proposed method was effective and efficient and can solve larger real-world PMP instances.

Choe et al. (2011) presented a heuristic method for re-marshaling problems. Their proposed method aims to find an efficient intra-block re-marshaling plan for given loading order and they assume that each block is equipped with two cranes that cannot move across each other. The proposed method also aims to minimize the interference between the cranes during stacking operations. Their test results showed that the proposed approach can generate an efficient re-marshaling plan in a reasonable time.

To sum up, the literature discussed above includes many outstanding articles considering container stacking problems to minimize the number of relocations during the retrieval process, but there has been no study considering container stacking operations in an empty container depot. As mentioned in other parts of our study, in most port container yards, container stacks can be accessed from the top of stacks but in the empty container depot because of the handling equipment access capacity only containers in the first row can be accessed. Thus, different constraints must be considered since the containers in the depot can be blocked not only by containers stacked on top of them but also next to them.

2.3. Simulation Use in Container Terminal Problems

Considering general container terminals, many containers are transferred between parties in the container logistics chain including between ships and shore, or empty container terminals and port, or consignees and container yards. Container terminals show some of the highest stochastic in today's industry. Furthermore, their internal stochasticity is combined with an equally stochastic external environment (Petering, 2007). Because of this compounded stochasticity, modeling a problem in this industry using a deterministic model is not appropriate. Therefore, a good solution strategy is using a simulation model.

We can divide operations research methodologies into three main categories: deterministic optimization, stochastic modeling, and simulation. Each of these categories will be discussed shortly from the point of view of container terminals.

Deterministic optimization models are the most common methodology used in articles on container shipping problems. The common structure of these problems is first proposing an integer mathematical model and solving small static size problems. Then the structure continues to solve medium-size static problems heuristically. As a final step, the heuristic is proposed to produce near-optimal results for large size sample problems. However, as we mentioned above, because of the stochasticity in the container terminals, the methodology proposed for the container terminal operations should explicitly consider this.

Stochastic modeling has been widely used when the simulation is not available for modeling systems if the state space is small, the state transition has a regular structure, and the transition times between states have special properties such as exponential or Erlang distributions (Petering, 2007). Nevertheless, in container terminals, there are dozens of trucks and lifters and thousands of container locations causing thousands of possible states. Consequently, the number of possible states at a container terminal exceeds almost the number of atoms on earth. Besides, the transition times between states at a container terminal do not exhibit suitable properties for stochastic modeling. Because of those reasons, stochastic modeling is not appropriate to model container terminal operations.

Simulation is the methodology that fits best the stochastic nature of container terminal operations dealing with thousands of state spaces. The main advantage of using simulation is that it facilitates the evaluation of different alternatives for the design and policies. Simulation is useful to design new terminals, make modifications to existing terminals, and evaluate the benefits of new resources or impacts of operation policies. Furthermore, simulation helps us to evaluate the performance using established industry metrics.

Container terminals are large and long-term investments. In addition to that, the activities in container terminals are also costly and complex. Due to the steady increase of global product flows, container terminal operations are critical to be competitive. Consequently, when other research methodologies cannot analyze this problem accurately, there is a need for a validated and verified simulation model to explore complex container terminal operations in more detail (Nam et al. 2002).

Papers surveying the research on container terminal simulation models have been done by Angeloudis & Bell (2011), Dragovic et al. (2017), and Rashidi & Tsang (2013). According to some survey papers, advanced simulation-based modeling use has been increasing to support terminal planning processes (Angeloudis & Bell, 2011; Stahlbock & Voß, 2008; Steenken et al., 2004; Vis & De Koster, 2003). The most extensive review paper presenting simulation model studies in port development with a focus on container terminals is done by Dragovic et al. (2017). In this study, the authors reviewed 209 papers presenting a simulation model of a port or container terminal operations with 10 literature review papers, published over 54 years (1961-2015). In this study, the authors summarized the reviewed papers based on (1) the journals in which these papers have been published; (2) the type of software that was used to develop the simulation models; (3) the main features of the simulation models; (4) the specific port (if any) that inspired the development of the simulation models, and (5) the general topic (application area) investigated. They concluded that discrete-event simulation is one of the most popular techniques in port or container terminal operations modeling. The number of papers published during 2000-2015 is almost six times the number of papers published before 2000. According to Dragovic et al. (2017), the main reasons behind that increase are improved knowledge and experience in port simulation modeling. In addition to that, the increased demand for precise and dependable tools to solve complicated port problems in a competitive sector triggered the use of simulation models in maritime shipping. Further, with the starting of the Industry 4.0 era, most ports and container terminals recently built more organized databases which are essential supports for simulation model usage.

Angeloudis & Bell (2011) and Rashidi & Tsang (2013) considered a limited number of simulation studies that analyzed the impact of management decisions on the performance of containers. Dragovic et al. (2017) included the 30 papers reviewed by Angeloudis & Bell (2011) and all six papers reviewed by Rashidi & Tsang (2013).

As Dragovic et al. (2017) mentioned in their review paper, there are 23 journal papers considering the container terminal subarea among the total 25 port simulation model journal papers published in 2015. As mentioned in Dragovic et al. (2017) and Xu et al. (2015), there are a large number of studies considering container terminal simulation. Those studies discussed various decision-making problems. However, among them, few notable simulation studies are relevant to the layout design and stacking operations in container terminals, which are the problems that this study attempts to solve in an empty container depot.

Petering (2009) and Petering & Murty (2009) developed a discrete event simulation with an object-oriented architecture to analyze the effect of block width and block length, respectively, on the throughput of handling systems. In their models, predefined events update the system states and activate the subsequent events when these events are triggered. They used simulation models written and compiled using C++. Those studies assume a flexible dimension of the terminal area, which means that when either block length or width is fixed, the other one changes to keep the block capacity the same. Petering (2011) performed nine studies related to strategic and tactical container terminal management. The author compared the productivity using gross crane rate as a measure of productivity for various scenarios generated based on storage capacity, size, and configurations of handling resources; vehicle dispatching policy; and terminal size.

Wiese et al. (2009) presented a mixed-integer linear model to find layout configurations for container terminals with transfer lanes. They developed a simulation model designed in

Tecnomatix Plant Simulation 8.1 to evaluate the proposed layout configuration and the adequacy of the linear model for planning container terminal layouts.

Kemme (2012) conducted a simulation study to investigate the effects of storage block layout and automated yard crane systems on the long-run performance of RMG storage yards. The author evaluated the effects of four RMG systems and 385-yard block layouts (differing in block length, width, and height) on the yard and terminal performance. They implemented the simulation model using Tecnomatix Plant Simulation 8.2.

Liu et al. (2004) developed a simulation model to evaluate two commonly used yard layout configurations where automated guided vehicles (AGVs) are used. Their study results showed that higher performance can be gained using automated vehicles and the yard layout has an impact on the number of AGVs needed as well as terminal performance. They used ‘‘Matlab’’, ‘‘Simulink’’ and ‘‘Stateflow’’ to perform the simulation scenarios.

Zhou et al. (2016) developed a two-stage stochastic programming model supported with a simulation model of terminal operations developed in Arena 10.0 for mega container terminals. The main goal of their methodology is to obtain a cost-effective and reliable design solution to the layout and equipment deployment strategy considering parallel yard layout terminals with transfer lanes. They applied their methodology to the terminal of Shanghai Yangshan Port Area in China as a case study.

Cordeau et al. (2015) introduced a heuristic framework embedding a simulation model to manage the routing of multi-trailer systems and straddle carriers in a maritime terminal. They estimate waiting times using discrete-event simulation replications, while the other parameters are fixed in their model. The main contribution of their study is that simulation-based optimization supports the scheduling and resource allocation within the housekeeping process. Although the simulation model alone usually serves as a tool to test and compare a limited number of alternative scenarios, they proposed a simulation-based optimization implemented in Java 7 to make the process an automatic search for an optimal solution.

Zhao & Goodchild (2010) proposed a simulation-based optimization method for the allocation of outbound containers in automated container terminals. The proposed framework was built using Timed-Colored-Petri-Net in the Tecnomatix Plant Simulation 11 simulation software to evaluate the quay crane waiting time of storage plans. They proposed two heuristic optimization approaches; Particle Swarm Optimization and Genetic Algorithm, to form a complete simulation-based optimization method. In a hybrid of simulation and optimization methods, simulation is used to evaluate candidates generated by the optimization procedure while the heuristic optimization is used to search for the best solution to the outbound containers allocation problem.

Güven & Eliiyi (2018) used simulation to compare a proposed mathematical model of stacking policies to determine stacking positions for incoming export, transit, import, and empty containers. In their model, the stacking position for each incoming container is determined when the container arrives at the port. They compared three different policies: (1) random stacking, (2) attribute-based stacking, and (3) relaxation of a 3-tons constraint using a discrete-event simulation model. The simulation model is coded with C#.

Woo & Kim (2011) used a simulation model conducted in eM-plant to evaluate four different space allocation rules. They also compared proposed formulas for determining the size of the space requirement for different arrival patterns of vessels and compositions of container groups in outbound container yards. Guldogan (2010) evaluated the effect of four different storage policies using a discrete-event simulation model. The author separated the problem into two sub-problems and solved these sub-problems using separate decision rules. At the first level, the block number is specified, and, in the second level, the column, row, and tier numbers are determined.

In addition to the studies mentioned above, the simulation method was also used to solve port landside problems such as congestion, waiting, resources idling, and emissions. These works are addressed from either the trucking operator’s perspective or the terminal operator’s perspective. Gracia et al. (2017) developed a simulation model using Arena 5 software of the characteristics of the San Antonio International Terminal in Chile. They analyzed the impact of lane segmentation strategies and booking levels on gate congestion. Azab et al. (2017) developed an integrated appointment system that provides collaboration between container terminals and trucking companies to determine the arrival schedule of trucks using the Flexsim-CT simulation package. In their system, terminal operators first use the simulation model to evaluate the turn-around times of trucks using truck companies’ preferred arrival times. Then, trucking companies schedule their arrival times using a mixed integer programming approach based on the estimated turn-around times from the simulation model. As a last step, terminal operators produce the final appointment times and container schedule using rescheduled appointment times of trucking companies.

Sharif et al. (2011) presented an agent-based simulation model approach to minimize congestion at terminal gates. They used the provided real-time gate congestion information and some simple logic for estimating the expected truck wait time without any collaboration with one another, which is the main difference from the other truck appointment studies. In addition to those studies, there are also studies (e.g., Islam, 2018, and He et al. 2013) evaluating the effect of truck-sharing policies to prevent congestion and make the total cost lower in big mega-containers and among containers.

Some other studies have used simulation models to consider container terminal operations. These are Bielli et al., 2006; Borovits & Ein-Dor, 1975; Bruzzone & Signorile, 1998; Chung et al., 1988; Dekker et al., 2006; Demirci, 2003; Duinkerken et al., 2006; El Sheikh et al., 1987; Gambardella et al., 1998; Grunow et al., 2005; Hartmann, 2004; Hayuth et al., 1994; Kia et al., 2002; Kozan, 1997; Lee et al., 2003; Merkuryev et al., 1998; Nam et al., 2002; Nevins et al., 1998; Ottjes et al., 2006; Parola & Sciomachen, 2005; Petering & Murty, 2006; Pope et al., 1995; Sgouridis et al., 2003; Shabayek & Yeung, 2002; Silberholz et al., 1991; Tahar & Hussain, 2000; Thiers & Janssens, 1998; Yang et al., 2004; Yun & Choi, 1999.

The contents of those simulation studies focus on different problems at different management levels of container terminals. However, none of those articles consider the empty container terminal which has a fundamental difference in operations and layout from container terminals in ports.

Some other simulation studies used simulation models in maritime logistics to solve operational-level decision-making problems, such as berth allocation scheduling for vessels, crane scheduling for discharging and loading containers, and vehicle dispatching (Al-Dhaheri et al., 2016; He et al., 2013; Legato et al., 2009; Legato et al., 2014; Legato et al., 2010; Osorio-Ramírez et al., 2014; Tao & Qiu, 2015; Zeng et al., 2015; Zeng & Yang, 2009).

On the other hand, there are other types of simulation studies focused on developing a simulation package to make the virtual design of a container terminal, rather than just using the simulation package software or coding the programming packages. Sun et al. (2012) designed and developed a general simulation platform named MicroPort composing of three layers: (1) Functions layer; (2) Applications layer; (3) Extensions layer. The functions layer consists of basic simulation functions; random number generators and the discrete-event schedulers. The application layer employs a multi-agent system to represent interactions among various types of resources and operation processes, and the extensions layer represents the user interface. Sun et al.

(2013) extended the previous simulation platform by implementing a geographic information system (GIS) into the extension layer and a multi-agent system (MAS) into the application layer to design and evaluate the operating capacity and efficiency of container terminals of arbitrary shape. While the GIS employed in the extension layer assists users in designing and modifying terminals visually and accurately considering pre-existing geological conditions, the MAS interprets the terminal configuration parameters from the extension layer to the simulation model. Le-Griffin et al. (2011) developed a simulation software using Microsoft Visual C++ to simulate the movements of trucks and equipment within a terminal network under given operational characteristics. They evaluated the impact of intra-terminal truck and equipment movements on the terminal's overall performance at southern California ports.

Overall, a review of literature has concluded that even though there are many outstanding articles used simulation methods in their studies, there has been no study on empty container depot operations and layout design. The summary of the literature about simulation models for container terminal problems is given in Table 2.4.

Table 2.4. Some research contributions to simulation use in container terminal problems

References	Application in terminal	Idea of content	Simulation tools
Petering, 2009		Evaluates different block widths using simulation.	C++
Petering & Murty, 2009		Evaluates different block lengths using simulation.	C++
Petering, 2011		Considers nine problems in strategic and tactical container terminal management, seven of which have not been previously addressed in the literature.	C++
Kemme, 2012		Investigates how the long-run performance of rail-mounted gantry crane storage yards is influenced by strategic decisions on the crane system and the layout of the yard blocks using a simulation model.	Tecnomatix Plant Sim.
Wiese et al., 2009		Validates and evaluates the attained layout configuration proposed by a mixed-integer linear model using a simulation model.	Plant Simulation
Liu et al., 2004	Norfolk International Terminal, USA	Develops and uses simulation models to demonstrate the impact of automation and terminal layout on terminal performance.	MATLAB
Zhou et al., 2016	Shanghai Yangshan Port, China	Proposes a simulation-based optimization framework to obtain a cost-effective and reliable design solutions to the physical layout and equipment deployment strategy of the yard at a mega container terminal.	Arena
Cordeau et al., 2015	Gioia Tauro, Italy	Embeds a simulation model in a local search heuristic to evaluate the impact of different vehicle schedules on congestion and throughput.	Java
Zhao & Goodchild, 2010		Uses simulation to evaluate the use of truck arrival information to reduce container re-handles during the import container retrieval process.	MATLAB
Woo & Kim, 2011		Uses a simulation study to evaluate the performance of some proposed space allocation rules.	eM-plant

2.4. Conclusion

To conclude this chapter, there has been much research considering terminal operations, mainly about the optimization of yard design, storage space allocation, and stacking operations. While some of these focused on a specific case study, some of them used general specifications of terminals based on the authors' knowledge. The use of modeling and simulation was a common method used throughout.

There are three main research gaps identified. First, although many research studies considered the effect of handling tools on container operations efficiency, all handling tools have had the same access capability to blocks. There has been no study which considered a limited access handling tool that has access to blocks only from the side (the first row or the first three rows of a block). Limited access handling tools make the number of relocations greater and this limitation restricts the possible stacking locations for an incoming container.

Second, stochasticity is an inherent characteristic in any container yard. Many studies either used deterministic methods or considered a specific uncertainty in a specific activity. There is a need for tools that can help to analyze the impacts of various uncertainties in container yards. To the best of our knowledge, this study is the first study attempting to evaluate a typical empty container depot from the depot operator's perspective considering dry empty containers. We use Markov chains to model uncertainty in a general way which alleviates the need for application specific discrete-event simulation models.

Although there have been some studies considering container terminals worldwide, few consider empty container depot. However, there is a growing need for both deterministic and stochastic research in the areas of integrated empty container depot operations. To address this gap, this study considers a case study of a depot located in Placilla, Chile near one of the busiest ports in South America. In addition to that, even though some studies compare different layout structures and block sizes for port container terminals, to the best of our knowledge, there is no such study considering empty container layout. This dissertation provides insight for future research by considering a new objective of decreasing the cycle time of top-lifters in the depot. In the literature, the common objectives are minimizing the number of re-marshaling, truck turn-around times, and ship berthing times considering overhead cranes.

The basic aim of this research is to improve the operations in an empty container depot. This research analyzes stacking operations and identifies improvements in layout configurations. The main purpose is to propose layout solutions to improve the overall performance of the depot for both rectangular and non-rectangular container yards. In light of this framework, the main research questions can be summarized as:

1) How does handling equipment affect operations?
2) How do the arrival and retrieval rates affect stacking operations?
3) How does the change of block size affect depot operations?
4) How does the block size (length, depth, and height) along with the depot layout design affect operations?
5) How does the shape of a yard (rectangular and non-rectangular) affect the operations?

3. Relocations in Container Depots for Different Handling Equipment Types: Markov Models

3.1. Abstract

This paper proposes a family of Markov models to analytically characterize the distribution of the number of relocations per retrieval in a container depot. We focus on empty container yards, which, while ubiquitous in worldwide logistics, have rarely been studied in the literature, as most prior research has addressed container movements in ports. There are significantly different aspects of relocations in an empty container versus port side depots. We build on the few models available in the literature by 1) expanding the assumed material handling equipment type (we consider three of the most common types used in practice), and 2) allowing for container arrivals during the retrieval process. These aspects are rarely considered but are particularly relevant for empty container depot practices. We show the effect of various yard configurations and material handling equipment types on the probability distribution of the number of relocations. Our approach can also consider time periods of imbalance by assuming an arrival rate greater than or less than the retrieval rate. The results of these models can be used in planning yard layouts, selecting material handling equipment, and determining staffing and overtime levels. While we focus on empty container yards, the models can be applicable to port side container areas as well, particularly ones in developing countries where overhead yard cranes are not employed as often.

3.2. Introduction

Empty container depots are found throughout the world and the decision problems related to their optimal design and operation are growing in importance as port areas become congested and the land value close to ports increases. These depots serve as inspection, repair, and storage facilities for containers in between shipping activities. However, these depots have not attracted much attention in the literature and best practices for their design and operations tend not to be fully understood. This paper contributes to addressing this gap by proposing an exact analytical model for evaluating the distribution of the number of relocations per container retrieval considering any of the three most commonly used types of handling equipment: top-lifter, reach-stacker, and overhead yard crane. Yard crane is rarely used in empty container depots as these instead use top-lifters (most popular) and reach-stackers. Further, in empty container depots, individual containers are continuously arriving and being picked up. No previous model has studied these alternative material handling methods or considered arrivals taking place during retrievals. Both aspects are especially important for modeling empty container depots. Therefore, this paper is the first to present an exact mathematical model that realistically deals with container relocations in empty container depots. This model can help estimate the amount of labor needed to retrieve containers, choosing the best material handling equipment type, or designing the most effective container yard bay layout. Our purpose is not to compare the superiority of different material handling options but rather to characterize the resulting operational behavior in a yard with a given set of material handling equipment.

Container relocations which are inevitable when containers are stacked in bays. Hence, it is important to be able to accurately and quickly estimate the number of such movements for given yard design. Scholl et al. (2018) posit two main uses for such a procedure: planning and optimization. For planning purposes, an estimate of the number of relocations is needed to evaluate the retrieval time for a crane (or other material handling equipment). Similarly, from the optimization perspective, many designs may need to be assessed to evaluate alternative terminal or depot structures during layout selection (Gupta et al., 2017; Li & Yip, 2013; Wiese et al., 2010) or to find the best storage slot for arriving containers (Zhang et al., 2003).

In the literature, the most cited handling equipment type is the yard crane (also called the rail-mounted gantry crane (RMG), rubber-tired gantry crane (RTG), or overhead bridge crane (OBC)) (Steenken et al., 2004). Yard cranes have access from the overhead direction of a bay and are very efficient but require substantial investment as well as considerable infrastructure, limiting the flexibility of the yard layout. There are other handling tools often used: reach-stackers and top-lifters (also called container forklift trucks or dedicated container handlers). Although these types of handling equipment can be used similarly to yard cranes, they are most common in small and medium-size yards where they are used for container transportation in addition to handling. Top-lifters are often considered interchangeably with reach-stackers in the literature (e.g., Maldonado et al., 2019, Guerra-Olivares et al., 2018), however, they differ substantially from an operational aspect. Top-lifters only have access to the closest row in a bay, while reach-stackers usually can access up to three rows deep with varying height allowance. Both are generally less efficient compared to overhead cranes but are cheaper and allow for more flexible operations.

This paper contributes to the literature by proposing a family of Markov process models for evaluating relocations in container yards. Building on the existing approaches, our model is the first that is suitable for analysis in empty container yards since existing methods do not allow for container handling equipment types other than overhead cranes nor consider container arrivals concurrent with retrievals, both attributes commonly found in empty container depots.

The remainder of the paper is organized as follows. Section 2 summarizes the related literature. The proposed model is presented in Section 3, starting with modeling assumptions and then the Markov process description. Section 4 includes computational results and discusses some of the implications of the proposed model. Finally, Section 5 provides concluding remarks and recommendations for further research.

3.3. Literature Review

Sun & Yin (2017) reviewed 17,163 articles published from 1990 to 2015 and found that logistics planning and control at seaport container terminals is among the most popular transportation research fields. For detailed reviews on container terminals and their operations the reader is referred to Carlo et al., 2013, 2014; Gharehgozli et al., 2016; Günther & Kim, 2006; Liu et al., 2016; Murty et al., 2005; Stahlbock & Voß, 2008; Steenken et al., 2004; Vis & De Koster, 2003.

The container storage unloading problem specifically focuses on container retrievals from a storage area and can also be termed the block relocation problem (BRP) (Caserta et al., 2011; Kim & Hong, 2006; Tanaka & Takii, 2016) or the container relocation problem (CRP) (Forster & Bortfeldt, 2012), see also, Ku & Arthanari, 2016; Lehnfeld & Knust, 2014. We use the term CRP to refer to these kinds of problems. The problem aims to minimize the number of relocations for removing blocking containers when they are retrieved from stacks based on a given retrieval order. The basic version of CRP assumes that the retrieval order of containers is known and there are no arrivals during the retrieval process. This version, usually known as the static CRP, was studied by Kim & Hong (2006), Petering & Hussein (2013), Zehendner et al. (2017), and Zeng et al. (2019), among others. However, it is often not realistic since while some containers in a stack of a yard are retrieved, incoming containers may be added to the same stack concurrently. The version of the CRP allowing arrivals is termed the dynamic container relocation problem (DCRP) (Akyuz & Lee, 2014; Ku & Arthanari, 2016) or the stacking problem (SP) for general blocking problems (e.g. steel plate stacking) (Expósito-Izquierdo et al., 2015; B. I. Kim et al., 2011; Rei & Pedroso, 2013). There have been different approaches to solving the CRP in the literature, both exact (Bacci et al., 2020; Quispe et al., 2018; Tanaka & Mizuno, 2018; Tanaka & Voß, 2019; Zhu et al., 2019) and heuristics, such as a tree search heuristic (Zhang et al., 2016), beam search (Bacci et al., 2019; Ting & Wu, 2017), GRASP (Jovanovic et al., 2019a), genetic algorithm (Ji et al., 2015), ant colony algorithm (Jovanovic et al., 2019b) and greedy algorithm (Jovanovic & Voß, 2014). da Silva Firmino et al. (2019) proposed both exact (A* search algorithm) and heuristic (reactive GRASP) methods to solve a CRP variant that minimizes the crane working time. López-Plata et al. (2017) formulated the block relocation problem as an integer programming model considering the container waiting times. They developed a look ahead heuristic to improve the computational efficiency to tackle medium and large size instances. López-Plata et al. (2019) formulated a new integer model addressing the block relocation problem considering the operating cost. The paper proposed both an exact algorithm (A* search) for small size problems and a heuristic algorithm based on A* search to solve larger problems.

There are only limited approaches in the literature that do not assume a known retrieval sequence. According to Steenken et al. (2004), a container typically spends three to five days in a port side container yard, and there is often uncertainty regarding the time when each container will be retrieved. In empty container depots, a container spends much longer on average in the yard, further complicating knowing when each container will be retrieved (or in what order containers will be retrieved). In the case of a known retrieval order, the main problem is in determining the optimal solution for that specific case. However, if the incoming order is unknown, even evaluating the overall number of relocations for a given policy is challenging.

If the retrieval order is unknown, it is often assumed to be random with a known probability distribution enabling the evaluation of stochastic properties associated with the number of relocations for a particular yard design and retrieval order distribution. Watanabe (1991) proposed an accessibility index method to estimate the number of relocations in container terminals for both straddle carriers and crane systems. De Castilho & Daganzo (1993) proposed general expressions for the expectation and the variance of the number of handling moves for import container terminals with access lanes. They considered two different storage strategies: keeping all stacks the same height and segregating containers based on arrival times, assuming that a container is randomly selected for the next retrieval.

Kim (1997) proposed a model to calculate the expected number of relocations in a container yard where the handling equipment only has access from the top of bays (e.g., overhead cranes). The author was interested in evaluating the expected number of relocations if all containers in a bay are removed in a random order without arrivals. An exact method was proposed coupled with a regression model and an approximated formula for easy estimation, showing that this proposed method improves upon Watanabe (1991)'s approach.

Some authors have investigated the effect of yard layout, such as block size, number of blocks, and type of overhead crane (e.g., Kemme, 2012; Kim et al., 2008; Lee & Kim, 2010a, 2010b, 2013; Petering, 2009; Petering & Murty, 2009; Wiese et al., 2010; Wiese et al., 2011, 2013). Among these, Kim et al. (2008); Lee & Kim (2010b, 2013); Wiese et al. (2010, 2013); and Zaerpour et al. (2019) used Kim (1997)'s proposed approach to evaluate different yard designs and variations of overhead cranes based on the expected number of relocations for block designs.

Kim and Hong (2006) proposed a branch-and-bound algorithm and a heuristic decision rule to find slots for relocated blocks (boxes, pallets, containers, etc.). They considered cases with precedence relationships among groups and individual blocks. They assumed that there was no pre-marshaling and containers of the same category could be retrieved interchangeably to minimize the number of relocations. The authors compared the performance of these two methods and presented numerical results on problems with the largest size of 30 containers for a single bay.

Lee & Lee (2010) proposed a three-phased heuristic to minimize the number of container movements along with the crane working time. They showed that their heuristic found better results than Kim and Hong (2006)'s heuristic and could solve instances up to 10 bays with up to a total of 700 containers. Later, Kim et al. (2016) proposed a heuristic algorithm with the same objective of Lee & Lee (2010). They showed that their algorithm improves upon both Kim and Hong (2006) and Lee & Lee (2010)'s heuristic algorithms to improve the objective function value and reduce computational effort.

Kim et al. (2000) developed a dynamic programming model to determine the optimal storage location for arriving export containers minimizing the number of relocations for loading operations. They also developed a classification procedure to make a decision tree for real-time decisions. Zhao & Goodchild (2010) evaluated how the use of truck arrival information can reduce container relocations during the retrieval process of import containers. They used simulation to model various levels of truck arrival information and bay configurations. Similar to Zhao & Goodchild (2010), Zeng et al. (2019) developed a mathematical model that simultaneously optimizes the pickup sequence and the rehandling plan to minimize the total number of rehandles. They designed five heuristic algorithms to obtain solutions in real-time to improve the computation efficiency.

Imai et al. (2006) developed a mathematical programming model to minimize the estimated number of relocations for a previously defined loading sequence. Saurí & Martín (2011) introduced three new stacking strategies based on the containers' arrival and departure rates and the storage yard characteristics. They developed a mathematical model using a probabilistic distribution function to estimate the number of relocations. Their results showed that the optimal strategy depends on the stacking height and the relationship between vessel headway and container dwell time. Vidovic & Kim (2006) proposed a Markov-chain model and approximating mathematical models for estimating the cycle-time of three-stage material handling systems that consist of a quay crane, a yard crane, and multiple transporters. The approximating models considered probability theory and obtained accurate calculations. They compared their results with simulation study results. There are also a few papers integrating CRP with the space allocation problem for short-term planning in container terminals such as Zhou et al. (2020).

To the best of our knowledge, all of these studies considered only cranes as the handling equipment. In this paper, we relax this assumption by proposing models for the other two commonly used types of equipment: top-lifter and reach-stacker. Note that many port rich countries, such as Chile, often do not use cranes in their port side container yards (Guerra-Olivares et al., 2015; Guerra-Olivares et al., 2018) and most empty container depots use top-lifters. Further, we generalize existing approaches by focusing on characterizing the distribution of the number of relocations, as opposed to just expected values, allowing for estimation of variance, quantiles, etc. Finally, since the proposed model is analytical, it can be readily incorporated in an optimization framework for determining optimal equipment type, staffing, yard layout design, or capital investment.

3.4. Markov Chain Model for Container Handling

An important tool to model stochastic processes is the Markov chain. The main property of the Markov chain is that the next state is independent from the past and only depends on the current state. This property is used to predict the future state of a stochastic process. Since there are many movements (both arrivals and retrievals) in container yards, container movements show stochastic behavior. To predict the container bay configuration state frequency in the long term, container movements can be modeled as a Markov chain model. We use a discrete Markov chain model though using a continuous one would be possible also. Since the bay state changes for every possible event (arrival or retrieval), a Markov chain model can calculate every possible state's probability in the long run. We assume that each event occurs one at a time. For example, if there are multiple container requests, we treat each container retrieval as independent from each other.

We model the system as a Markov chain, where states represent bay configurations, and transitions are triggered by container retrievals or arrivals. The model is exact and analytical, unlike simulation approaches. We develop a different Markov model for each material handling type: crane, top-lifter, and reach-stacker. We consider container arrivals because in an empty container depot this is unavoidable during the retrieval process.

A transition matrix may be represented by a graph in which each node is a state and an arc (i, j) represents the transition probability p_{ij} between the states. Figure 3.1 gives the graphical representation of the transitions between states (possible configurations of a bay). The state transition diagram defines the transitions of possible bay configurations. Note that we assume that the arrival probability λ, and retrieval probability μ are fixed and independent from the state. The model could be readily modified to incorporate unequal arrival and retrieval probabilities.

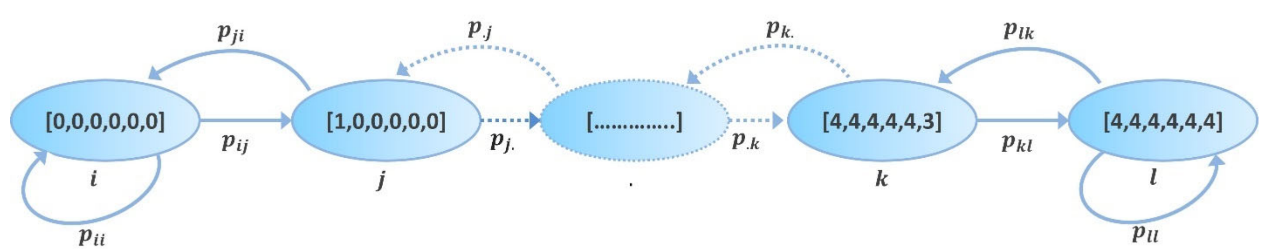


Figure 3.1. Markov chain structure for possible bay configurations

In the following subsections, we describe the assumptions made regarding the container handling process. Assumptions 1 to 9 are general and are made for all three types of equipment. Assumptions C1-C2, T1-T3, and R1-R5 are specific for the crane, top-lifter, and reach-stacker, respectively.

3.4.2. Modeling Assumptions

3.4.2.1. General Model Assumptions

Assumptions 1 to 6 are adapted from Kim (1997). The rest are designed to expand upon the model of Kim (1997) by allowing for container arrivals and different types of handling equipment.

Assumption 1. Containers are stacked in blocks consisting of a rows, b bays, and c tiers (see Figure 3.2). Container blocks are typically composed of 10 to 30 bays.

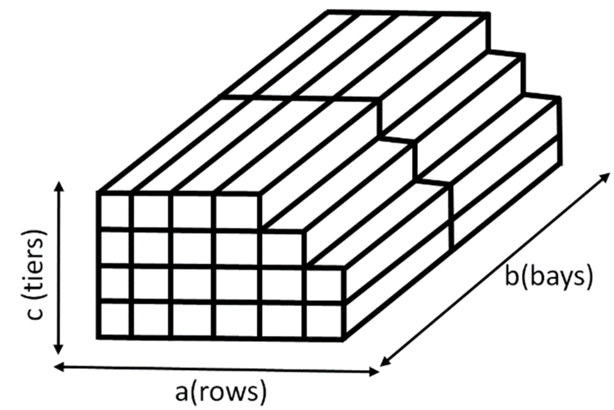


Figure 3.2. Design of a container block

Assumption 2. Different types of containers (20 feet and 40 feet, or Class 1 and Class 2) are not mixed within the same bay. This is generally true in most empty container depots.

Assumption 3. Each relocated container is moved to a different slot in the same bay to access a target container. In other words, there is no relocation between bays. The relocated container is positioned at the lowest possible slot in the bay. If there are multiple available rows at the same height, the relocated container is placed arbitrarily at one of those. This assumption is typical in container yards and means that each bay is modeled separately, i.e., the Markov models proposed below can be constructed for a single bay.

Assumption 4. Containers cannot be placed higher than the number of tiers (c) even when temporarily relocating blocking containers. Blocking containers first need to be retrieved, and then may need to be relocated back after the target container's retrieval so as to not block any empty slots (this is an issue for the top-lifter and reach-stacker which do not have access from the overhead edge of the bay, see Assumptions T3 and R5 below and the corresponding examples).

Assumption 5. Random pick up: each container has an equal probability to be retrieved next (p = 1/ total number of containers in a bay). This assumption is appropriate for empty container depots where containers vary considerably in dwell time at the depot. Depending on the shipping company, the class and size of the container, and the variability of onward demand, any container might be the target for the next pick up.

Assumption 6. The configuration of a bay with a rows can be denoted as $[n_1, n_2, n_3, ..., n_a]$, where each element gives the number of containers in the corresponding row. For example, the configuration of the stack in Figure 3.3 is denoted by [4,3,3,2,1,2]. This can be seen as a consequence of Assumptions 3 and 5, which imply that bays can be modeled separately and there is no need to differentiate between individual containers in each row.

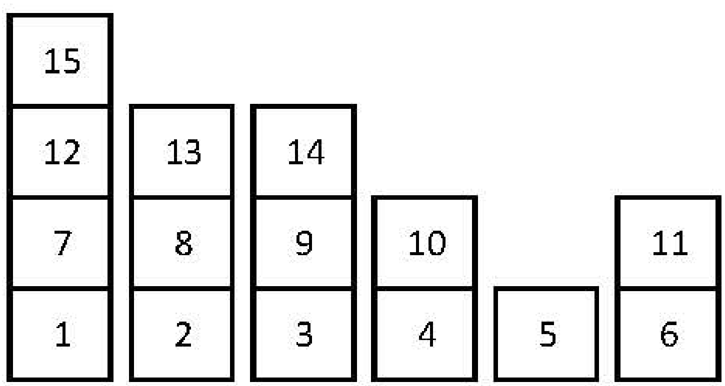


Figure 3.3. An example of bay configuration [4,3,3,2,1,2]

Assumption 7. There may be new container arrivals in between retrievals. We assume that arrival and retrieval requests form an independent Poisson process with constant rates λ and μ respectively, i.e., all events are independent from each other and happen at constant rates. This then means that the probability that an arrival happens before retrieval is $\frac{\lambda}{\lambda+\mu}$, which we will refer to as the *arrival probability* (similarly, $\frac{\mu}{\lambda+\mu}$ gives the probability that a retrieval happens before an arrival). Again, for empty container depots, this assumption is consistent with reality.

Assumption 8. Any incoming container is placed in the lowest available tier.

Assumption 9. If there is a container arrival and the bay is full, container placement is not allowed. Similarly, there can be no retrieval if the bay is empty.

3.4.2.2. Assumptions for the Yard Crane (Top Access) Handling Model

A yard crane access diagram is depicted in Figure 3.4. The following assumptions describe the retrieval process in this case. Note that the model in Kim (1997) was proposed specifically for this type of equipment, and hence some of the assumptions are adapted from there.

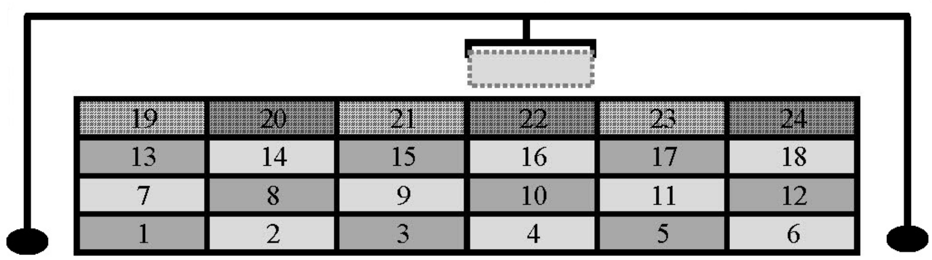


Figure 3.4. Yard crane handling illustration (Top access)

Assumption C1. A yard crane picks up a container from the overhead direction of a bay, thus, in this case, the container row is not relevant. For example, the number of relocations for the configurations [4,3,3,2,1,2] and [4,3,3,2,2,1] are the same for any retrieval.

Assumption C2. If there are multiple available same height slots for a relocated or an incoming container, a container is placed arbitrarily at one of those.

For example, consider a full bay with six rows and four tiers. If a target container is in the bottom slot (tier 1) of any row, three containers above must be relocated to access the target container. Since they are not allowed to be stacked above tier 4 (Assumption 4), they need to be relocated outside of the bay (in the roadway temporarily for example) and then back, resulting in six relocations (three to move blocking containers, and three to return them).

3.4.2.3. Assumptions for the Top-lifter Handling Model

Top-lifter retrieval is shown in Figure 3.5 and Figure 3.6. The following assumptions are made.

Assumption T1. Retrievals and arrivals are processed from the same edge of a bay. Note that container 1 in Figure 3.5 denotes the earliest arrived (longest dwell time) container in a bay and so on. This is typical of stacking strategies at empty container depots.

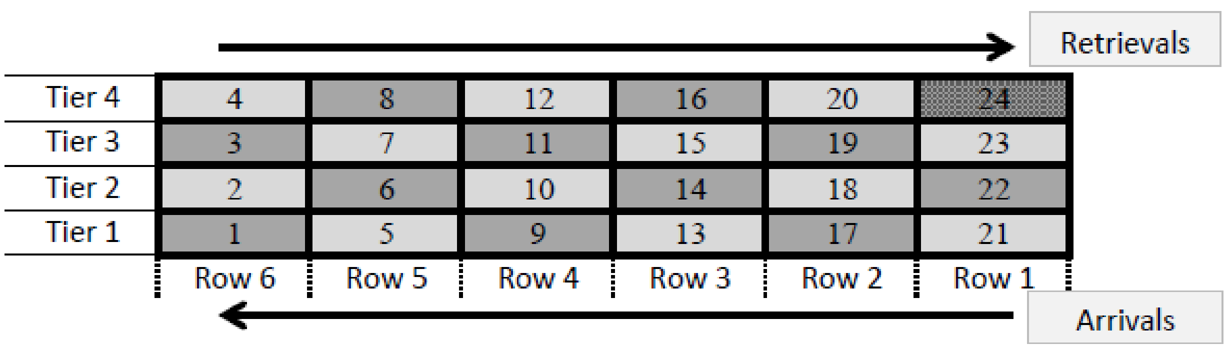


Figure 3.5. Top-lifter access order

Assumption T2. The top-lifter has access only to containers located in slots on the far edge row (right edge or row 1 in Figure 3.6). Thus, all containers located in blocking rows in a bay need to be first relocated to access any of the containers in other rows. Consequently, blocking containers need to be removed from the bay and placed back into the same bay, involving two relocations per container.

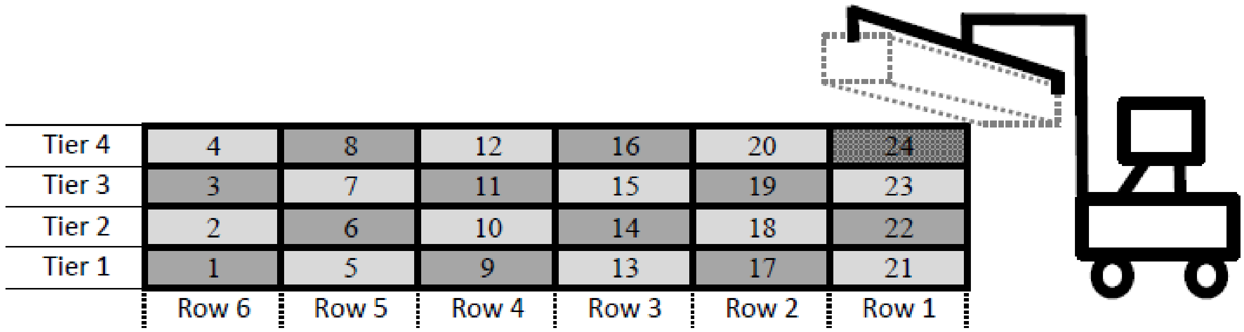


Figure 3.6. Top-lifter handling illustration (far right edge of a bay – first row access)

Assumption T3. All relocated and arriving containers are placed in the easiest slot, which is the top tier of the far edge row (far right row and highest tier in Figure 3.6). As shown in Figure 3.7, if container G arrives at a bay configuration in Figure 3.7 (a) below, it is placed in the slot of Tier 3 and Row 1 (Figure 3.7 (b)). This is consistent with yard operations.

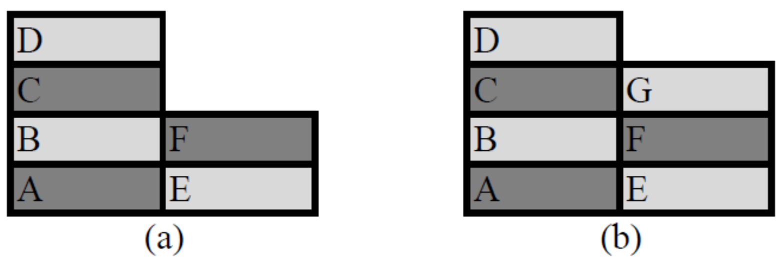


Figure 3.7. Incoming container placement example

3.4.2.4. Assumptions for the Reach-stacker Handling Model

The reach-stacker retrieval diagram is given in Figure 3.8. The assumptions below are made for this case. Note that the specific reach capacity (eight tiers of height and three rows deep) represents a practical case but is not critical for the model. Analogous models can readily be constructed for different types of reach-stackers.

Assumption R1. The reach-stacker can access up to eight tiers of height in the far edge row.

Assumption R2. The reach-stacker can access only three rows from the edge of a bay, with height decreasing by one for each row from the edge, i.e., it can access up to eight, seven, and six tiers for the three edge rows, respectively.

Assumption R3. To retrieve a container, the reach-stacker needs to relocate containers in the blocking rows at the same height as a target container. For example, if the target container (container 14) is in the slot of the sixth tier and third row from the access edge of a bay, all containers located in the sixth tier and above in the first and second rows (containers 22, 23, 24, 30, 31, 32 and, 15 and 16) need to be relocated to reach the target container (see Figure 3.8).

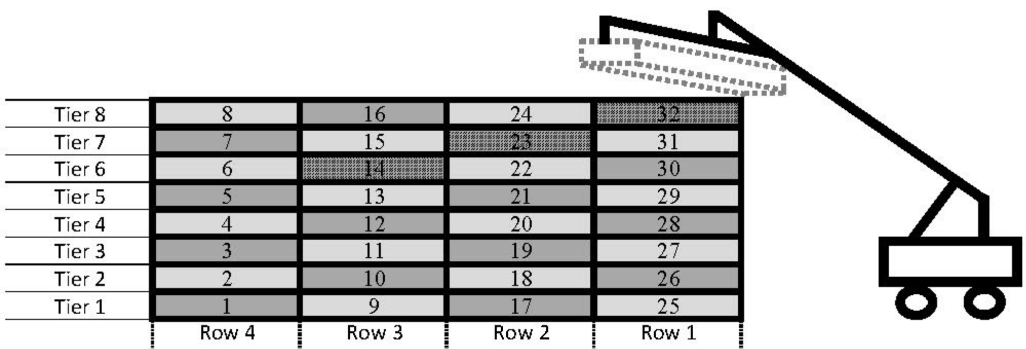


Figure 3.8. Reach-stacker handling illustration (multiple rows access)

Assumption R4. If a target container is in a slot higher than the reach-stacker's access height for a row, all containers located in blocking row/s need to be relocated until the reach-stacker can access the target container. For example, if the target container is in the seventh tier of the fourth row from the access edge in Figure 3.8, the reach-stacker must relocate all containers (container 17-32) located in the first and second rows along with containers 8,15, and 16. Note that the reach-stacker can access up to the seventh tier in the second row without relocating containers below the seventh tier in the first row if the reach-stacker can access up to eight tiers in the first row.

Assumption R5. As with the top-lifter, all relocated containers and arriving containers are placed starting from the non-access edge of a bay, filling all rows up to the maximum height level of a bay design.

As an example, consider configuration [7,7,6,2] in Figure 3.9. If the target container is 12, first, containers 21 and 22 need to be relocated to relocate container 14. After relocating container 14, containers 20, 13, and 19 need to be relocated to access container 12 resulting in a total of six relocations. After target container 12 is retrieved, the relocated containers need to be placed back in the bay filling the slots starting from the slot located in row 3 and tier 5. This process results in a total of 12 relocations.

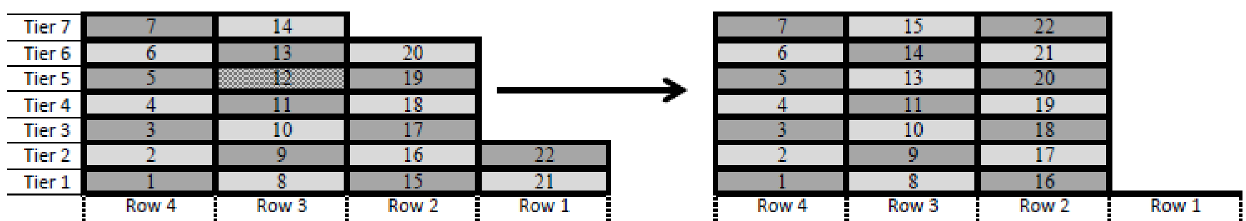


Figure 3.9. Reach-stacker placement illustration

3.4.3. Markov Model Representation for the Number of Relocations

The model for container retrievals and arrivals is constructed as a discrete Markov stochastic process (Markov chain). Next, we formally describe the process for model construction and calculation of the number of relocations. Note that each pair of handling equipment type and bay design (number of tiers and rows) necessitates its own Markov model.

Step 1. Construct the set of states. In this context, the container bay configuration described in Assumption 6 can represent a state, i.e., the set of states is a collection of vectors $[n_1, n_2, \dots, n_a]$, $n_k \in 0 \dots c$ where a and c are the number of rows and tiers, respectively. We will use an index i

to refer to the states, and denote 0 as the state corresponding to an empty bay, and $FULL$ for a full bay (i.e., $n_j = c$ for all j).

Step 2. Identify possible transitions and calculate transition probabilities. Transitions between states happen according to container arrivals and retrievals. Assumptions 5-7 ensure that the Markov property (transitions depend only on the present state and not on the sequence of events that preceded it) is satisfied. In any state other than 0 and $FULL$, the probability that the next transition is due to arrival is as described above, $\frac{\lambda}{\lambda+\mu}$, where λ and μ are the arrival and retrieval rates. Given a particular state and the assumptions corresponding to the handling equipment type, it is straightforward to determine the possible outcomes of either a retrieval or an arrival.

Due to a large number of states (and corresponding transitions), we will not describe the calculation of each individual transition probability separately and instead will use one specific state as an example. Consider the bay given in Figure 3.3 for a yard crane, and the bay configuration [4,3,3,2,1,2] (a bay with six rows and four tiers). (Recall from Assumption C1, configurations [4,3,3,2,1,2] and [4,3,3,2,2,1] result in an equal number of relocations for the yard crane.) Transitions happen when there is either a new arrival or retrieval. Table 3.1 summarizes the possible transitions due to retrievals with the corresponding probabilities and the number of relocations. Note that here we consider probabilities conditioned on the next transition being caused by a container retrieval. For example, the transition from [4,3,3,2,2,1] to [4,3,3,2,2,0] happens with conditional probability 5/15, since there are 15 containers in the starting configuration (each can be retrieved with the same probability) and five of those (Containers 2, 3, 4, 5, or 6 in Figure 3.3) lead to the configuration [4,3,3,2,2,0]. Considering that a retrieval happens with probability $\frac{\mu}{\lambda+\mu}$, the transition probability for transition [4,3,3,2,2,1] to [4,3,3,2,2,0] is $\frac{5\mu}{15(\lambda+\mu)}$. For the same initial state, an arriving container would cause a transition to state [4,3,3,2,2,2] (see

Assumption 8), with corresponding transition probability $\frac{\lambda}{\lambda+\mu}$. The rest of the states can be processed in the same manner.

While the example above is for the case of a crane, an analogous procedure can be used for constructing Markov models for a top-lifter and a reach-stacker. For example, consider configuration [4,2,0,0,0,0] in Figure 3.7(a) with six containers in a bay of six rows and four tiers for a top-lifter. Whichever container (A, B, C, D, E, or F) is retrieved from the bay configuration of [4,2,0,0,0,0], the next configuration will be [4,1,0,0,0,0]. Similarly, if there is an arrival, the next bay configuration will be [4,3,0,0,0,0]. The rest of the transition matrix for a top-lifter and the matrix for a reach-stacker can be constructed in the same manner.

Step 3. Construct transition matrix *P*. Putting together the probabilities for all states we can then construct the transition matrix. For the example above, there are 210 possible states for a bay of six rows and four tiers resulting in a 210 by 210 transition probability matrix.

Step 4. Calculate limiting probabilities $\boldsymbol{\pi}$. It is easy to see that the constructed Markov chain is ergodic for all bay designs and equipment types, hence, there exists a vector of limiting (steady-state) probabilities π, which can be calculated with the standard steady-state equilibrium equation $\pi P = \pi$ with the constraint $\sum_i \pi_i = 1$.

Step 5. Calculate the desired relocation statistics. Each retrieval results in several container relocations. As with Step 2, for any particular state transition and handling equipment type, it is straightforward to determine the values for the number of relocations (see the last column of Table 3.1 for the same example used in Step 2). Note that a transition from a given state may result in a different number of relocations, depending on which container is picked up. For state $i = [n_1, \ldots, n_a]$ we will denote x_k^i as the number of relocations if container k is retrieved, where $k =$

$1, \ldots \sum_j n_j$. Knowing the limiting probabilities, we can then calculate all required statistics for the long-run number of relocations. For example, its average is given by

$$E[\text{number of relocations per retrieval}] = \sum_{i:[n_1,\ldots,n_a]} \pi_i \sum_{k=1}^{\sum_j n_j} \frac{x_k^i}{\sum_j n_j}. \quad (3.1)$$

Standard deviation, quantiles, or other statistics or moments can be calculated similarly.

Table 3.1. Possible configurations after a retrieval from a bay [4,3,3,2,2,1]

Resulting configuration	Conditional Probability	Container no. picked up (corresponding # of relocations)
[4,3,3,2,2,0]	5/15	2(2), 3(2), 4(1), 5(0), 6(1)
[4,3,3,2,1,1]	2/15	10(0), 11(0)
[4,3,2,2,2,1]	4/15	8(1), 9(1), 13(0), 14(0)
[3,3,3,3,2,0]	1/15	1(3)
[3,3,3,2,2,1]	2/15	7(2), 15(0)
[3,3,2,2,2,2]	1/15	12(1)

3.5. Analytical Results for the Markov Models

The proposed Markov models can be used as decision support tools for comparing different container handling equipment types as well as alternative bay designs. Additionally, the models' outcomes can be used to choose proper staffing levels and estimate utilization levels for operations at various percentiles of the activity distribution. Note that the model is analytical, so it finds exact (not approximated), essentially closed form, values for container relocation statistics. To illustrate this approach, we next compare the performance of the three equipment types for two typical bay capacities with a different number of rows. The procedure described in the previous section was implemented in Matlab R2019b, and all experiments were conducted on a PC with Intel Xeon E5-1650 v2 3.5 GHz CPU with 64 GB RAM. The corresponding code is available at https://github.com/ezk0013/ExpectedNumberofRelocation.

Figure 3.10 and Figure 3.11 show results for the average number of relocations for the cases of bays with the capacity of either 12 or 20 containers for varying number of rows. Here, we assume that arrival and retrieval rates are equal. We can conclude that the top-lifter is dominated by both the crane and the reach-stacker for all bay designs considering relocations, as can be expected. In fact, since all blocking containers must be relocated to access a target container using the top-lifter, the overall expected number of relocations is the same for any bay design with the same capacity.

The numbers of relocations for the crane and the reach-stacker vary with different depth and height designs even though the bay capacity is fixed. In the trivial case, when the number of rows is the same as the bay capacity (i.e., a height of one tier), the reach-stacker and top-lifter are equivalent. Since the crane can access containers from overhead, it achieves the lowest expected number of relocations compared to the other two equipment types. The expected number of relocations decreases when the number of rows increases for the crane because it corresponds to the lower tier height for the same capacity. For the reach-stacker, relocations first decrease, and then increase as the number of rows increases. Since the reach-stacker has access to the first three rows (8^{th} tier, 7^{th} tier, and 6^{th} tier), the number of relocations decreases when the number of rows increases, up to three rows, then increases since the containers in blocking rows must be relocated to reach the target container access. (This behavior is observed only if the maximum number of tiers of a bay design is less than the reach-stacker's access height level (6-tiers in our example) for the 3^{rd} row.) This behavior is similar for both 12- and 20-container bays. Note that we do not show the number of relocations of the 2-row bay design for the reach-stacker because we assume that the reach-stacker can access only up to 8-tiers height.

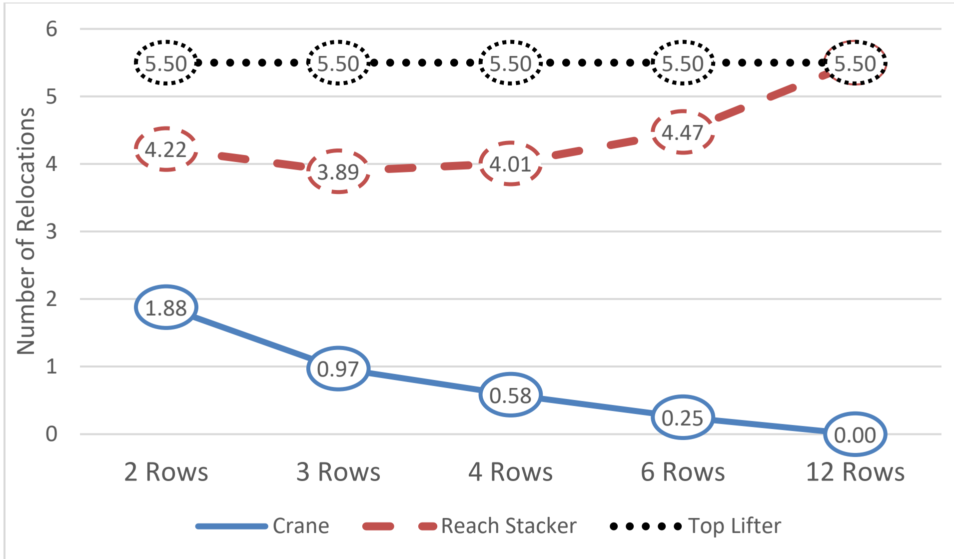


Figure 3.10. The expected number of relocations for a bay of 12 containers

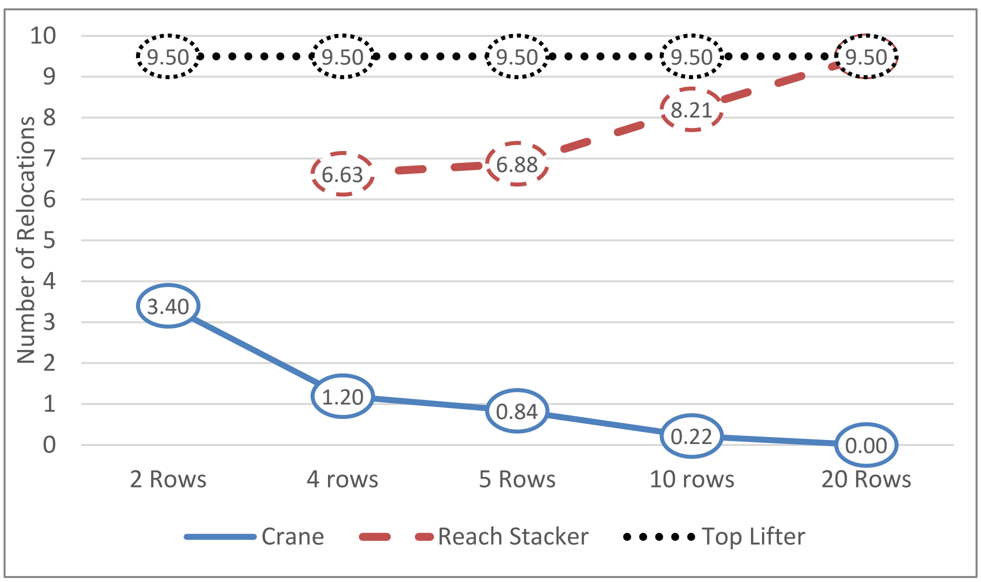


Figure 3.11. The expected number of relocations for a bay of 20 containers

We now demonstrate how the expected number of relocations changes for different bay configurations and changing bay capacity. Figure 3.12 depicts the cases of 5 to 8 tiers and 1 to 9 rows (capacity from $5 \times 1 = 5$ to $8 \times 9 = 45$). As can be expected, when the depth or height increases (with constant height or depth, respectively), the top-lifter and the reach-stacker require more container relocations. However, when the depth of a bay increases with a fixed height, crane relocations slightly decrease even though bay capacity increases. Since the crane has overhead access to a bay, increasing the depth for the same height decreases the probability of each container retrieval (because the total number of containers is greater). When the height increases with a constant depth, the expected number of relocations increases for each type of handling equipment, which is intuitive as there are more possible blocking containers in the system. Note also that as the height increases to 8 tiers the difference between the top-lifter and the reach-stacker decreases.

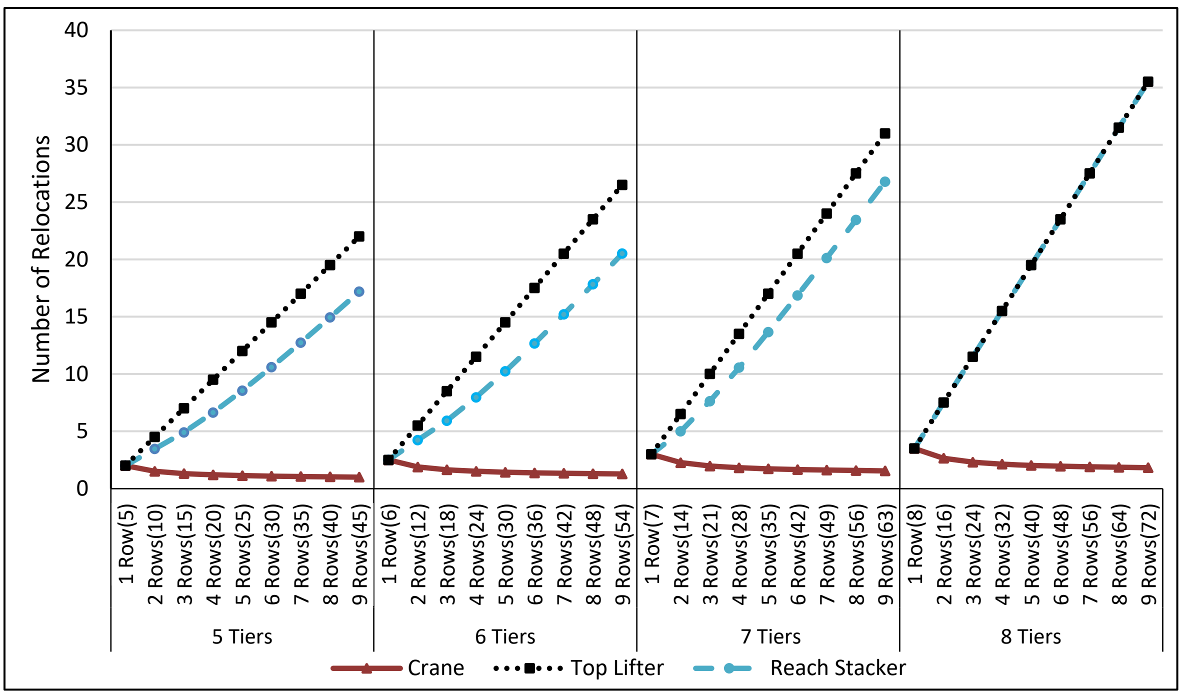


Figure 3.12. The expected number of relocations for different depth and height bay designs for different handling equipment and capacities (shown in parentheses on the *x*-axis). Note that the top-lifter and the reach-stacker have equal numbers for the 8-tiers design.

Observe that the proposed model characterizes the whole distribution of the number of relocations, allowing for the calculation of any corresponding statistic, e.g., standard deviation (SD). Note that this is not the case (or at least not as easily achievable) for some of the models previously proposed in the literature. To demonstrate this property of the models, we calculated the first, second, and third quartiles. From the box and whisker plots (Figure 3.13) and quartiles tables in Appendix A (A3, A6, and A9), we can conclude the strong right-hand skewness of the distributions. This is not surprising as the number of relocations is lower bounded by zero. We can also observe that the minimum, maximum, median, first quartile, and third quartile values are the same for different depth (number of rows) bay designs with the same height (number of tiers) bay design for yard cranes. For example, 4 rows and 5 tiers have the same statistical values as 5 rows and 5 tiers. These variabilities of the values for the number of relocations can be helpful for managers and planners in resource allocation, shift planning, and overtime estimations. This is the first paper to put forth a closed-form approach to calculating these moments and percentiles, and these can be used along with expected values to better inform decisions concerning yard planning and operations. This is especially important in empty container depots as many experience strong seasonality and expected value behavior may differ considerably from how the operations are actually realized over the course of time.

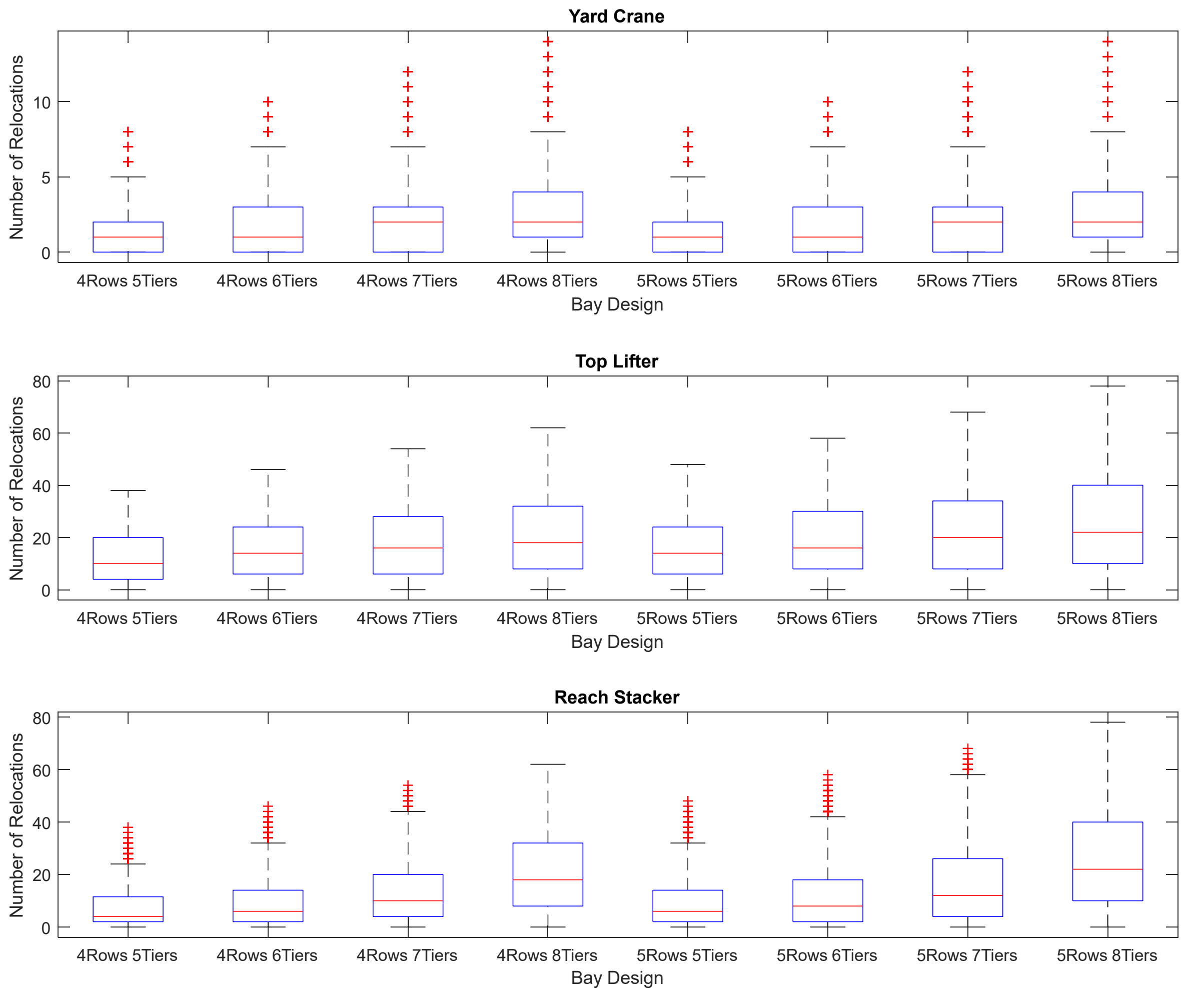


Figure 3.13. Box and whisker plots for the number of relocations for different depth and height bay designs for different handling equipment

Finally, observe that the ratio between the retrieval and arrival rates, or equivalently arrival probability (see Assumption 7), is an important parameter in our models. Figure 3.14 and Table A10 in Appendix A report the average number of relocations for the three equipment types for a bay of 4 rows and 6 tiers, as the arrival probability changes from 0 to 1 (this corresponds to retrieval probability changing from 1 to 0). Naturally, higher arrival rates always correspond to (probabilistically) more containers in the bay, therefore the average number of relocations monotonically increases. If the arrival probability is close to zero, then in the long run the bay spends most of the time empty, and usually, a retrieval does not require any blocking container relocations (i.e., close to 0 average number of relocations). On the other hand, an arrival probability close to 1 results in nearly full bays most of the time and a greater number of relocations. It is interesting to note that this dependency is highly nonlinear, with the average number of relocations relatively flat as arrival probability changes from 0 to 0.4 and from 0.6 to 1, while undergoing very rapid growth in between.

It is worth noting that an important limitation of the model can arise for larger-sized bays due to the curse of dimensionality. For example, a bay with 12 rows and 8 tiers results in 125,970 states. For this reason, as seen in Appendix A, calculations for four of the largest bay configurations resulted in an "out of memory error". However, in practice, bays this large are rare.

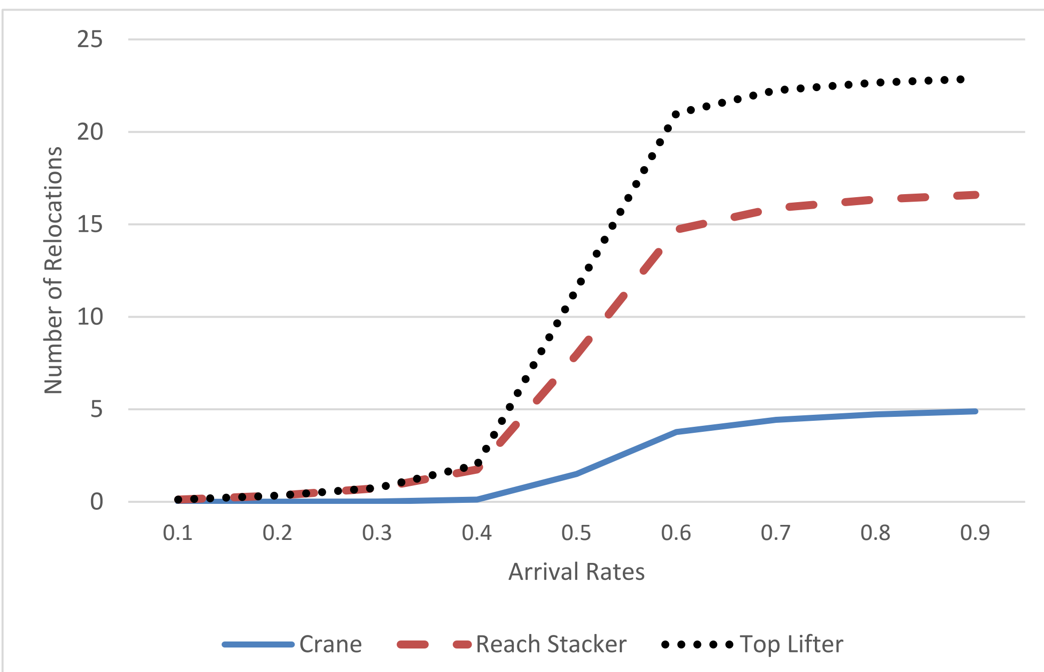


Figure 3.14. The number of relocations for a bay of 4 rows and 6 tiers for different handling equipment with different arrival probabilities

3.6. Conclusions and Prospects for Future Work

Container terminal yard design and handling equipment selection are important strategic decisions in maritime logistics especially given the increase in container transportation volume and lack of land space. The models herein are applicable to any container yard but we focus particularly on empty container depots which have not been well addressed in the literature. Many material handling activities in container yards consist of relocating blocking containers in order to reach the target ones. In this paper, we propose novel Markov models to characterize the distribution of the number of relocations for a random pick up while considering simultaneous container arrivals for three standard types of container handling equipment. These models are the first to consider different material handling equipment, and arrivals occurring during the retrieval process, both of which are crucial in empty container depots. The models allow for analysis given different bay configurations and material handling equipment types both in terms of the expected value and stochastic distribution of the number of container relocations. Note that the models are both exact (that is, not heuristics) and are computationally tractable for all but the larger bay dimensions. Arrival rate (or alternatively retrieval rate) can take any value so that periods of imbalance can also be considered.

We demonstrate the performance of the approach by calculating the expected values, standard deviations, and quartiles of relocations for a random pick up for a set of bay designs (heights and depths) and three handling equipment types. The comparison of the three commonly used handling equipment types shows that the lowest expected number of relocations occurs for yard cranes, as expected. Even though most port yards use yard cranes, port yards in developing countries and most empty container depots instead use top-lifters or reach-stackers. These have a higher expected number of relocations, with the predominantly used top-lifter requiring the most relocations.

Besides, we can use the model to calculate any other moments and the percentiles of the distributions. We observe that the distribution of the number of relocations for a random pick up is quite disperse with a strong positive skewness.

With this model, a cost analysis could be carried out in a future study aimed at choosing material handling equipment and yard design, balancing investment with operating costs. Relocation time can be evaluated using the model proposed in this paper in addition to the number of relocations. Relocation time estimation is an important variable for truck turnaround and cycle times which affect ship berthing time. It is worth emphasizing, that while we explicitly designed the model to describe top-lifters, reach-stackers, and yard cranes, similar models could be developed for other equipment types. Finally, re-marshaling could be incorporated and the Markov models adapted accordingly.

4. Expected Relocation and Placement Times for Top-lifters

4.1. Abstract

In this chapter, we calculate the expected relocation and placement times for various bay designs based on the previous chapter. The calculated time metrics are used in the subsequent chapter for the proposed layout optimization model. Even though we consider three different common handling equipment in container yards (yard crane, reach stacker, and top-lifter) in the previous chapter, we only focus on the top-lifter (TL) handling in this chapter. Since the TL is the most common handling equipment in empty container yards and we have an available time study for top-lifter handling, we calculate the TL handling retrieval and placement times. However, the proposed Markov model can be implemented with other handling equipment with the available data.

4.2. Introduction

The main target of this dissertation is proposing an analytical model for layout optimization in a container yard operated by a TL with the main focus on empty container yards. For this purpose, we calculate the retrieval and placement times which are two important activities that keep the TL busy. We calculate the expected times of retrieval and placement for various bay designs in this chapter to be used for layout optimization in the next chapter.

Recall the formula (4.1) used in the previous chapter to calculate the expected number of relocations for various bay designs per retrieval where $i = [n_1, \ldots, n_a]$ refers to all possible configurations as a result of container arrivals and retrievals. x_t^i denotes the number of relocations if container t is retrieved, where $t = 1, \ldots \sum_j n_j$. After calculating the limiting (steady-state) probabilities π, we calculate all required statistics for the long-run number of relocations.

$$E[\text{number of relocations per retrieval}] = \sum_{i:[n_1,\ldots,n_a]} \pi_i \sum_{t=1}^{\sum_j n_j} \frac{x_t^i}{\sum_j n_j} \quad (4.1)$$

We will use retrieval time rt_t^i when target container t is retrieved and placement time pt_t^i when container t is placed, instead of using the number of relocations x_t^i in equation (4.1) so we can calculate the expected time per retrieval or placement. Note that retrieval time rt_t^i includes relocation time rlt_b^i that spent by TL for relocating blocking containers to reach the target container. We introduce the following notation to describe the procedures to calculate the expected time per retrieval and per placement for various bay designs using equation (4.1). The notation for retrieval and placement time calculations is as follows (Table 4.1):

Table 4.1. Notation for retrieval and placement time calculation

Notation	**Description**
r	the number of rows (i.e., depth) in a bay
r_b	the current row number of the blocking container (before relocation)
r_b'	the new row number of the blocking container (after relocation)
t_b	the current tier number of the blocking container (before relocation)
t_b'	the new tier number of the blocking container (after relocation)
r_t	the row number of the target container
t_t	the tier number of the target container
v	the average velocity in meters per second of the TL on a driving lane
st	the stacking time of a relocated container after a target container retrieval
ut	the unstacking time of a relocated container to reach a target container
dt	the driving time of a TL in a bay (excluding the driving time in driving lanes)
rlt_b^i	the relocation time of a blocking container b to retrieve a target container in a given state i
rt_t^i	the retrieval time of a target container t in a given state i
RT	the expected retrieval time per retrieval
pt_t^i	the placement time of an incoming container t in a given state i
PT	the expected placement time per placement of an incoming container for a bay design

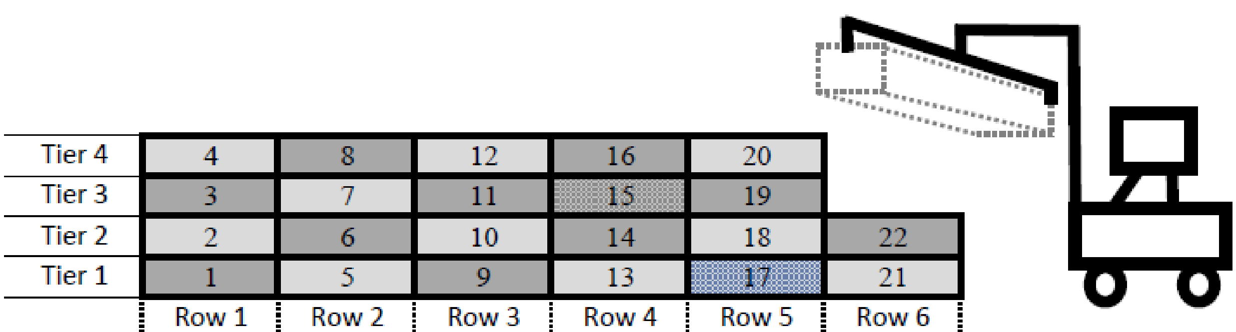


Figure 4.1. Notation example

We demonstrate the notation using the example given in Figure 4.1. Consider a target container 15 in the slot of row 4 and tier 3 in a bay design of 6 rows and 4 tiers which has 22 containers with bay configuration $i = [4,4,4,4,4,2]$. We want to calculate the relocation time for the blocking container 17 in row 5 and tier 1 along with the retrieval time of container 15 in row 4 and tier 3. Corresponding values to calculate the time metrics are:

$$r = 6, r_b = 5, r_b' = 4, t_b = 1, t_b' = 4, r_t = 4, \text{and } t_t = 3 \quad (4.2)$$

Since we already defined the steps for the Markov chain in the previous chapter, we will not describe all calculations separately, and instead will explain how to find the retrieval time of a container rt_t^i along with the relocation time rlt_b^i, and the placement time of a container pt_t^i.

4.3. Expected Retrieval Time per Retrieval for a Bay Design

In this section, we show the calculation of the expected retrieval time per retrieval RT for various bay designs. The calculated retrieval time also involves the relocation time of blocking containers. Thus, we first calculate the relocation time for a blocking container followed by the retrieval time calculation.

After calculating the total relocation time to access a target container, we sum this and the actual retrieval time of the target container once the blocking containers are removed. This total value is used to find the expected retrieval time per container retrieval to evaluate layout designs in the next chapter.

We calculate the relocation time for a blocking container as the sum of both the handling time and the driving time. The handling time is calculated based on a regression model built by the research group at the Pontifical Catholic University of Valparaíso (PUCV) in Chile (Bravo, 2018). The driving time is calculated based on the TL driving distance from/to the container row to/from the driving lane, and the speed of the TL. Both the driving time and the handling time calculations are explained below.

4.3.1. Driving Time of a Blocking Container Relocation to Access a Target Container

We assume that the TL needs to drive from the edge of a bay on the driving lane side to retrieve a blocking container and drive back to the driving lane. After retrieving the blocking container, the TL needs to temporarily place it outside of a bay to reach a target container. We term the time spent by TL horizontally to retrieve and stack a blocking container "driving time".

We assume that the TL has an average velocity v of $2.22\ m/s$ ($8\ km/h$) whether it is carrying a container or not. However, our calculation method is applicable for unequal loaded and unloaded TL speeds. We assume the standard container width is 8 $feet$ (2.438 m) which is the distance that TL drives per block row from/to the edge of a bay. Using the given parameters, we calculate the TL driving time per container (row) as:

$$\text{TL driving time per container (row)} = \frac{2.438\ m}{2.22\ m/s} = 1.0971\ s\ per\ container \tag{4.3}$$

The distance that the TL needs to drive to reach the blocking container and carry it to the outside of the bay is calculated as:

$$\text{TL driving distance to retrieve a blocking container} = 2 * (r - r_b) \tag{4.4}$$

Note that we use a coefficient of 2 since the TL needs to drive to reach a container row and to drive the same distance back to the driving lane. It needs to place the blocking container outside of the bay after retrieving it. We assume that there is one pick-up per blocking container.

Similarly, the distance that the TL needs to drive to place the temporarily relocated blocking container back to the bay after the target container retrieval is calculated as:

$$\text{TL driving distance to place a blocking container} = 2 * (r - r_b') \tag{4.5}$$

Note that the blocking container's row could change to a new row r_b' after the target container retrieval since the target container slot becomes available. Thus, if the blocking container is in the first tier, its new row r_b' is updated as the one row behind (left in Figure 4.1) the current row which is $r_b - 1$. Otherwise, the blocking container new row r_b' stays same as current row r_b. Thus, the driving time that TL needs to relocate a blocking container is calculated as:

$$dt = 1.0971\, s * 2\, [(r - r_b) + (r - r_b')] \tag{4.6}$$

4.3.2. Handling Time of a Blocking Container Relocation to Access a Target Container

The handling time of the relocation of a blocking container to retrieve a target container is the sum of both the unstacking time and the stacking time of that blocking container. Once again, the blocking container first needs to be carried outside of a bay. We term this process "unstacking" and the time spent vertically to access and retrieve the container as "unstacking time" or ut. We calculate the unstacking time using the regression model by Bravo (2018) as follows:

$$ut = 0.7 * {t_b}^2 + 1.1 * t_b + 10.8 \tag{4.7}$$

Similarly, the TL needs to stack (place) the blocking container back to the bay after the target container retrieval. We call this process "stacking" and the time spent vertically to place the container in a slot is termed "stacking time" or st. We calculate the stacking time using the regression model by Bravo (2018) as follows:

$$st = 1.7 * {t_b'}^2 - 4.2 * t_b' + 13.7 \tag{4.8}$$

The height of the blocking container (i.e. tier number) changes after the target container retrieval. The updated tier is one tier below the relocated container's current tier except if the blocking container is in the first tier. If the relocated container is in the first tier, the relocated container is placed back in the top tier of the row behind (left) of its current row.

4.3.3. Relocation Time of a Blocking Container

After finding the driving time dt, the unstacking time ut, and the stacking time st for a blocking container to reach the target container, we calculate the relocation time of a blocking container as the sum of these three times.

$$rlt_b^i = dt + ut + st \tag{4.9}$$

Consider the same example as in Figure 4.1. The target container 15 is located in row 4 and tier 3 in the bay design of 6 rows and 4 tiers which has 22 containers (a configuration of [4,4,4,4,4,2]). The TL needs to relocate seven blocking containers (16-22) to retrieve the target container 15. We need to find the relocation time for each blocking container (16-22) to find the expected relocation time for the target container 15. The relocation time for container 17 $rlt_{17}^{i=[4,4,4,4,4,2]}$ in the slot of row 5 and tier 1 to reach the target container 15 is shown as an example. We calculate the $rlt_{17}^{i=[4,4,4,4,4,2]}$ as:

$$\begin{aligned} dt &= 1.0971 * 2\,[(6-5) + (6-4)] = 6.58\,s \\ ut &= 0.7 * 1^2 + 1.1 * 1 + 10.8 = 12.6\,s \\ st &= 1.7 * 4^2 - 4.2 * 4 + 13.7 = 24.1\,s \\ rlt_{17}^{i=[4,4,4,4,4,2]} &= dt + ut + st = 43.28\text{ s} \end{aligned} \tag{4.10}$$

dt in equation (4.10) shows the TL driving time to relocate blocking container 17. ut shows the TL time to unstack blocking container 17 to reach target container 15. st shows the time TL to stack blocking container 17 back to row 4 and tier 4 after the target container 15 retrieval.

4.3.4. Total Relocation Time for a Target Container

After we calculate the relocation time for each blocking container to retrieve the target container, we sum all relocation times of all blocking containers to find the total relocation time for a target container. Using the example given in Figure 4.1, we can show the relocation time calculation for target container 15 as:

$$\begin{gathered} Total\ relocation\ time\ for\ a\ target\ container\ 15 = \sum_{b=16}^{22} rlt_b^i \\ Blocking\ containers\ for\ the\ target\ container\ 15 \\ = \{16,17,18,19,20,21,22\} \end{gathered} \tag{4.11}$$

4.3.5. Retrieval Time of a Target Container

In addition to the total relocation time of all blocking containers of a target container, we include the retrieval time of the target container to calculate the expected retrieval time per retrieval for each bay design. We calculate the retrieval time of a target container as:

$$rt_t^i = [1.0971\, s * 2\,(r - r_t)] + [0.7 * {t_t}^2 + 1.1 * t_t + 10.8] \tag{4.12}$$

The first square bracket of the equation (4.12) refers to the time spent by the TL to drive to the target container row from the driving lane and carry it back to the driving lane to load onto a truck. In other words, the time spent by the TL horizontally to retrieve the target container. The second square bracket refers to the time that the TL spends to retrieve the target container from its tier, in other words, the time spent vertically to retrieve the target container from its slot. Note that we only use the one way driving time part of the equation (4.6) and the unstacking time ut (equation (4.7)) that are used to calculate a blocking container relocation time (equation (4.10)) since this is for a retrieval.

4.3.6. Expected Retrieval Time for a Bay Design

After finding the retrieval time along with the total relocation for each target container for each possible state of a certain bay design (i.e., depth and height), we generate an equation for the expected retrieval time per retrieval for various bay designs based on the equation (4.1) as:

$$RT = \sum_{i:[n_1,\ldots,n_a]} \pi_i \sum_{t=1}^{\sum_j n_j} \frac{rt_t^i + \sum_b rlt_b^i}{\sum_j n_j} \tag{4.13}$$

Note that the second summation part of equation (4.13) refers to the expected retrieval time for each possible bay configuration (state) of a certain bay design.

The pseudo-code of the expected retrieval time calculation algorithm is given below.

Pseudo-code for the for the expected retrieval time calculation algorithm

```
Find all possible bay configurations (states) for a bay design (depth and height)
Find steady-state probabilities for each possible bay configuration (state)
    FOR ALL possible bay configurations for a bay design
        FOR ALL containers (as a target container) in a bay configuration (state)
            Find all blocking containers
                FOR ALL blocking containers for a target container
                    Calculate relocation time of a blocking container
                END FOR
            Add retrieval time of a target container
        END FOR
        Find the expected retrieval time for a bay configuration
    END FOR
Calculate the expected retrieval time per retrieval for a bay design
```

Figure 4.2. Pseudo-code for the expected retrieval time calculation

4.4. Expected Placement Time per Container Arrival for a Bay Design

We calculate the placement times for various bay designs in this section. We use the term "placement" to distinguish incoming container stacking from the term "stacking" we use for a relocated container. We term the time spent both vertically and horizontally to place an incoming container in its assigned slot as "placement time" or pt_t^i. We calculate the placement time similarly to the calculation of the retrieval time discussed in the previous section. Since we assume that both relocated and arriving containers are placed in the easiest slot, which is located at the top tier of the far edge row, there is no relocation during container placement (see Assumption T3 in the previous chapter).

We calculate the placement time for a container as:

$$pt_t^i = [1.0971\, s * 2\, (r - r_t)] + [1.7 * t_t{}^2 - 4.2 * t_t + 13.7] \tag{4.14}$$

The first square bracket in the equation (4.14) refers to the time that TL spends to carry an incoming container to the assigned container row from a driving lane and driving back to the driving lane after unloading the container. The second square bracket in equation (4.14) refers to the time that TL spends to place (stack) the incoming container in its tier, in other words, the time spent for vertical movement by the TL to stack the incoming container in its slot. Note that we only use the one-way driving time part of the equation (4.6) and the stacking time st (equation (4.8)) that are used to calculate a blocking container relocation time (equation (4.10)) since this is for placement and there is no blocking container to deal with.

After finding the placement time for a container arrival for each possible configuration (state) of a bay design (i.e., depth and height), we generate an equation for the expected placement time per placement based on the equation (4.1) as:

$$PT = \sum_{i:[n_1,\dots,n_a]} \pi_i \, \frac{pt_t^i}{\sum_j n_j} \tag{4.15}$$

Note that there is only one possible placement for each possible state because of the assumption we make that the arriving container is placed in the easiest slot. Since the TL can access only the edge row on the side of the driving lane, there is one easiest slot which is the top available tier at the edge of the bay.

4.5. Analytical Results

The generated models can be used to calculate the expected retrieval and placement times for decision support tools using variable driving, stacking, and unstacking speeds and also for comparing different bay designs operated by TLs. To illustrate this approach, we show the TL placement and retrieval times for two typical bay capacities with different numbers of rows.

Figure 4.3 and Figure 4.4 show results for the average times of retrieval and placement of a TL for the cases of bays with a capacity of either 12 or 20 containers for varying numbers of rows. We assume that arrival and retrieval rates are equal.

We can conclude that both retrieval and placement times decrease when the depth and height are in their middle levels, as can be expected. Both retrieval and placement times are the lowest when the bay design is 4 rows and 3 tiers for a 12 container capacity and 5 rows and 4 tiers for a 20 container capacity. Another conclusion we can make is that stacking deeper instead of higher is more time-efficient using an average speed of 8 km/h and the regression models of stacking and unstacking times by Bravo (2018) for TLs operated container yards.

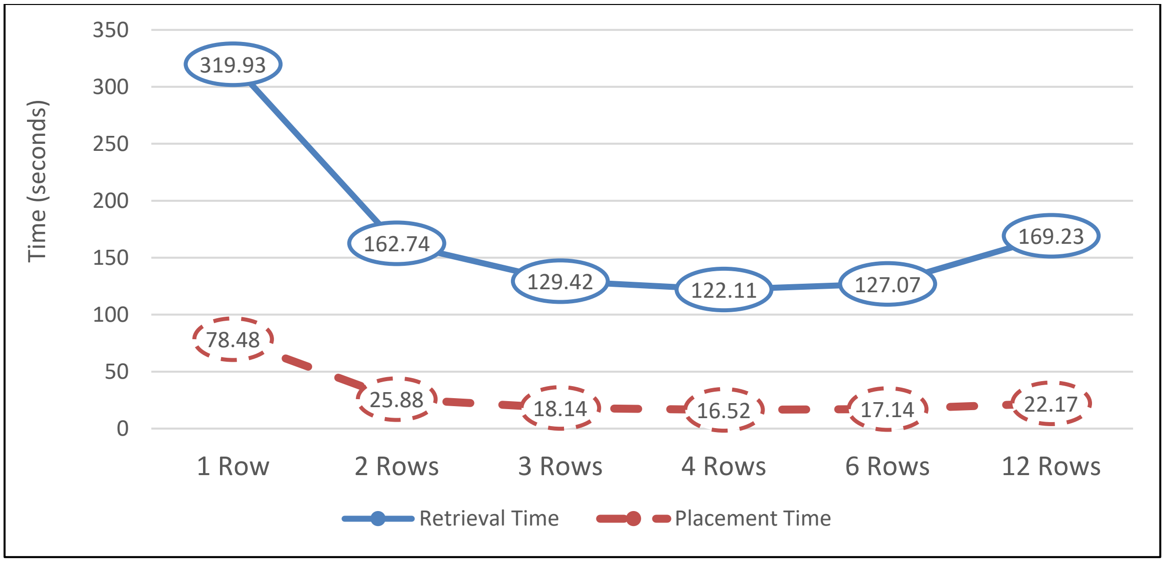


Figure 4.3. The expected time metrics for a bay of 12 containers

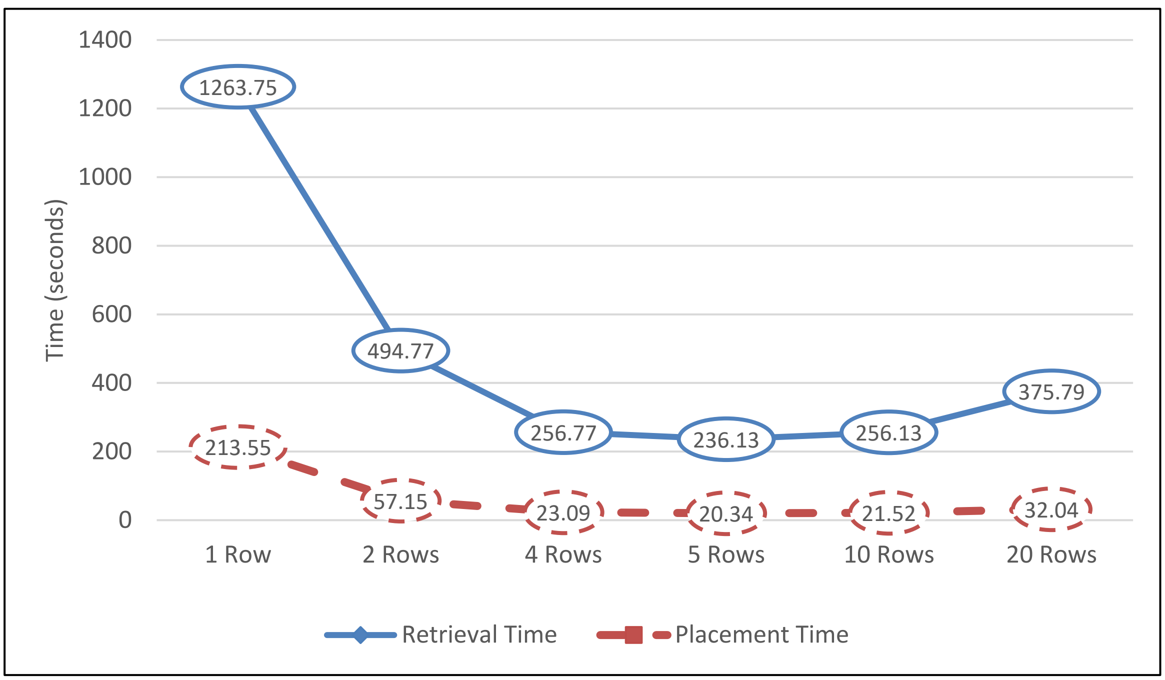


Figure 4.4. The expected time metrics for a bay of 20 containers

We now demonstrate how the expected times of retrieval and placement change for different bay configurations and changing bay capacity. Figure 4.5 and Figure 4.6 depict the cases of 5 to 8 tiers and 1 to 9 rows (capacity from $5 \times 1 = 5$ to $8 \times 9 = 45$). As can be expected, when the depth or height increases (with constant height or depth, respectively), the top-lifter requires a longer time for both retrieval and placement. However, when the depth of a bay increases with a fixed height, the incremental retrieval time increases while the incremental placement time is fixed at 1.0971 s for each row increased. Similarly, when the height of a bay increases with a fixed depth, the retrieval time incrementally increases with while the incremental placement time is fixed of 5 s from 5 tiers to 6 tiers, 6.1 s from 6 tiers to 7 tiers, and 7.2 s from 7 tiers to 8 tiers.

In addition to the average times, we show standard deviations and the coefficient of variations for various possible bay designs in Appendix B. This allows container yard designers/managers to assess the best design for their operations and also to estimate times and staffing needs.

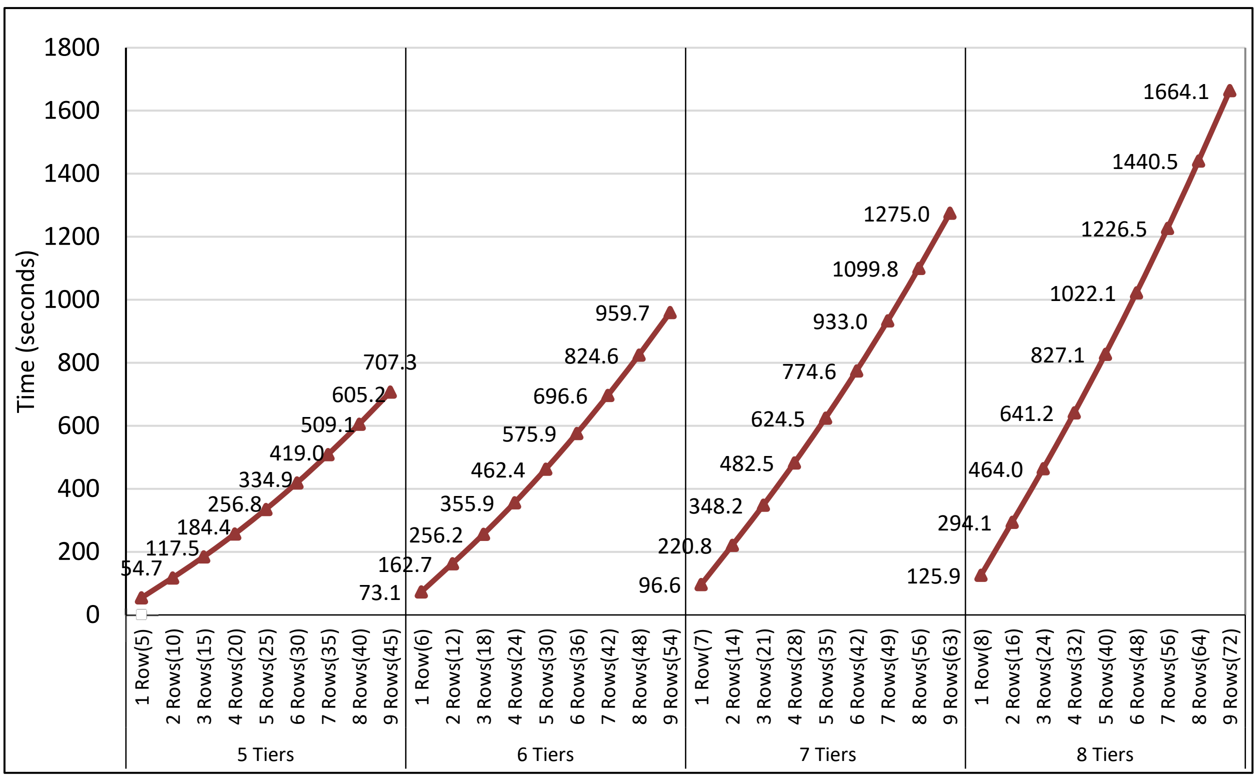


Figure 4.5. The expected retrieval times for different depth and height bay designs, and capacities (shown in parentheses on the x-axis)

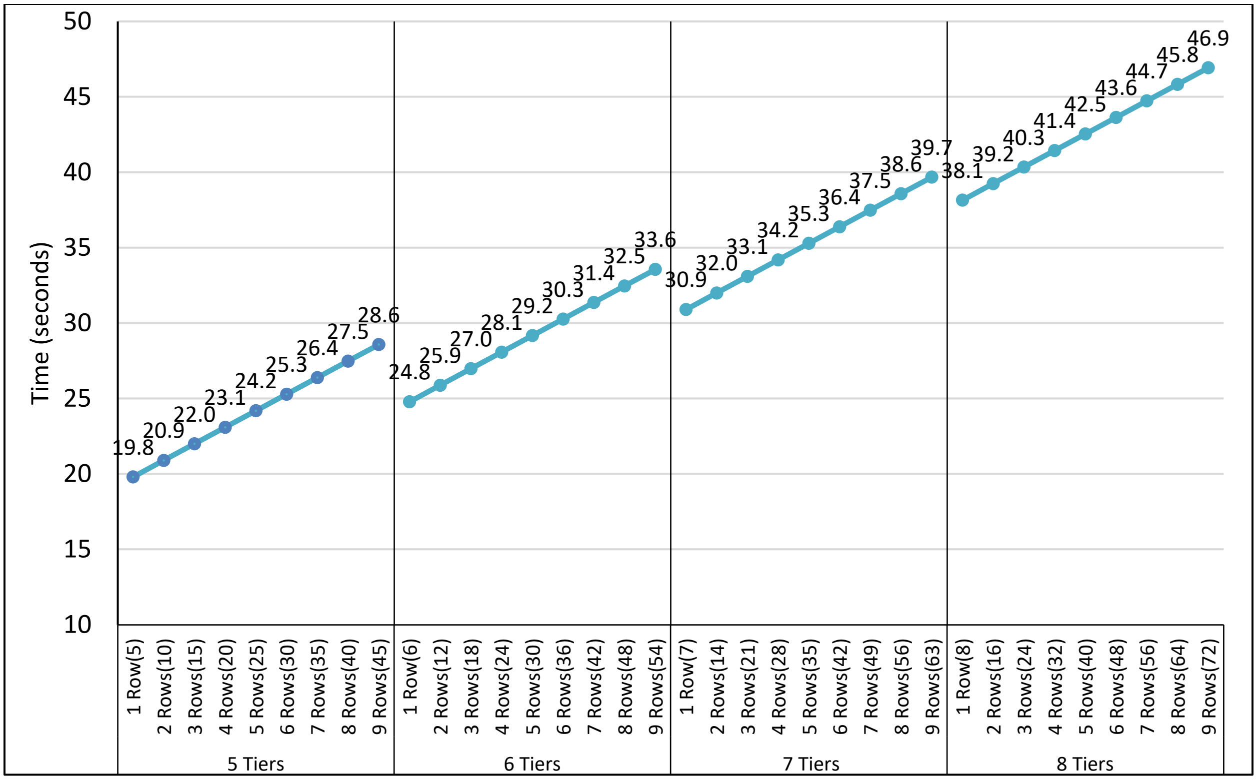


Figure 4.6. The expected placement times for different depth and height bay designs, and capacities (shown in parentheses on the *x*-axis)

4.6. Conclusions

Container terminal yard design is an important decision in maritime logistics. In this chapter, we use the unit time results from an earlier regression model using actual time observations. We produce the expected times for retrievals and placements along with their standard deviations. We use these time metrics in the next chapter to assess alternative yard designs for both rectangular and non-rectangular container yards along with the other important time metric i.e., travel time.

5. An Analytical Model for Top-lifter Operated Container Yard Layout Designs

5.1. Abstract

This chapter presents a method for designing the layout of container yards where top-lifters are used to stack and transfer containers in the yard. A method to determine the number of blocks on the x-axis (vertical) and y-axis (horizontal), along with the number of driving lanes on both axes, is proposed. Also, the size of the blocks based on the number of rows, tiers, and bays is determined. For estimating the effects of the design variables on the top-lifter cycle time, formulas to estimate the expected travel distance of the top-lifters are derived. These are then translated to time of travel. The Markov chain model proposed in the previous chapter is used for the time of retrieval and placement by the top-lifters. Together, the total time (travel, retrieval, and placement) are then used to evaluate alternative empty container yard layout options. Numerical examples are provided to illustrate the layout design procedure.

5.2. Introduction

The layout of a container yard is an important factor for efficient container handling operations and has a powerful effect directly and indirectly on the ships' berth time. For designing the layout of a container yard, the number of driving lanes (equivalently, the number of blocks on both x- and y-axes) must be determined. In this chapter, the effects of layout design variables on the expected cycle time of top-lifter operations are analyzed considering the expected travel distance and the number of container relocations.

This chapter first considers a typical layout type for empty container yards in which blocks are laid out parallel to the gate side of the yard with a reception area at the center of that side. The reception area is the place where incoming containers are inspected and allocated to container slots. The proposed methodology can be used for any container yard where top-lifters (TLs) are the primary handling equipment in the container yard. Figure 5.1 illustrates driving lanes and container blocks in a typical container yard where TLs are used. This kind of container terminal is seen in port container yards in developing countries such as Chile (location of our case study) but also in small and medium-size ports in any country, and most empty container depots because of the relatively lower cost and larger mobility. Top-lifters travel between storage bays and the reception area, which is assumed to be at the center of a side in a rectangular yard. Although there may be cases where the gate and reception areas are in different locations than the ones shown in Figure 5.1, an analysis similar to the procedure described can be followed to obtain similar results. Note that the reception area is different from the gate. In the reception area, incoming containers are inspected and assigned to slots based on container specifications. The gate is the yard's access point to the outside in which trucks come in and out of the yard.

Figure 5.1 shows the main variables and parameters for the proposed method. The variable l defines the length of a block in terms of the number of bays, where each bay has the length of L. The variable r defines the depth of a block in terms of the number of rows, each row has a width of W. The parameters L and W refer to the length and the depth, respectively, of a ground slot for storing a twenty-foot container (TEU). The parameter YL defines the length of the yard, and YD defines the depth of the yard. The parameters δ_x and δ_y define the number of bays and rows needed to install a vertical and a horizontal driving lane, respectively. The variable b_x defines the number of vertical blocks in the layout separated by vertical driving lanes. The variable b_y defines the number of horizontal blocks in the layout separated by horizontal driving lanes. The variables d_x and d_y define how many vertical or horizontal driving lanes are used, respectively. Note that all blocks are of the same size.

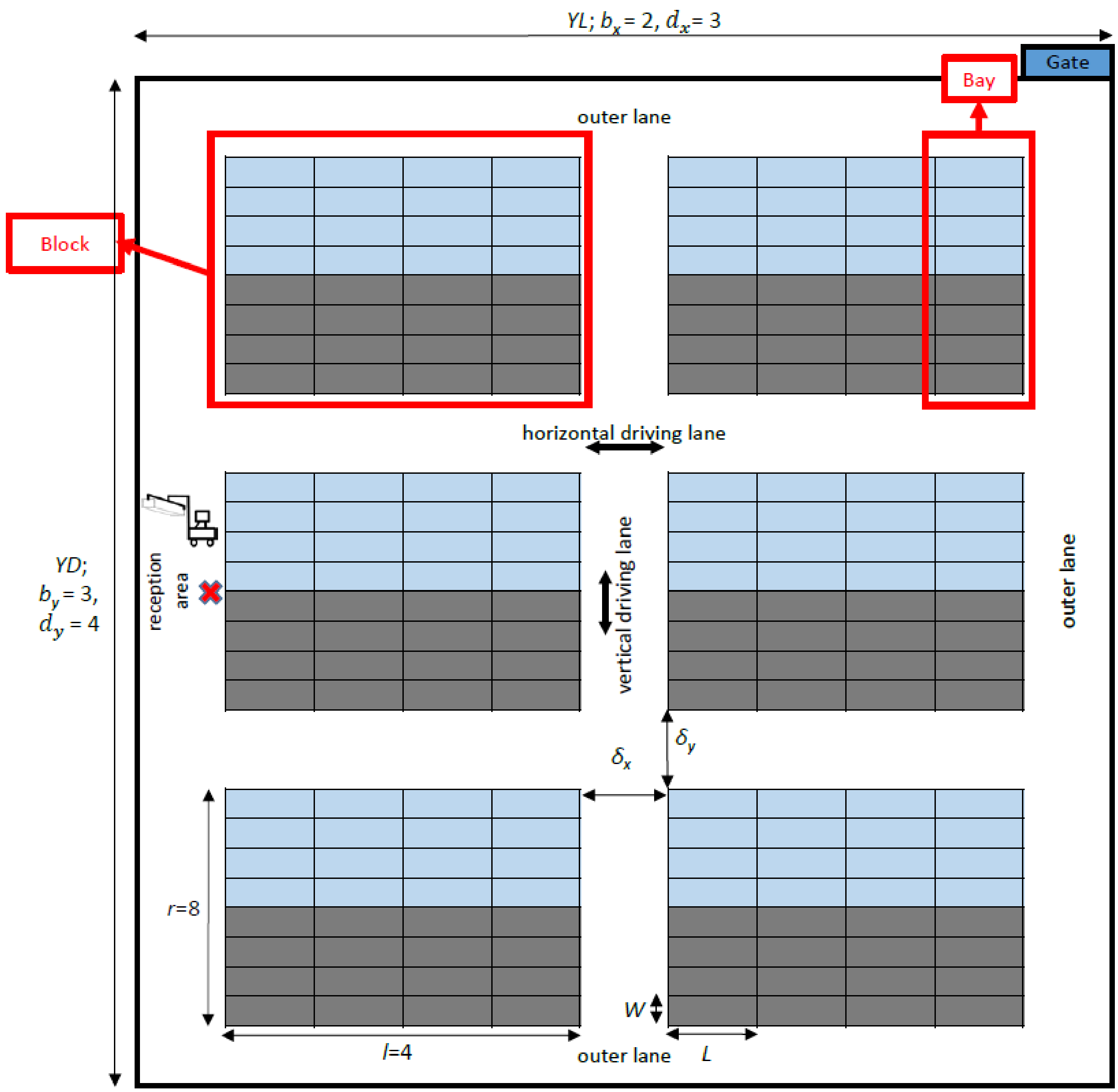


Figure 5.1. A typical container yard where top-lifters (TLs) are the primary handling equipment

The handling operations involve retrievals and placements by TLs in a yard. During retrieval operations, when an external unloaded truck arrives at a container terminal, it is routed to a bay where the assigned container will be retrieved based on the container specifications. There could be multiple containers with the same specifications in an empty container depot. The yard operators assign trucks to a bay from which the truck driver will pick up. When the truck arrives at a bay in the yard, a TL retrieves the container from a stack. This action is termed a "retrieval operation" (Figure 5.2a). After the retrieval operation, the truck loads the container onto the truck.

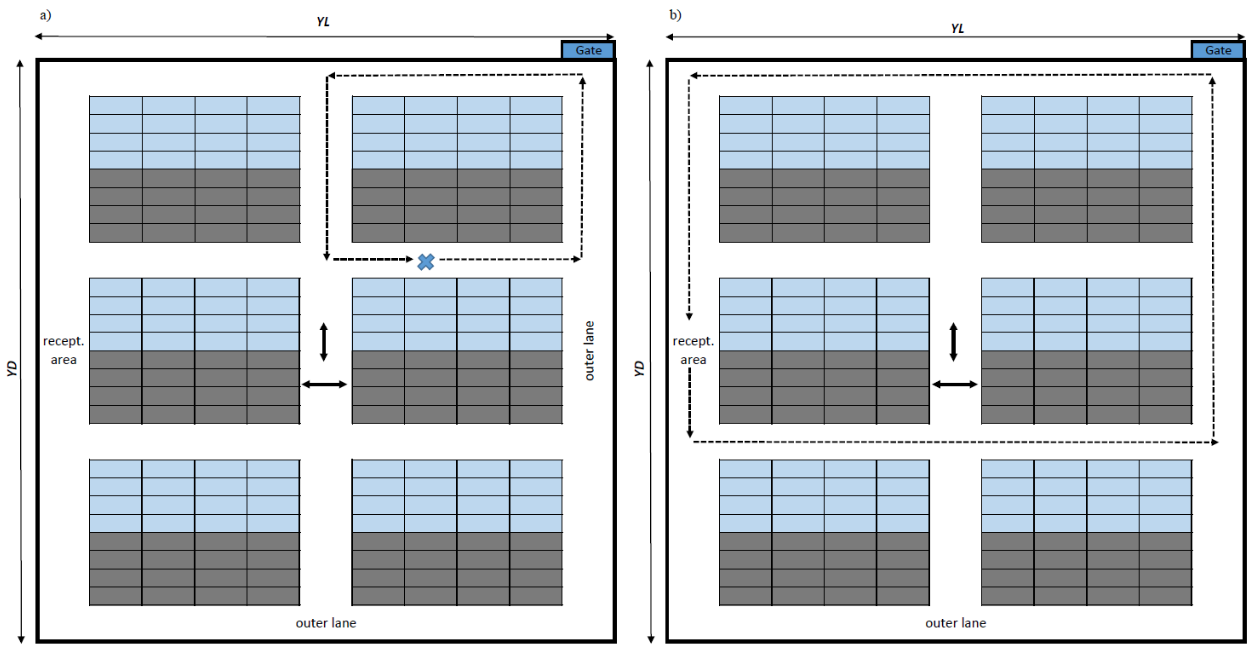


Figure 5.2. A truck travels in a yard a) Picking up a container b) Dropping off a container

During placement operations, when a loaded truck arrives at a container terminal, it is routed to a reception area where the container is inspected. If the container does not require maintenance, it is assigned to a bay based on the container specifications. The assigned container is placed in a slot, and this action is termed a "placement operation" (Figure 5.2.b). Note that there could be multiple available container slots for a container based on container specifications in a container yard.

There are two types of movement in container yards, truck travel, and handling equipment (TL in this chapter) travel. A truck travels to deliver or pick up a container in a yard. If the truck delivers a container, it travels from the gate to the reception area along the x-axis driving lane (outer lane) closest to the gate to deliver it at the reception area. After delivering the container at the reception area, the truck drives out along the next horizontal driving lane closest to the inspection area. A

U-turn is impossible for a truck in driving lanes due to its large turning radius. The other type of truck movement is picking up a container from a bay. A truck travels along the x-axis (horizontal) driving lane prior to the driving lane in which the target container bay resides. After a container is loaded onto the truck by the TL, the truck leaves the container yard by the gate, following the shortest route through the yard.

The other movement type is handling equipment travel. There could be multiple handling equipment available for container handling in a yard. Yard operators schedule and assign each handling equipment based on its availability and location, and the container handling operation urgency. Handling equipment is used to load a container onto a truck, unload a container from a truck, and retrieve and place a container from/to a slot. In addition to this, top-lifters (and reach stackers), straddle carriers, and RTGs are used for container transfer within a container yard. Depending on the TL's most recent and assigned container's locations, we assume that the possible TL travels are as follows:

i) From the reception area to an assigned container bay to place a container after the inspection process,

ii) From a bay to the reception area to unload a container from a truck at the reception area,

iii) From a bay to another bay to retrieve a container after loading a container on a truck or placing a container in a bay.

This chapter proposes an approach to choose the sizes of the blocks for a given size of a rectangular shaped yard, followed by adapting this to a non-rectangular shaped yard and L-shaped yard. Decisions about layout will affect the cycle time of TL, which will strongly affect retrieval and placement operations. The layout design also affects the yard's storage capacity.

5.3. Optimizing the Layout of the Yard

We need to determine the number of driving lanes (aisles), or equivalently, the length (the number of bays) and the depth (the number of rows) of blocks in the yard. When the number of bays or the number of rows decreases, the number of driving lanes increases, and the expected travel distance of TLs is reduced. However, in this case, as the total area for driving lanes becomes large, the stacking ground space decreases. To stack the required number of containers in a smaller area, the stacking height (the number of tiers) must be increased, which results in a higher number of relocations during retrieval operations and might exceed the maximum allowed. Thus, there must be an optimal length of a block that minimizes the cycle time of TLs. The cycle time is the expected total time spent by a TL from the arrival of a container to the yard until its departure from the yard. In other words, the cycle time is the expected TL time spent to handle the container (including travel within the yard) for a container while the container is in the yard.

To calculate the expected travel distance, we make the following assumptions.

I. We use a "block" as the fundamental unit in the design. Each block is formed by consecutive bays (length) and rows (depth) separated by driving lanes on both the x-axis and y-axis, respectively (see Figure 5.1).

II. When a TL is idle, it is parked at its last location. It stays at its last location until the next handling assignment (going to the reception area or a bay for retrieval or placement).

III. TL travel cycles can start from either the reception area or a storage bay for retrieval or placement. However, we assume there could be three possible location states to calculate the expected travel distance. Since the transition probabilities for traveling to any bay for placement or retrieval are different, the three possible states assumption is reasonable. We name the three different states: reception, retrieval bay, and placement bay.

IV. The handling operation by a TL occurs uniformly over the entire yard. Every retrieval or placement can occur in any container storage slot with equal probability without considering container class, size, type, etc.

V. Our objective function considers tradeoffs of block length and depth on TL performance, minimizing TL's expected cycle time (handling + traveling).

VI. A TL travels in the middle of the driving lanes. We consider the travel time from the middle of the driving lane to a bay access point for the TL movement as y-axis travel time. In addition to that, we assume that the TL reaches a container at the center of a bay. In other words, the TL needs to travel to the center of a bay, and the half bay distance is used to calculate travel time on the x-axis.

VII. There is only a container handling after each possible TL movement (one handling at a time). However, multiple retrievals can happen consecutively at the same location resulting in 0 distance traveled.

VIII. Each block within the entire yard is of equal size.

IX. The widths of horizontal and vertical driving lanes must be large enough for TL and truck travel. The width of the horizontal driving lane is measured based on the number of rows and the width of the vertical driving lane is measured based on the number of bays.

X. We use a 20-foot container (TEU) as the basic measure to enumerate all possible blocks and driving lane sizes.

This study considers TL time for determining the optimal configuration of a layout. The TL time includes travel, retrieval, and placement times. For constructing the objective function, we consider the effects of the layout decision variables on the cycle time of TL.

The handling and travel times of a TL are dependent on the layout of blocks in the yard. The waiting times of a truck or a TL depend on the number of TLs and the arrival rate of trucks, which are not the main issues of this dissertation. Thus, among all of the time elements of trucks and TLs, there are only three time elements which depend on the yard layout:

1) The travel time of trucks between the gate and the reception or the assigned container bay for unloading or loading, respectively
2) The time of a TL for handling (relocation, retrieval, and placement of containers)
3) The time it takes the TL to travel within the depot.

Since trucks belong to trucking companies, we exclude truck travel time from the objective function, as pointed out in Kim et al. (2008).

In this chapter, we propose an analytical model to design a container depot layout minimizing the expected cycle time of a top-lifter. The following notation is used to describe the procedures for optimizing yard layouts.

Table 5.1. Parameters for yard layout optimization

Parameters	Description
YL	yard length
YD	yard depth
L	the length of a 20-foot container (TEU) slot
W	the width of a 20-foot container (TEU) slot
δ_x	the number of bays to place a vertical driving lane
δ_y	the number of rows to place a horizontal driving lane
χ	maximum allowed average stacking height
v	the average velocity in meters per second of a top-lifter on the driving lanes
C	the average storage capacity required in the yard (TEU)

Table 5.2. Variables for yard layout optimization

Variables	Description
l	the length of a block by the number of bays (decision variable)
r	the width of a block by the number of rows (decision variable)
b_y	the number of horizontal blocks on the y-axis (decision variable)
b_x	the number of vertical blocks on the x-axis (decision variable)
d_x	the number of vertical driving lanes where the loss of ground space is compensated for by increasing average stacking height
d_y	the number of horizontal driving lanes where the loss of ground space is compensated for by increasing average stacking height
G	the number of ground slots resulting from the layout design
T	the average stacking height by the number of tiers; $T = C/G$
D_{Total}	the expected travel distance of a top-lifter (meters)
Dx	the expected x-axis travel distance of a TL cycle (meters)
Dy	the expected y-axis travel distance of a TL cycle (meters)
tr	the expected time that a TL spends to retrieve a container including the relocation time of a container (seconds)
tp	the expected time that a TL spends to place a container (seconds)
tt	the expected travel time that a TL spends for travel (seconds)

In all previous studies, to the best of our knowledge, handling equipment travel speed and handling times were constant for loaded or unloaded handling equipment, and placement or retrieval to the different height slots (e.g., Kim et al., 2008; Wiese et al., 2013). They assume fixed travel speeds for loaded and empty handling equipment and for relocation time per relocation. This is quite a simplification. By contrast, we consider variable speeds to calculate handling and traveling times, making the calculations more realistic. We assume the handling equipment has different travel speeds whether it is loaded or empty. We consider the relocation time based on the container slots (tier and row number). In addition to that, we use the regression model proposed by Bravo (2018) using real data from the empty container depot in Chile to calculate stacking and unstacking times.

The area allocated for the yard is assumed to be given. Once b_x and b_y in the yard are determined, the values of the other decision variables are automatically determined. Thus, the number of decision variables in this problem is two. Travel time is proportional to the travel distance of TLs. The other time term, the handling time, depends on both the retrieval and placement of containers. The relocation time of blocking containers is included in the retrieval time herein. Thus, the problem can be stated as follows:

$$z = tr + tp + tt \tag{5.1}$$

$$subject\ to\ T \leq \chi \tag{5.2}$$

The following will discuss how to estimate the value of tt given values of b_x and b_y. Since the search space is quite small, minimizing the objective function (5.1) can be obtained by enumerating all the possible combinations of b_x and b_y. For a given value of YL and YD, as the value of b_x (the number of vertical blocks) or b_y (the number of horizontal blocks) increases, the number of vertical or horizontal, respectively, driving lanes increases. This results in higher stacks and shorter travel distances in the yard. Note that the objective function (5.1) assumes that containers are retrieved in random order, which is a realistic assumption in most empty container depots. However, in some cases, in some port yards, the retrieval sequence of containers can be pre-determined, or containers can be reshuffled or pre-marshaled to reduce the number of relocations. In this case, the coefficient of the first term tr can be adjusted instead of using 1 in our model. Constraint (5.2) provides the constraint that the proposed design does not violate the stacking height restriction.

5.4. Estimating the Expected Time of Retrieval and Placement of a Container

This section explains the formulas for evaluating storage capacities of container yards for a given storage requirement and the derivations of the expected time of retrieval for a specified container yard layout.

The number of ground slots on which containers can be stacked is expressed as equation (5.3). The area for container stacking decreases as the number of driving lanes (d_x and d_y) increases. Equation (5.3) reflects the total number of ground slots excluding the area for all driving lanes.

$$G = r * l * b_x * b_y \tag{5.3}$$

The expected average number of tiers can be calculated as follows:

$$T = \frac{C}{G} \tag{5.4}$$

C is the required capacity. As the height of bays increases, the storage capacity increases proportionally. However, the number of relocations required for retrieving a container also increases as does the expected time of relocations (The previous chapters discuss methods for estimating the number and time of relocations for retrieving a container). The number of bays and rows per block can be calculated as follows:

$$l = \left\lfloor \left(\frac{YL - \delta_x * d_x}{L} \right) * \frac{1}{b_x} \right\rfloor \tag{5.5}$$

$$\frac{r}{2} = \left\lfloor \left(\frac{YD - \delta_y * d_y}{W} \right) * \frac{1}{2b_y} \right\rfloor \tag{5.6}$$

We calculate the half depth of a block in equation (5.6) because we assume that blocks are accessed from driving lanes, and each block row is accessed until reaching the center of the block (Figure 5.3). Thus, we also use the half depth to calculate the retrieval and placement times in the previous section to be included in the objective function.

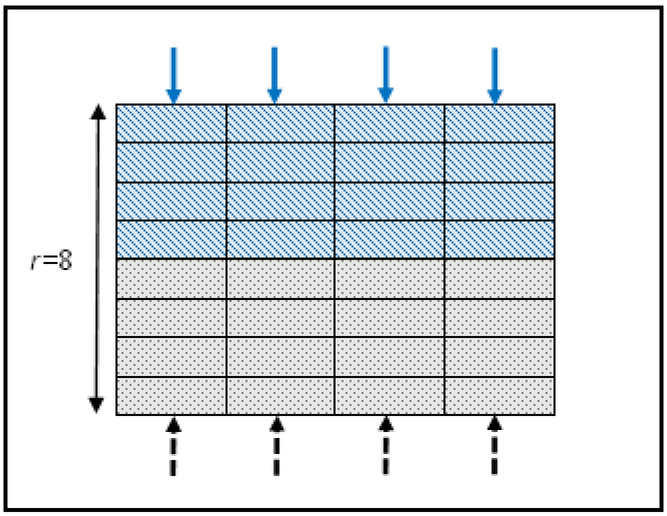


Figure 5.3. Block access from driving lanes (two edges of a block on the y-axis) to the center of the blocks

We use the previous chapter's output for retrieval time as an input to the model in this chapter. The general procedure is shown in Figure 5.4. The previous chapter proposes a family of Markov models to analytically characterize the number of relocations for random retrieval while considering simultaneous container arrivals for TLs and other conventional container handling equipment in container yards. We also considered regression models derived from a time study directed by the research team at PUCV in Chile (Bravo, 2018). The expected time of retrieval, including relocation time, is calculated based on the given number of rows and tiers of a bay design. We assume that there is no pre-marshaling nor reshuffling to reduce relocations. As the values of b_x and b_y increase, the area for stacking containers becomes smaller because of the larger ground space consumed by driving lanes. For a given yard area, this means that the stacking height must be increased, which results in a higher expected time of relocations. A possible yard layout is composed of a single block with only outer driving lanes, making the relocation time shorter. Because of larger storage ground space, the block height decreases. However, the TL must travel the whole yard distance for any handling in this kind of layout. Thus, in a layout with more driving lanes, TL can travel less. More driving lanes result in lower travel time but higher handling time for a fixed storage space.

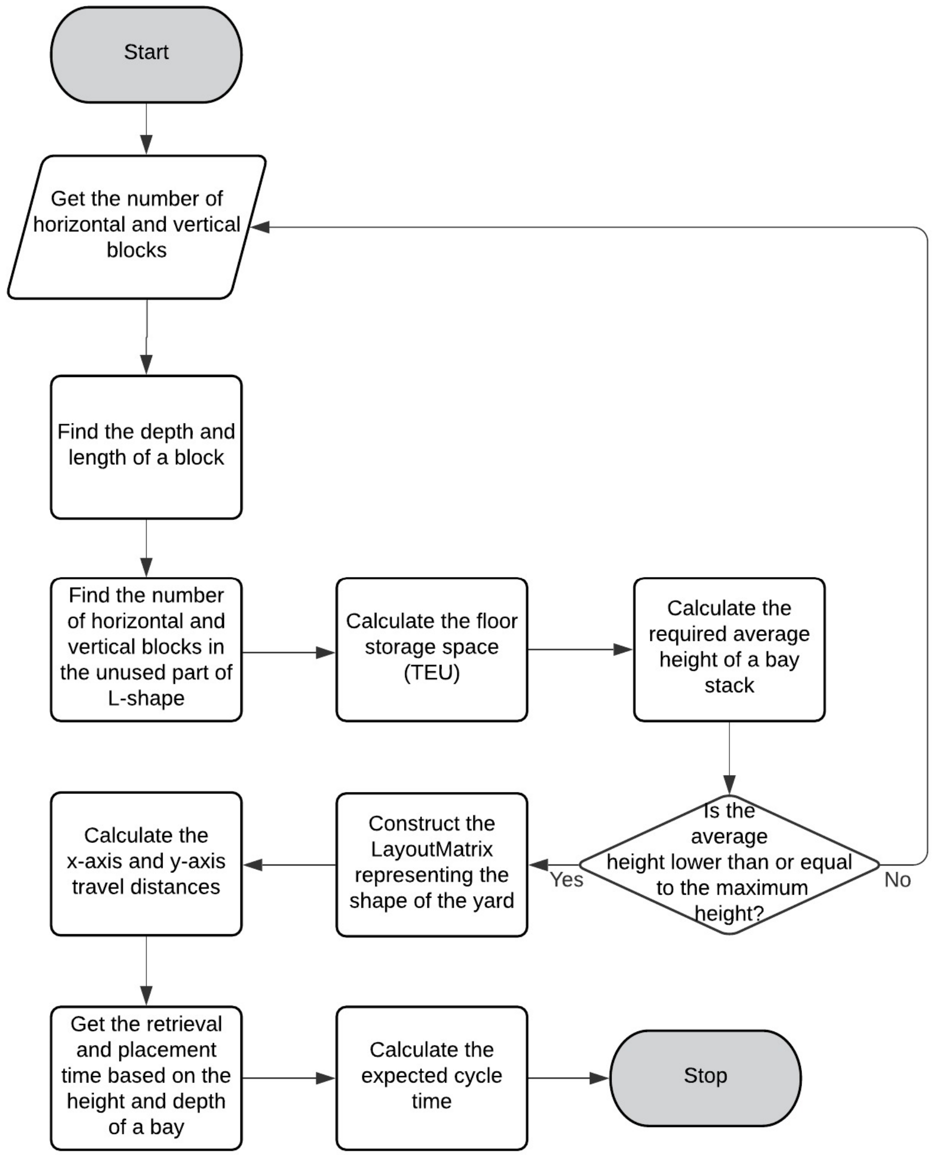


Figure 5.4. The flowchart of the expected cycle time calculation

5.5. The Expected Travel Distance of TLs in a Rectangular Yard Layout

This section derives formulas for the expected travel distance and travel time of TLs. The following assumptions are introduced to derive the formulas for the expected travel distance:

1. TLs can travel in either direction while in driving lanes.

2. TLs travel in the center of the driving lanes and drive until the center of a bay to handle containers, that is all handling operations take place with the TL in the center of the bay. We

include the driving lane width to calculate the travel distance, which is different from other studies in the literature (e.g., Kim et al., 2008).

3. The reception area is in the center of the depth side of the rectangular yard (Figure 5.1), as in our case study. However, different reception area locations can be analyzed using the same procedure introduced in this chapter.

4. The probabilities for transitions from one location to another location are given in Table 5.3. However, these probabilities can be altered to different percentages depending on the assumptions. We assume that a TL needs to transfer an incoming container in a bay, so the probability from reception to placement bay is 1. Suppose a TL is in a bay after loading a container onto a truck. In that case, the TL can travel to two locations, either to the reception area or to a bay. The TL can travel to the reception area to unload a container from a truck or to a bay to load a container on a truck with equal probabilities. Last, if a TL is in a bay to place a container following a transfer from the reception area, the TL can travel to either the reception area or a bay. The TL can travel back to the reception area to unload another new incoming container or to a bay to load a container onto a truck.

Table 5.3. State transition probabilities for a top-lifter

	Reception	Retrieval bay	Placement bay
Reception	0	0	1
Retrieval bay	0.5	0.5	0
Placement bay	0.5	0.5	0

TLs travel on horizontal and vertical driving lanes. Thus, the travel distance can be represented by the x-axis travel distance and the y-axis travel distance. We derive the expected travel distance values on both x-axis and the y-axis as functions of b_x, b_y, δ_x, δ_y, l, r, L, and W in the yard.

Based on the transition probabilities in Table 5.3, we can calculate steady-state probabilities ($\boldsymbol{\pi_{inspection}}, \boldsymbol{\pi_{retrieval}}, \boldsymbol{\pi_{placement}}$), as shown in Table 5.4.

Table 5.4. Long term (steady) state probabilities

$\boldsymbol{\pi_{inspection}}$	$\boldsymbol{\pi_{retrieval}}$	$\boldsymbol{\pi_{placement}}$
0.3333	0.3333	0.3333

To calculate the total travel distance (D_{Total}), we consider x-axis distance (Dx) and y-axis distance (Dy) separately. Using the calculated steady-state probabilities, we can calculate expected x-axis and y-axis travel distances considering the possible next state. We evaluate the cases where TL is in any of these three states. We only consider one layout type, given in Figure 5.1. However, the proposed model can be implemented to any similar yard layout (we will show this in Section 5.6 when we consider an L-shaped layout).

5.5.1. Travel Distance on the x-axis for a Rectangular Shape

5.5.1.1. The TL is in the Reception Area (x-axis)

When the TL is in the reception area, the only possible location that the TL can travel to is a placement bay since the incoming container needs to be placed in its assigned bay. We derive the equation of the expected distance for the case where the TL is in the reception area below.

The distance that the TL needs to travel to the far left edge of the block closest to the reception area on the x-axis is $\frac{\delta_x}{2} * L$, assuming that the reception area is in the center of the outer driving lane (Figure 5.5). This distance estimate is the first part of the equation (5.7).

If the TL travels to the block closest to the reception area on the x-axis, the distance that the TL needs to travel is zero, excluding the distance in the first part of the equation. The probability that the TL needs to travel to the closest block is $\frac{1}{b_x}$. The probability that the TL needs to travel to the second closest block is also $\frac{1}{b_x}$ and the distance the TL needs to travel is $(l + \delta_x) * L$ from the far left edge of the closest block to the far left edge of the second-closest block Figure 5.5). This is the second part of the equation (5.7).

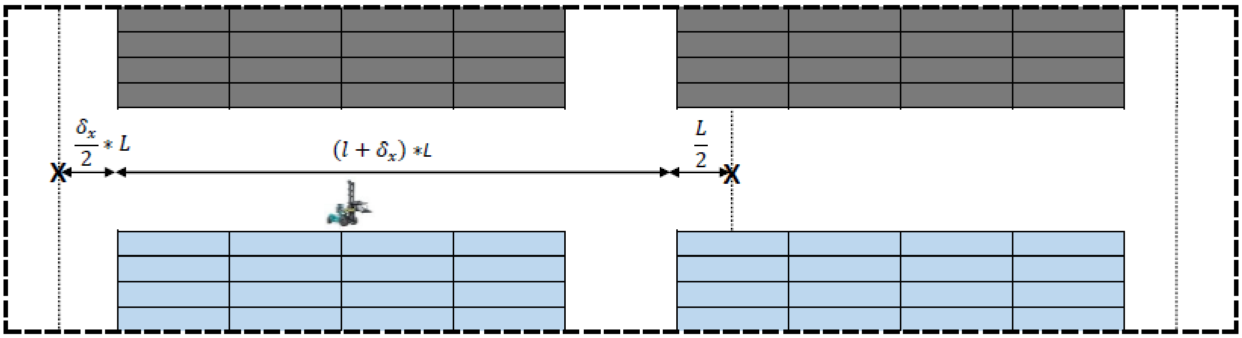


Figure 5.5. x-axis distance from the reception area to the possible placement bay

Similarly, the probability that the TL needs to travel to any bay in a block for placement of a container is $\frac{1}{l}$. The distance that the TL needs to travel to the bay closest to the reception area is $\frac{L}{2}$, because we assume that the TL needs to be in the center of a bay to handle the container (Figure 5.5). The distance to the second closest bay is $\frac{3L}{2}$, and the third closest bay is $\frac{5L}{2}$, and so on. This is the third part of the equation (5.7). Thus, if it is in the reception area, the overall distance estimate of the TL is:

$$Dx_{reception} = \frac{\delta_x}{2} * L + \sum_{k=0}^{b_x - 1} \frac{1}{b_x} * k * (l + \delta_x) * L + \sum_{k=1}^{l} \frac{1}{l} * \frac{(2k-1)}{2} * L \qquad (5.7)$$

5.5.1.2. The TL is in a Retrieval Bay (x-axis)

The TL can travel to two possible locations, either the reception area to pick up a container for placement in a bay or to a retrieval bay to retrieve a container for loading on a truck.

i) If the TL travels to the reception area, the x-axis distance is equal to the distance from the reception area to any bay, called $Dx_{reception}$, as derived above.

$$Dx^{i}_{retrieval} = Dx_{reception} \tag{5.8}$$

ii) If the TL goes to another retrieval bay from a retrieval bay, we evaluate two cases separately: $b_x = 1$ and $b_x > 1$.

To derive an equation for $b_x = 1$, we first examine the condition that the origin and destination bays are in the same horizontal driving lane. In this case, the distance depends solely on the number of bays l. The probability that a randomly chosen origin retrieval bay and the possible destination retrieval bay are identical is $\frac{1}{l}$. In this case, the x-axis distance is zero. The probability that k bays need to be traveled is $\frac{2(l-k)}{l^2}$ (see Kim et al., 2008) with a distance of $k * L$. Thus, the first distance estimate $Dx^{ii}_{retrieval(A)}$ in the case that the origin and destination bays are in the same horizontal driving lane is;

$$Dx^{ii}_{retrieval(A)} = \sum_{k=1}^{l-1} \frac{2(l-k)}{l^2} * k * L = \frac{L(l^2-1)}{3l} \; (Kim\ et\ al., 2008) \tag{5.9}$$

Then, we derive an estimate for the case where the origin and destination bays are in different horizontal driving lanes. In this case, the distance estimate $Dx^{ii}_{retrieval(\mathrm{B})}$ has to be changed since the TL needs to drive some extra distance towards the closest vertical driving lane to switch to the horizontal driving lane. Again, we assume that the TL needs to travel from the center of one bay to the center of the other bay to reach a container.

The probability that $k = \delta_x + m \;\; \forall m = 1, .., (l-1)$ bays need to be traveled is $\frac{2m}{l^2}$ with a distance of $(\delta_x + m)L$ for. However, the probability that $\delta_x + l$ bays need to be traveled is $\frac{l}{l^2}$. Since there is a single possible destination bay when the TL travels $\delta_x + l$ bays from the origin bay in either direction towards the horizontal driving lane, the probability is $\frac{l}{l^2}$. Note that the destination bays are different if the TL travels $\delta_x + 1$ to $\delta_x + l - 1$ bays in either direction towards the horizontal driving lane. Let us assume that a block length l is 4 bays (Figure 5.6) and the vertical driving lane width δ_x is 1 bay. When $k = 4$ bays, i.e., $k = \delta_x + m$ bays, the TL can make six ($2m$) different paths in total in both the left and right directions. If the TL travels 4 bays towards the left direction, it can travel to bays a^l, b^l, and c^l from bays a, b, and c, respectively. If the TL travels 4 bays in the right direction, it can travel to bays b^r, c^r, and d^r from bays b, c, and d, respectively (Figure 5.6.a). Note that the TL cannot reach any other horizontal driving lane if it travels 4 bays from bay a towards right direction or from bay d towards left direction. However, the TL can make only 4, i.e., $l = 4$, possible paths when $k = 5$ bays, i.e., $k = \delta_x + l$ bays, in each of the left and right direction, for 8 possible paths total. If the TL travels towards the left direction, it can travel to bays a^l, b^l, c^l, and d^l and if it travels towards right direction, it can travel to the bays a^r, b^r, c^r, and d^r which are the same destination bays from each possible origin bays a, b, c, and d (Figure 5.6.b). Therefore, the second distance estimate $Dx^{ii}_{retrieval(B)}$ in the case where the origin and destination bays are in different horizontal driving lanes is;

$$Dx^{ii}_{retrieval(\mathrm{B})} = \frac{\left[\sum_{k=\delta_x+1}^{l+\delta_x} 2(k - \delta_x) * k\right] - (l + \delta_x) * l}{l^2} * L \qquad (5.10)$$

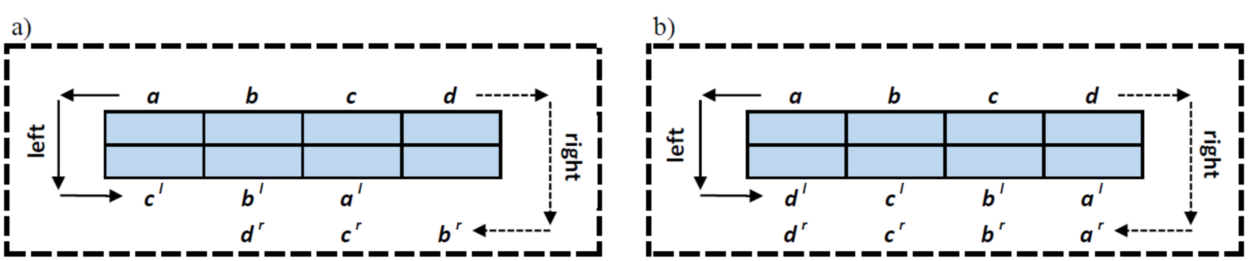


Figure 5.6. Possible destination points a) If the TL travels $k = 4$ bays there are six possible destinations b) If the TL travels $k = 5$ bays there are four possible destinations, i.e., there are only m possibilities instead of $2m$. The superscript denotes the travel direction, left or right.

When $b_y = 1$, the probability that a randomly chosen origin and destination bays are in the same horizontal driving lane is $\frac{2}{4}$. The probability that a randomly chosen origin and destination bays are in different horizontal driving lanes is also $\frac{2}{4}$. When $b_y = 2$, the probability that a randomly chosen origin and destination bays are in the same horizontal driving lane is $\frac{6}{16}$. The probability that a randomly chosen origin and destination bays are in different horizontal driving lanes is $\frac{10}{16}$. Similarly, when $b_y = 3$, the probability that a randomly chosen origin and destination bays are in the same horizontal driving lane is $\frac{10}{36}$. The probability that a randomly chosen origin and destination bays are in different horizontal driving lanes is $\frac{26}{36}$, and so on. Thus, the distance estimate $Dx^{ii}_{retrieval(1)}$ in case of $b_x = 1$ is:

$$\begin{aligned} Dx^{ii}_{retrieval(1)} &= \frac{2\left[1 + 2\left(b_y - 1\right)\right]}{\left(2b_y\right)^2} Dx^{ii}_{retrieval(\mathrm{A})} \\ &\quad + \frac{2\left[\left(2b_y - 1\right) + \left(b_y - 1\right)2\left(b_y - 1\right)\right]}{\left(2b_y\right)^2} Dx^{ii}_{retrieval(\mathrm{B})} \\ &= \frac{2b_y - 1}{2b_y^2} Dx^{ii}_{retrieval(\mathrm{A})} + \frac{2b_y^2 - 2b_y + 1}{2b_y^2} Dx^{ii}_{retrieval(\mathrm{B})} \end{aligned} \tag{5.11}$$

Second, we derive an estimate for the case where $b_x > 1$. When $b_x > 1$, the distance estimate $Dx^{ii}_{retrieval(2)}$ has to be changed since the TL has to drive extra distance if it travels to a bay located in a different vertical block. The probability that the origin and destination bays are in the same vertical block is $\frac{1}{b_x}$. In this case, the distance can be expressed by $Dx^{ii}_{retrieval(1)}$. The probability that z blocks need to be traveled (that is, the bays are in different vertical blocks) on the x-axis is $\frac{2(b_x - z)}{{b_x}^2}$ (again, see Kim et al., 2008). The expected distance that the TL needs to travel a single block on the x-axis is $\left[\sum_{k=\delta_x+1}^{(l+\delta_x)} \frac{k-\delta_x}{(l)^2} * k + \sum_{k=1}^{l-1} \frac{k}{(l)^2} * [2l - k + \delta_x]\right] L$. Similarly, the expected distance that the TL needs to travel two blocks on the x-axis is $\left[\sum_{k=2*\delta_x+1+l}^{2(l+\delta_x)} \frac{k-[l+2\delta_x]}{l^2} * k + \sum_{k=1}^{l-1} \frac{k}{l^2} * [2l - k + 2\delta_x]\right] L$. Thus, we can write the equation for the expected distance that the TL needs to travel z blocks on the x-axis as; $\left[\sum_{k=z*\delta_x+1+(z-1)l}^{z(l+\delta_x)} \frac{k-[(z-1)l+z*\delta_x]}{l^2} * k + \sum_{k=1}^{l-1} \frac{k}{l^2} * [(z+1)l - k + z * \delta_x]\right] L$. Thus, the second overall distance estimate that the TL needs to travel from a retrieval bay to another retrieval bay on the x-axis where $b_x > 1$ is:

$$Dx_{retrieval(2)}^{ii} = \frac{1}{b_x} Dx_{retrieval(1)}^{ii} + \left[\sum_{z=1}^{b_x-1} \frac{2(b_x - z)}{{b_x}^2} * \left(\sum_{k=z*\delta_x+1+(z-1)l}^{z(l+\delta_x)} \frac{k - [(z-1)l + z * \delta_x]}{l^2} * k + \sum_{k=1}^{l-1} \frac{k}{l^2} * [(z+1)l - k + z * \delta_x] \right)\right] L \tag{5.12}$$

Please note that in the case of $b_x = 1$, $Dx_{retrieval(2)}^{ii}$ reduces to $Dx_{retrieval(1)}^{ii}$.

The total expected travel distance when the TL is in a retrieval bay using Table 5.3 probabilities is:

$$Dx_{retrieval} = 0.5 * Dx_{retrieval}^{i} + 0.5 * Dx_{retrieval}^{ii} \tag{5.13}$$

5.5.1.3. The TL is in a Placement Bay (x-axis)

The TL can travel to two possible locations, either to the reception area to pick up another container for placement or a retrieval bay to retrieve a container for loading on a truck. The expected distance is equal to the travel distance that is calculated in Section 5.5.1.2.

$$Dx_{placement} = Dx_{retrieval} \tag{5.14}$$

Considering the steady-state probabilities and the expected travel distance when the TL is in any possible location (reception area, retrieval bay, or placement bay), the total expected x-axis distance is:

$$Dx = \pi_{reception} * Dx_{reception} + \pi_{retrieval} * Dx_{retrieval} + \pi_{placement} * Dx_{placement} \qquad (5.15)$$

5.5.2. Travel Distance on the y-axis for a Rectangular Shape

We can calculate the expected y-axis travel distance considering three possible states, similar to the cases we considered for the x-axis travel distance calculations.

5.5.2.1. The TL is in the Reception Area (y-axis)

If the TL is in the reception area, it needs to travel to a placement bay since an incoming container needs to be placed in its assigned bay. We now evaluate the expected travel distance on the y-axis when the TL is in the reception area for two cases where the number of horizontal driving lanes are odd and even, respectively.

Case 1: d_y is odd: The probability that the TL travels to a bay along any horizontal driving lane is $\frac{2}{2(d_y-1)}$ except for the outer horizontal driving lane bays. There are bays located on both sides of ordinary driving lanes; however, bays are located only on one side of outer driving lanes. The probability that the TL travels to a bay in an outer driving lane is $\frac{1}{2(d_y-1)}$. The y-axis travel distance from the reception area to bays located in the driving lane where the reception area is located is zero since the reception area is in the center of the depth side of the rectangular yard (Figure 5.7). The distance to the second closest driving lane bays is $(\delta_y + r)W$, and the third closest driving lane bays is $2\,(\delta_y + r)W$ and so on. In addition to the distance that TL needs to travel to the center of the horizontal driving lane, it needs to travel an extra distance of $\frac{\delta_y}{2}W$ to reach the first row of the bay (Figure 5.7). This leads to:

$$Dy_{reception}^{odd} = \left[2\frac{1}{2(d_y-1)}\frac{(d_y-1)}{2} + \sum_{k=1}^{\frac{d_y-1}{2}} 2\frac{2}{2(d_y-1)}(k-1)\right](\delta_y + r)W + \frac{\delta_y}{2}W \tag{5.16}$$

Equation (5.16) can be written as:

$$Dy_{reception}^{odd} = \left[\frac{1}{2} + \sum_{k=2}^{d_y-1} \frac{2}{2(d_y-1)}\left|k - \left\lceil\frac{d_y}{2}\right\rceil\right|\right](\delta_y + r)W + \frac{\delta_y}{2}W \tag{5.17}$$

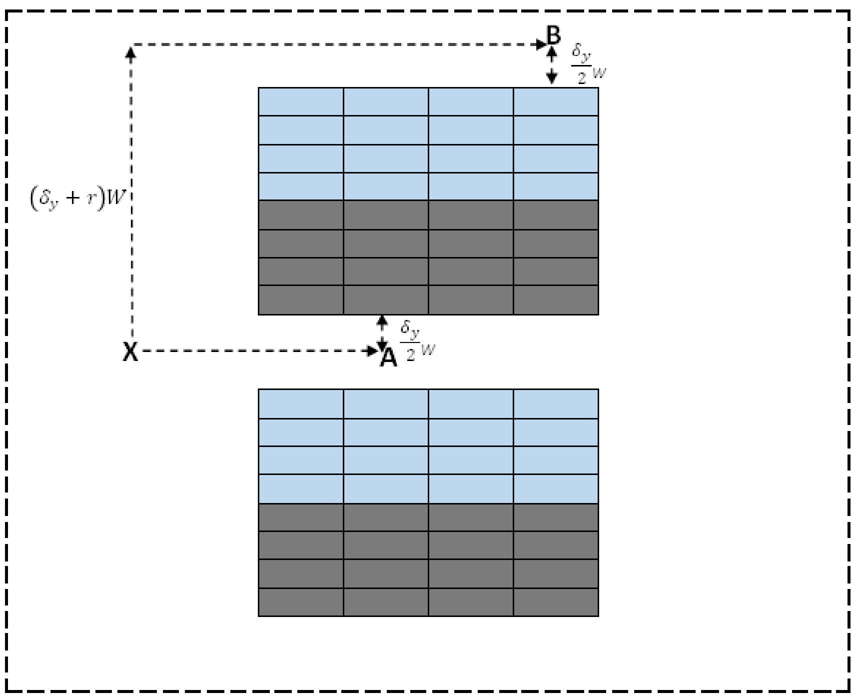


Figure 5.7. y-axis distance from the reception area to the possible placement bay when d_y is odd

Case 2: d_y is even: The probability that the TL travels to any driving lane bay is $\frac{2}{2(d_y-1)}$ except for the outer driving lane bays. The probability that the TL travels to an outer driving lane bay is

$\frac{1}{2(d_y-1)}$. The y-axis distance to the two closest driving lanes bays is $\frac{(\delta_y+r)W}{2}$ (Figure 5.8). The distance to the second closest driving lane bays is $\frac{3(\delta_y+r)W}{2}$, and the third closest driving lane bays is $\frac{5(\delta_y+r)W}{2}$ and so on. Like the case when d_y is odd, the TL needs to travel an extra distance of $\frac{\delta_y}{2}W$ to reach the first row of the bay. This leads to:

$$Dy_{reception}^{even} = \left[2\frac{1}{2(d_y-1)}\frac{(d_y-1)}{2} + \sum_{k=1}^{\frac{d_y}{2}-1} 2\frac{2}{2(d_y-1)}\left(\frac{1}{2}+(k-1)\right)\right](\delta_y + r)W + \frac{\delta_y}{2}W \tag{5.18}$$

Equation (5.18) can be written as:

$$Dy_{reception}^{even} = \left[\frac{1}{2} + \sum_{k=2}^{d_y-1} \frac{2}{2(d_y-1)}\left|k - \left(\frac{d_y}{2}+\frac{1}{2}\right)\right|\right](\delta_y + r)W + \frac{\delta_y}{2}W \tag{5.19}$$

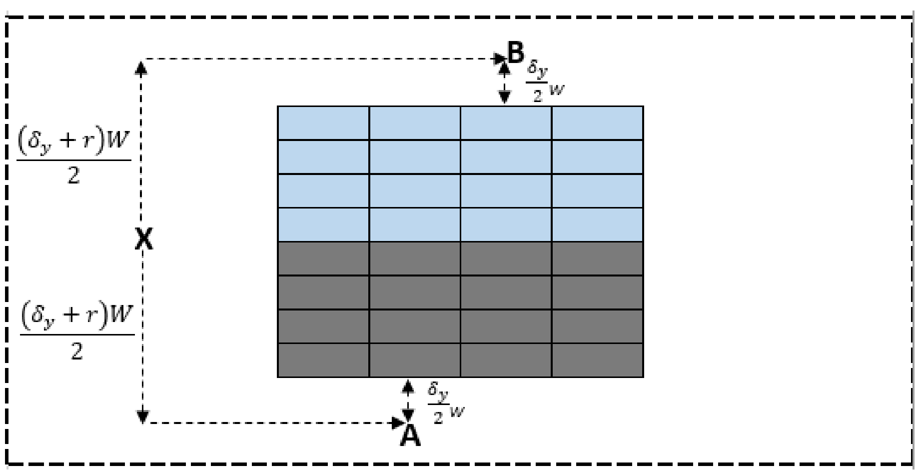


Figure 5.8. y-axis distance from the reception area to possible placement bay when d_y is even

While the first part of the square bracket in equations (5.17) and (5.19) consider only the expected travel distance along the outer driving lanes, the second part of the square bracket considers the expected travel distance to ordinary horizontal driving lanes. The second part of the square brackets in equations (5.17) and (5.19) calculates the expected distance, excluding the outer driving lanes.

5.5.2.2. The TL is in a Retrieval Bay (y-axis)

The TL can travel to two possible locations, either to the reception area to pick up a container for placement or to another retrieval bay to retrieve a container for loading on a truck.

i) If the TL travels to the reception area, the expected travel distance is equal to the distance when the TL travels from the reception area to a bay, as calculated in Section 5.5.2.1.

$$Dy^{i}_{retrieval} = Dy_{reception} \tag{5.20}$$

ii) If the TL travels to another retrieval bay, the possible destination bay can be in any horizontal driving lane. The probability that a randomly chosen origin retrieval bay and the destination retrieval bay are in the same horizontal driving lane is $\frac{2}{[2(d_y-1)]^2}$ except for the bays along the outer driving lane. However, suppose the origin and destination bays are located along the outer lanes. In that case, the probability that the TL travels from the origin bay to the destination bay along the same driving lane is $\frac{1}{[2(d_y-1)]^2}$. In this case, the y-axis distance is zero. However, when the origin and destination bays are in different horizontal driving lanes, the probabilities and distances will differ. The probability that one driving lane distance (measured as a block distance) needs to be traveled is $\frac{8}{[2(d_y-1)]^2}$ when $d_y = 3$, $\frac{16}{[2(d_y-1)]^2}$ when $d_y = 4$, $\frac{24}{[2(d_y-1)]^2}$ when $d_y = 5$, and so on. The probability that two driving lanes distance needs to be traveled is $\frac{2}{[2(d_y-1)]^2}$ when $d_y = 3$, $\frac{8}{[2(d_y-1)]^2}$ when $d_y = 4$, $\frac{16}{[2(d_y-1)]^2}$ when $d_y = 5$ and so on. The probability that three driving lanes distance needs to be traveled is $\frac{2}{[2(d_y-1)]^2}$ when $d_y = 4$,

$\frac{8}{[2(d_y-1)]^2}$ when $d_y = 5$, $\frac{16}{[2(d_y-1)]^2}$ when $d_y = 6$, and so on. In addition to the distance that the TL needs to travel from the center of a horizontal driving lane to the center of another horizontal driving lane, it needs to travel an extra distance of $\delta_y W$; the distance of $\frac{\delta_y}{2} W$ from the access point of the origin bay to the center of the driving lane and the other distance of $\frac{\delta_y}{2} W$ from the center of the driving lane to the access point of the destination bay. Using these relationships, we can write the expected distance if the TL travels from a retrieval bay to another retrieval bay as follows:

$$Dy_{retrieval}^{ii} = \begin{cases} \left(\frac{2(d_y-1)}{[2(d_y-1)]^2}\right)(\delta_y + r)W + \delta_y W \quad if\ d_y = 2 \\ \left(\frac{2}{[2(d_y-1)]^2}(d_y-1) + \sum_{k=1}^{d_y-2} \frac{8(d_y-k-1)}{[2(d_y-1)]^2} k\right)(\delta_y + r)W + \delta_y W\ if\ d_y > 2 \end{cases} \tag{5.21}$$

Equation (5.21) can be written as:

$$Dy_{retrieval}^{ii} = \begin{cases} \left(\frac{1}{2}\right)(\delta_y + r)W + \delta_y W \quad if\ d_y = 2 \\ \left(\frac{2(d_y-1)}{[2(d_y-1)]^2} + \sum_{k=1}^{d_y-2} \frac{8(d_y-k-1)}{[2(d_y-1)]^2} k\right)(\delta_y + r)W + \delta_y W\ if\ d_y > 2 \end{cases} \tag{5.22}$$

The total expected y-axis travel distance when the TL is at retrieval bay is:

$$Dy_{retrieval} = 0.5 * Dy_{retrieval}^{i} + 0.5 * Dy_{retrieval}^{ii} \tag{5.23}$$

5.5.2.3. The TL is in a Placement Bay (y-axis)

The TL can travel to two other locations, either to the reception area to pick up another container for placement or to a retrieval bay to retrieve a container for loading on a truck. The expected distance is equal to the travel distance calculated in Section 5.5.2.2.

$$Dy_{placement} = Dy_{retrieval} \tag{5.24}$$

Considering the steady-state probabilities and the expected travel distances for each possible state, the total y-axis distance is:

$$Dy = \pi_{reception} * Dy_{reception} + \pi_{retrieval} * Dy_{retrieval} + \pi_{placement} * Dy_{placement} \tag{5.25}$$

Using the calculated expected x-axis and y-axis distances, we can calculate the expected travel time tt as follows:

$$tt = [Dx + Dy]\frac{1}{v} \tag{5.26}$$

5.6. Adaptation for Non-Rectangular (*L*-shaped) Yard Layout

To the best of our knowledge, all studies in the literature except Wiese et al. (2010) considered only rectangular layouts. The Wiese et al. (2010) paper considers a special container yard layout, which they call yard layout with transfer lanes. In yards where cranes are used, either transfer lanes (where the horizontal transport mode, the truck, waits in a lane parallel to the block) or transfer points (where the horizontal transport mode waits at positions, transfer points, at the long side ends of the storage block) are used. In their layout type, trucks are used for transportation, and rubber-tired gantry cranes (RTGs) are used for stacking operations. They formulate the problem for a rectangular storage yard as a resource-constrained shortest path problem. They adopted the model with a variable neighborhood descent heuristic to solve non-rectangular instances and the shape of the yard is not restricted to any special geometric form. However, the stream points (where containers enter or leave the terminal area, e.g., the gate) are pre-selected and fixed. The decision variables in their study are lane positioning and the number of driving lanes instead of block size design. They restrict the possible block sizes using minimum and maximum boundaries to find the number and the positions of driving lanes. They assume a fixed block width since the RTG needs fixed width based on manufacturing specifications. As with this dissertation, they assumed that the storage yard area is fixed. The objective is to find the minimum handling cost composed of relocation costs by cranes and travel costs by trucks. Both costs depend on the length of the blocks, in other words on the number of driving lanes. The travel cost of the yard crane is ignored since it does not change with the length of the blocks. The transfer time of a container to a truck by a crane is neglected since it is not affected by the length of the blocks.

In their travel distance calculation, U-turns are not allowed for trucks, and a 20-foot container (TEU) size is used to enumerate all possible driving lanes. Distances for a round trip between stream points and modules are calculated using a TEU slot. A module is the combination of two blocks with transfer lanes. Each module is separated from each other by driving lanes, which are bi-directional compared to the one-way transfer lanes. Transfer lanes are reserved either for pickups or deliveries. They used the formula derived by Kim (1997) based on the height and depth of a bay to calculate the expected relocations. In their model, the number of rows can differ from each other for each driving lane unlike in a rectangular shaped yard where they must be equal. They used a coefficient called a load factor to determine the number of containers to be retrieved to find the relocations, but they do not consider placement time which is the time spent by handling equipment (RTG). They consider travel time in seconds per meter and a cost per second for yard truck travel, and rehandling time in seconds per rehandle and a cost factor per second for crane handling to calculate their objective function. They have a fixed cost coefficient for relocation and a truck travel cost coefficient.

Based on our observations, there are often non-rectangular shaped yards in both container depots and port terminal yards. Thus, we generalize our calculations to make them applicable to non-rectangular shaped yards in this section, more specifically, L-shaped yards, which are commonly found.

The probabilities will no longer be symmetric for non-rectangular shaped yards on both the x-axis and y-axis. In this section, we develop an algorithm to calculate the non-symmetric probabilities. We introduce the new notation in Table 5.5 (see Figure 5.9).

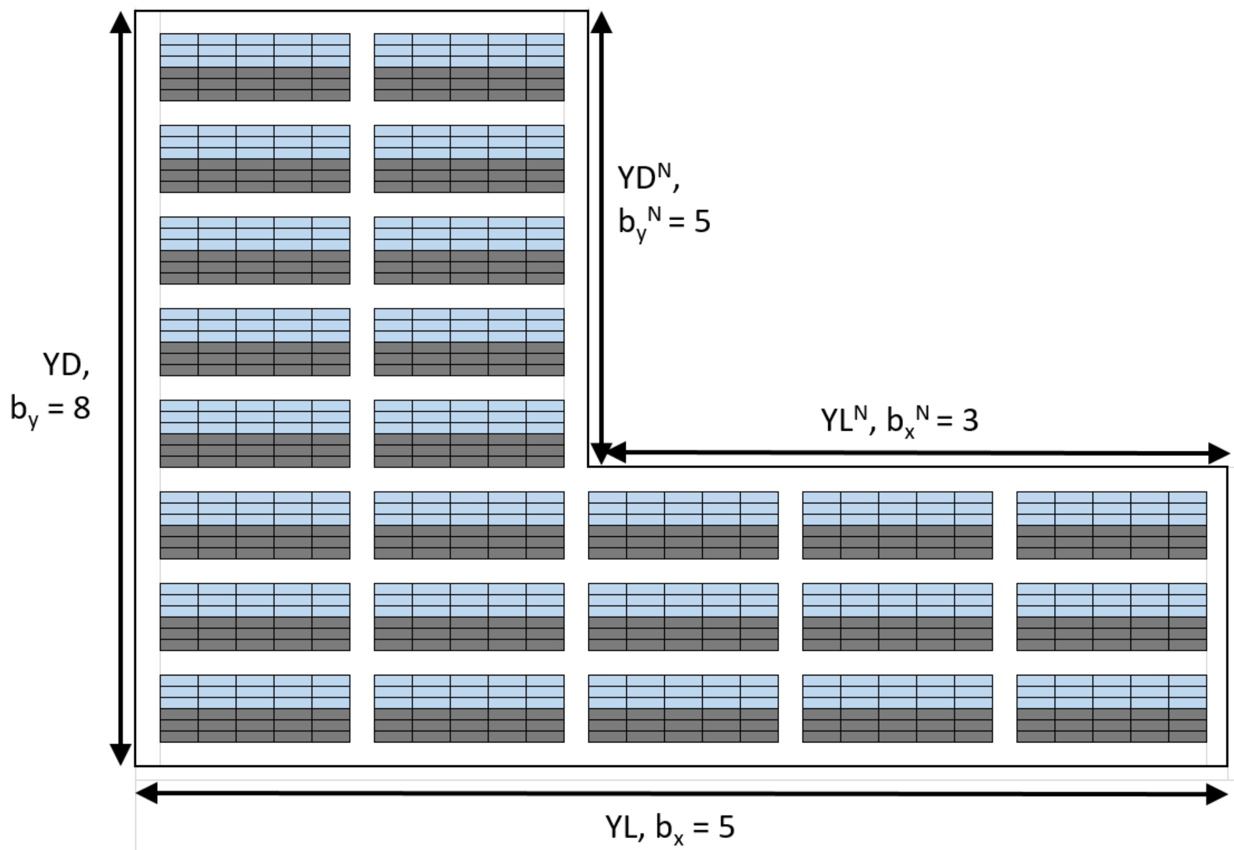


Figure 5.9. A typical non-rectangular (L-shaped) container yard layout

Table 5.5. Additional notation for non-rectangular shape

Variables	Description
${b_y}^N$	the number of blocks on the y-axis in the non-used part (outside of the L-shape)
${b_x}^N$	the number of blocks on the x-axis in the non-used part (outside of the L-shape)
G^N	the number of ground slots in the non-used part (outside of the L-shape)
G'	the number of ground slots ($G' = G - G^N$)

Using the additional notation, the average stacking height is calculated as follows:

$$T = \frac{C}{G'} \tag{5.27}$$

We define a matrix to calculate the travel probabilities called the "$Layout\ Matrix$". Note that the probability that the top-lifter needs to drive along the horizontal outer driving lanes is half of the probability that the TL needs to drive along an ordinary (middle) horizontal driving lane because bays are located only on the one side of the horizontal outer driving lanes. In addition to the non-symmetric characteristic of the probability calculations, the probability is not uniformly distributed among vertical and horizontal blocks in a non-rectangular yard layout. Consider the example of the L-shaped layout in Figure 5.9. We can describe the $Layout\ Matrix$ as:

$$Layout\ Matrix = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 2 & 2 & 0 & 0 & 0 \\ 2 & 2 & 0 & 0 & 0 \\ 2 & 2 & 0 & 0 & 0 \\ 2 & 2 & 0 & 0 & 0 \\ 2 & 2 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{5.28}$$

To show the calculations, we consider another small size example for $b_x = 5$ and $b_y = 3$ with ${b_y}^N = 2$ and ${b_x}^N = 2$. We can write the $m * n\, matrix$ for this example, where $m = b_y + 1\ and\ n = b_x$ as:

$$Layout\ Matrix = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 2 & 2 & 2 & 0 & 0 \\ 2 & 2 & 2 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{5.29}$$

The calculations of the travel probabilities for a non-rectangular yard layout are explained in the following section, similar to the rectangular yard layout calculations. Note that we only show the expected distance calculations that are different from those of the rectangular yard layout explained in Section 5.5.

5.6.1. Travel Distance on the x-axis for a Non-Rectangular Shape

5.6.1.1. The TL is in the Reception Area (x-axis)

Instead of using an equal probability of $\frac{1}{b_x}$ that the TL needs to drive from the reception area to each column of a block, we propose a general calculation method based on the $Layout\ Matrix$ in equation (5.7).

Considering the example in Figure 5.9, if the TL travels to the block closest to the reception area along the x-axis, the distance that the TL needs to travel is zero without considering the fixed distance of $\frac{\delta_x}{2}$ (half driving lane width) to the closest edge of the closest block. The probability that the TL needs to travel to any block in the closest column of blocks is $\frac{6}{22}$. The probability that the TL needs to travel to any block in the second or third column of blocks is also $\frac{6}{22}$. The distances that the TL needs to travel to the first or second closest column of blocks are $(l + \delta_x)L$ and $2(l + \delta_x)L$, respectively, excluding the fixed distance of $\frac{\delta_x}{2}L$. However, the probability that the TL needs to travel to any block in the fourth or fifth column is $\frac{2}{22}$, and the distances it needs to travel is $3(l+\delta_x)L$ and $4(l+\delta_x)L$, respectively, addition to the distance of $\frac{\delta_x}{2}L$. Thus, the expected distance that the TL needs to travel when it is in the reception area can be written as:

$$Dx_{reception} = \frac{\delta_x}{2}L + \sum_{k=0}^{b_x-1} \frac{sum[column\ (k+1)]}{sum\ [LayoutMatrix]} k(l+\delta_x)L + \sum_{k=1}^{l} \frac{1}{l}\frac{(2k-1)}{2}L \tag{5.30}$$

5.6.1.2. The TL is in a Retrieval Bay (x-axis)

We show only the expected distance formulation for the condition if the TL travels to another retrieval bay. The distance from a retrieval bay to the reception area is equal to the distance when the TL is in the reception area ($Dx^{i}_{retrieval} = Dx_{reception}$).

For the condition that the TL goes to another retrieval bay from a retrieval bay, we evaluate two cases separately: $b_x = 1$ and $b_x > 1$.

First, we derive the formula for the case $b_x = 1$. The number of possible destination bays for every origin bay in each horizontal driving lane is the number of bays in each horizontal driving lane in which the origin bay is located. The set of all possible destination driving lanes is the square of the total number of blocks in a yard. Based on the layout matrix, we can write the probability that the destination bay will be in the same driving lane as $\frac{\sum_{i=1}^{by+1}(sum[row\ i])^2}{(sum\ [LayoutMatrix]\ )^2}$.

Similarly, we can write the probability that the destination bay will be in a different driving lane as $\frac{\sum_{i=1}^{by+1}(sum\ [LayoutMatrix]\ - sum[row\ i]\ )(sum\ [row\ i])}{(sum\ [LayoutMatrix]\ )^2}$. Thus, the distance estimate $Dx^{ii}_{retrieval(1)}$ in the case of $b_x = 1$ can be written as:

$$Dx^{ii}_{retrieval(1)} = \frac{\sum_{i=1}^{b_y+1}(\text{sum[row i]})^2}{(\text{sum [LayoutMatrix] })^2} Dx^{ii}_{retrieval(A)} + \frac{\sum_{i=1}^{b_y+1}(sum\ [LayoutMatrix]\ - sum[row\ i])sum[row\ i]}{(sum\ [LayoutMatrix]\ )^2}\ Dx^{ii}_{retrieval(B)} \tag{5.31}$$

Next, we derive the formula for the case $b_x > 1$.

We use the $Layout\ Matrix$ to find the probability for each z blocks of travel. Since the TL can travel to either the left or the right side along the x-axis, we count all possible blocks in each horizontal driving lane for each block. We sum the number of preceding and succeeding columns in the $Layout\ Matrix$ for each column of blocks and multiply this summation by the summation of each column. The probability that the origin and destination bays are in the same column of blocks is $\frac{(sum[row\ i])^2}{(sum\ [LayoutMatrix]\ )^2}$. Similarly, the probability that z blocks need to be traveled on the x-axis is $\frac{\sum_{i=1}^{b_x}(sum[column\ (i-z)]+sum[column\ (i+z)])sum[column\ i]}{(sum\ [LayoutMatrix]\ )^2}$. We can write the equation (5.12) as follows:

$$Dx^{ii}_{retrieval(2)} = \frac{(sum[row\ i])^2}{(sum\ [LayoutMatrix]\ )^2}\ Dx^{ii}_{retrieval(1)} + \left[\sum_{z=1}^{b_x-1} \frac{\sum_{i=1}^{b_x}(sum[column\ (i-z)] + sum[column\ (i+z)])sum[column\ i]}{(sum\ [LayoutMatrix]\ )^2} * \left(\sum_{k=z*\delta_x+1+(z-1)l}^{z(l+\delta_x)} \frac{k-[(z-1)l + z*\delta_x]}{l^2}\ k + \sum_{k=1}^{l-1} \frac{k}{l^2} * [(z+1)l - k + z*\delta_x] \right)\right] L \tag{5.32}$$

5.6.1.3. The TL is in a Placement Bay (x-axis)

There is no change for this condition since $Dx_{placement} = Dx_{retrieval}$ as seen in equation (5.14).

5.6.2. Travel Distance on the y-axis for a Non-Rectangular Shape

5.6.2.1. The TL is in the Reception Area (y-axis)

We evaluate the expected travel distance for the y-axis distance when the TL is at the reception area in two cases where the number of horizontal driving lanes is odd or even, respectively.

Case 1: d_y is odd: For a non-rectangular yard layout, the probabilities need to change from the rectangular case since the number of accessible bays and blocks in each driving lane is not symmetric. We can write the probability that the TL needs to travel to the bays in each horizontal driving lane as $\frac{sum[row\ i]}{(sum\ [LayoutMatrix]\ )}$ using the $Layout\ Matrix$. The y-axis travel distance to the bays located in each driving lane can be written as $\left[\left|k-\left\lceil\frac{d_y}{2}\right\rceil\right|(\delta_y+r)W\right]$. k refers to the indices of a driving lane starting from the top edge of the yard and $\left\lceil\frac{d_y}{2}\right\rceil$ refers to the reception area's index. Then, we can generalize equation (5.17) to cover the rectangular and non-rectangular yard layouts as:

$$Dy_{reception}^{odd}=\left[\sum_{k=1}^{d_y}\frac{sum[row\ k]}{(sum\ [LayoutMatrix]\ )}\left|k-\left\lceil\frac{d_y}{2}\right\rceil\right|\right](\delta_y+r)W \tag{5.33}$$

Case 2: d_y is even: The probability that the TL travels to bays in each driving lane is $\frac{sum[row\ i]}{(sum\ [LayoutMatrix]\ )}$ using the $Layout\ Matrix$. The y-axis travel distance to the bays in each driving lane can be written as $\left[\left|k-\left(\frac{d_y}{2}+\frac{1}{2}\right)\right|(\delta_y+r)W\right]$. k refers to the indices of the driving lanes starting from the top edge of the yard, and $\left\lceil\frac{d_y}{2}\right\rceil$ refers to the index of the reception area. This leads to a generalization of equation (5.19) for both rectangular and non-rectangular yard layouts as:

$$Dy_{reception}^{even} = \left[\sum_{k=1}^{d_y} \frac{sum[row\ k]}{(sum\ [LayoutMatrix]\ )} \left| k - \left(\frac{d_y}{2} + \frac{1}{2} \right) \right| \right] (\delta_y + r)W \quad (5.34)$$

5.6.2.2. The TL is at a Retrieval Bay (y-axis)

We show only the expected distance formulation for the condition if the TL travels to another retrieval bay since the distance from retrieval to reception is equal to when the TL is in the reception area ($Dy_{retrieval}^{i} = Dy_{reception}$).

$$Dy_{retrieval}^{i} = Dy_{reception} \quad (5.35)$$

If the TL travels to another retrieval bay from a retrieval bay, the destination bay can be in any horizontal driving lane. The probability that a randomly chosen origin bay and the destination bay are in the same horizontal driving lane is $\frac{2}{[2(d_y-1)]^2}$, except the bays are in the outer driving lanes. If both the origin and destination bays are located along an outer lane, the probability that the origin and destination bays are in the same horizontal outer driving lane is $\frac{1}{[2(d_y-1)]^2}$. In this case, where the y-axis distance is zero. The probability that k driving lanes (block distance) need to be traveled on the y-axis is $\frac{\sum_{i=1}^{b_y+1}(sum[row\ (i-k)]+sum[row\ (i+k)])sum[row\ i]}{(sum\ [LayoutMatrix]\ )^2}$. We can write equation (5.22) as:

$$Dy_{retrieval}^{ii} = \sum_{k=1}^{d_y-1} \frac{\sum_{i=1}^{b_y+1} (sum[row\ i-k] + sum[row\ i+k])sum[row\ i]}{(sum\ [LayoutMatrix]\ )^2} k(\delta_y + r)W \quad (5.36)$$

5.7. Computational Experiments and Results

This section provides numerical examples of layout optimization of both rectangular and non-rectangular container yards. This work attempts to find b_x and b_y, minimize the objective function of (1). In the following numerical experiments, it is assumed that $v = 2.22\ m/s$, equivalent to

8 km/h, is the average travel speed of a TL in yards. We set $L = 6\ m$ and $W = 2.44\ m$ for 20-foot containers, reasonable assumptions. Note that without loss of generality, we only consider the 20-foot ground slots for all instances. It is assumed that the storage capacity of a common terminal is 5000 containers (of 20-foot containers). We assume that $YL = 174\ m$ and $YD = 203\ m$, the size of an empty container yard in Placilla, Chile, a typical facility. We set $\delta_x = 2\ bay$ and $\delta_y = 5\ rows$, which are vertical and horizontal driving lane widths, respectively. It is assumed that $\chi = 7\ tiers$, which is the common stacking height in empty container depots serviced by TLs. We enumerate the number of horizontal and vertical blocks from 1 to 10 in the algorithm and all enumerations give feasible solutions in the example.

5.7.1. Rectangular Shape

There is no feasible solution for more than 8 horizontal or 6 vertical blocks because of the stack height restriction. If there are more than 8 horizontal blocks or 6 vertical blocks, the storage capacity needs to be higher than 7 tiers, which violates the height restriction in our case study. Note that all enumerated layout configurations must provide greater than or equal to the minimum required capacity. Any decrease in the storage ground space is compensated for by changing the average stacking height. Figure 5.10, Figure 5.11, and Figure 5.12 show the expected time metrics for various b_x and b_y. Figure 5.10 shows the changes for travel and placement times changes. Figure 5.11 shows the retrieval time changes and Figure 5.12 shows the cycle time changes.

When the number of horizontal blocks increases with the fixed number of vertical blocks, the placement, the retrieval, and the cycle times decrease until there are 3 horizontal blocks, as expected (Figure 5.10, Figure 5.11, and Figure 5.12). Since the number of horizontal blocks increases, the number of rows (i.e., depth) per block decreases while the average number of tiers stays the same or slightly increases to compensate for the storage ground space loss. The decrease in time by decreasing the width outweighs the increase in time by increasing the height. Note that placement and retrieval times are dependent on the depth and the average height of the block. For the number of horizontal blocks greater than 3, there is no consistent pattern for the retrieval, the placement, and the cycle times. The decrease in the depth of the block does not consistently outweigh the increase in the height of the block for those designs ($b_y > 3$) since the block depth gradually decreases when there are more than 3 vertical blocks while the increase in the height is still small. We can also observe that the cycle time pattern is consistent with retrieval time since retrieval takes the majority of the time (Figure 5.11 and Figure 5.12).

We can conclude that cycle time increases with the increase in the number of vertical blocks with a fixed number of horizontal blocks in general with two exceptions. These are designs of $b_y = 3$ and $b_x = 2$, and $b_y = 6$ and $b_x = 2$. Since the storage ground space loss for the vertical driving lane is compensated for by increasing the height, the increase in the number of vertical blocks causes an increase in retrieval time or placement time. In these two designs, cycle time decreases because there is a decrease in travel time while the placement and the retrieval times stay the same. Note that travel time changes slightly compared to the change in retrieval time. Thus, the increase in retrieval time caused by the loss of the storage ground space outweighs the travel time.

When the number of vertical blocks increases, the number of driving lanes increases. Thus, the required storage ground space needs to be compensated for by an increase of the block height while the block depth is fixed (fixed number of horizontal blocks) (Figure 5.13). Increases in the block height cause an increase in retrieval time, and therefore cycle time. The depth of each block stays the same with the increase in the number of vertical blocks with a fixed number of horizontal blocks. However, the average height of a block stays the same or increases to compensate for the ground space loss with an increase in the number of vertical driving lanes. That makes the change to retrieval and placement times correlated with the depth of a block. We show the enumerated solutions in Table 5.6 below for a rectangular yard layout. The first five columns in Table 5.6 show that the number of horizontal blocks on the y-axis, the number of vertical blocks on the x-axis, the depth of a block, the length of a block, and the average height of a block to reach the minimum required capacity in the yard, respectively. Columns td, tr, tp, and z show the expected times for travel, retrieval, placement, and cycle times when the number of horizontal blocks (b_y) and the number of vertical blocks (b_x) are the given values. The r, l, and T values are determined based on the b_y and b_x values.

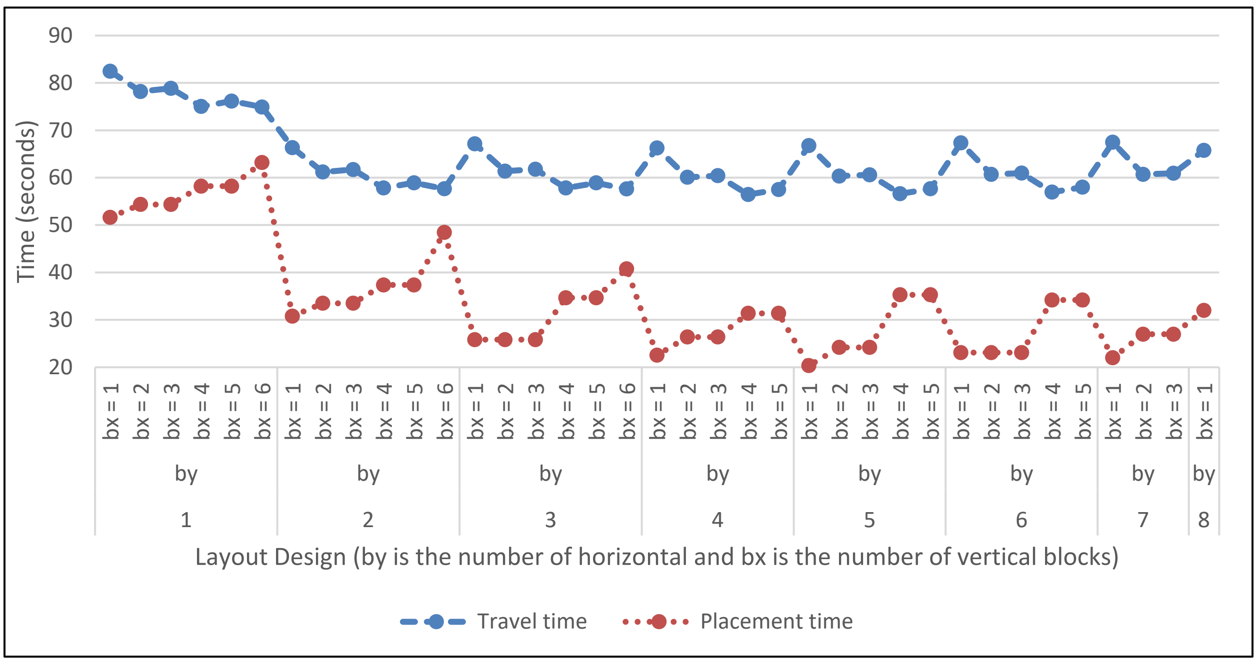


Figure 5.10. Travel and placement times vs. the number of vertical blocks b_x and the number of horizontal blocks b_y

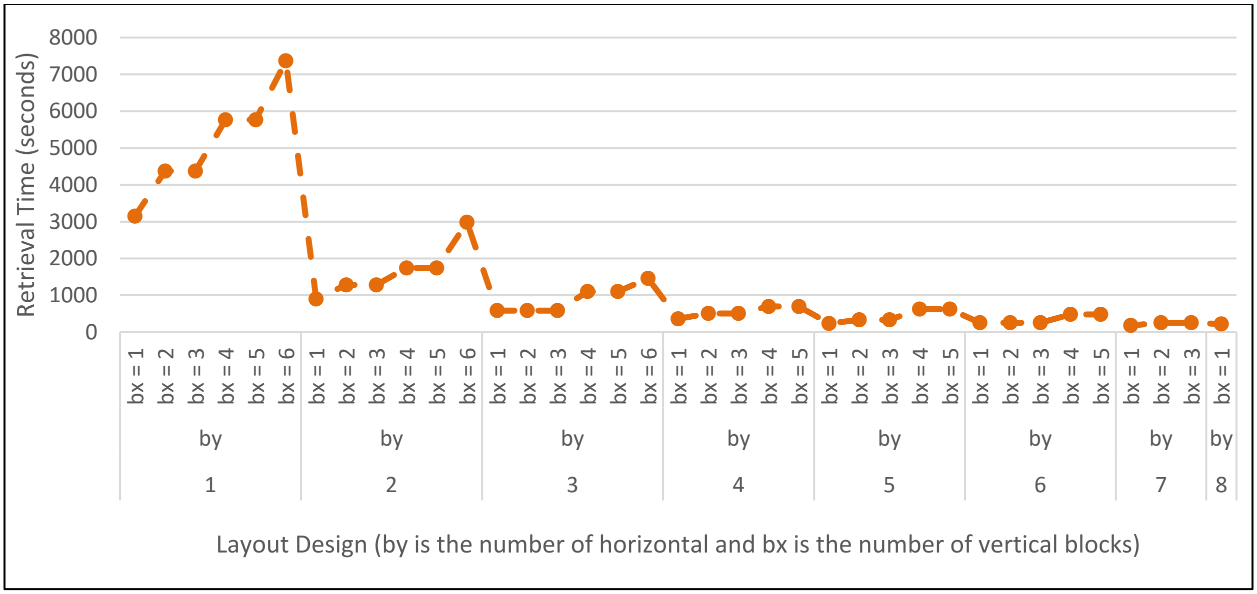


Figure 5.11. Retrieval time vs. the number of vertical blocks b_x and the number of horizontal blocks b_y

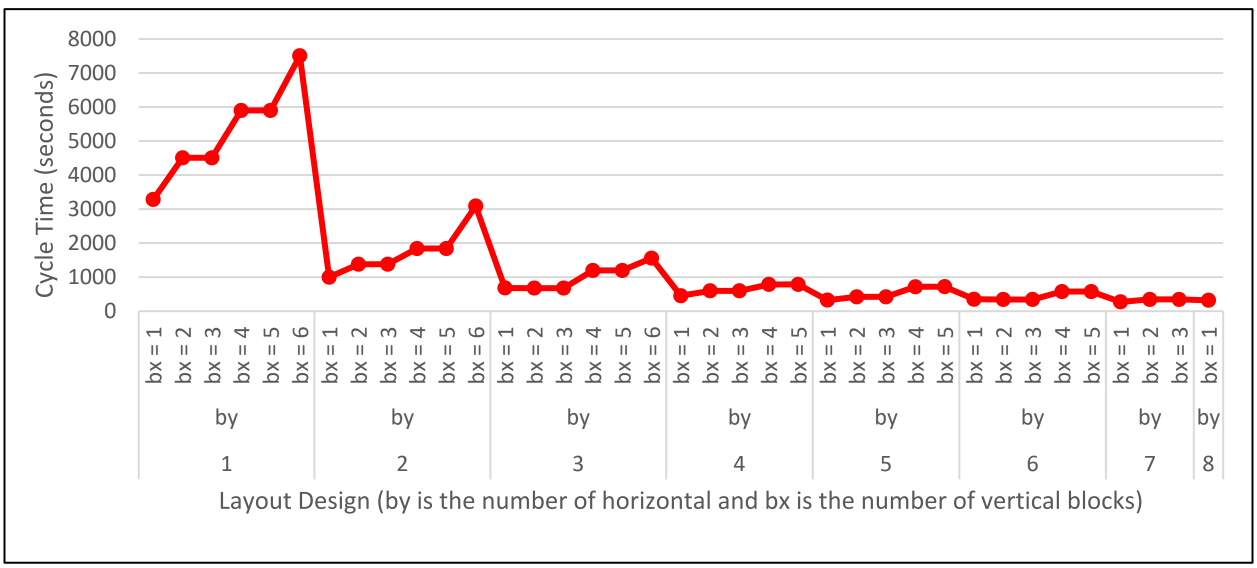


Figure 5.12. Cycle time vs. the number of vertical blocks b_x and the number of horizontal blocks b_y

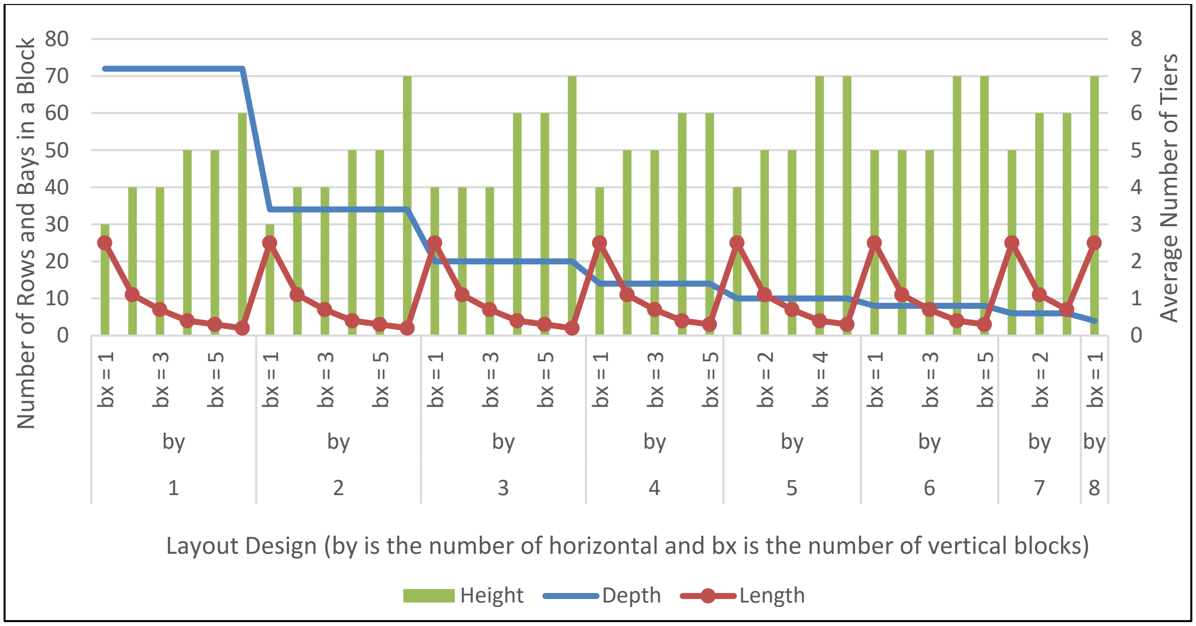


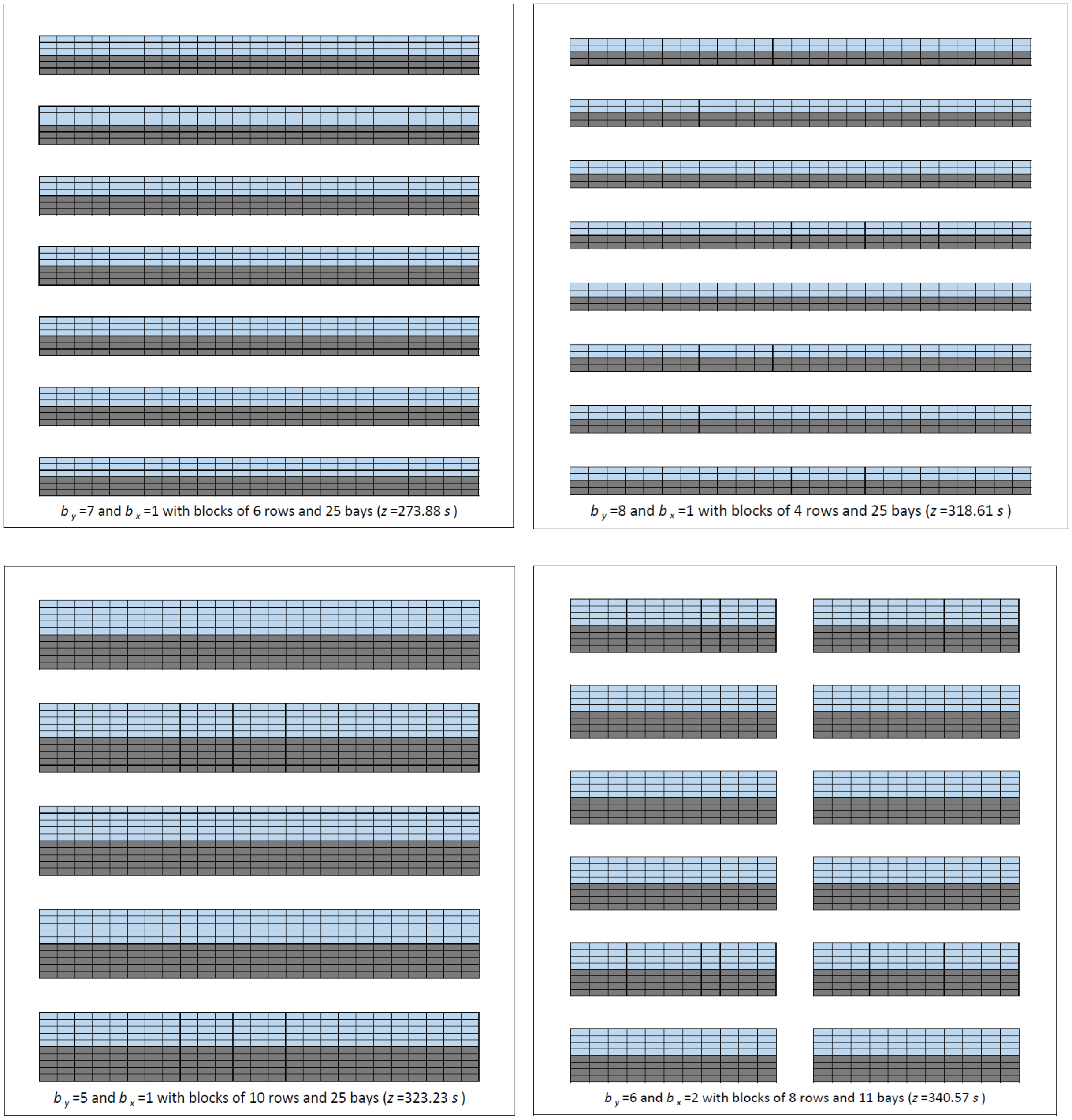
Figure 5.13. The block design (height, depth, and length) vs. the number of vertical blocks (b_x) and the number of horizontal blocks (b_y)

Table 5.6. Enumerated results for a rectangular yard with $\delta_x = 2$ bays and $\delta_y = 5$ rows with the best design shaded rows

b_y	b_x	*r*	*l*	*T*	*tt (s)*	*tr (s)*	*tp (s)*	*z (s)*
1	1	72	25	3	82.46	3147.94	51.63	3282.03
1	2	72	11	4	78.18	4373.70	54.35	4506.23
1	3	72	7	4	78.85	4373.70	54.35	4506.90
1	4	72	4	5	75.03	5765.93	58.20	5899.15
1	5	72	3	5	76.15	5765.93	58.20	5900.28
1	6	72	2	6	74.90	7367.82	63.18	7505.90
2	1	34	25	3	66.31	900.03	30.79	997.13
2	2	34	11	4	61.19	1282.42	33.50	1377.11
2	3	34	7	4	61.71	1282.42	33.50	1377.63
2	4	34	4	5	57.81	1743.33	37.35	1838.50
2	5	34	3	5	58.92	1743.33	37.35	1839.60
2	6	34	2	7	57.65	2982.26	48.45	3088.36
3	1	20	25	4	67.15	587.01	25.82	679.99
3	2	20	11	4	61.37	587.01	25.82	674.21
3	3	20	7	4	61.77	587.01	25.82	674.61
3	4	20	4	6	57.82	1102.15	34.66	1194.63
3	5	20	3	6	58.90	1102.15	34.66	1195.71
3	6	20	2	7	57.62	1458.72	40.77	1557.12
4	1	14	25	4	66.26	361.96	22.53	450.75
4	2	14	11	5	60.08	509.08	26.38	595.54
4	3	14	7	5	60.41	509.08	26.38	595.87
4	4	14	4	6	56.43	696.65	31.37	784.44
4	5	14	3	6	57.49	696.65	31.37	785.51
5	1	10	25	4	66.76	236.13	20.34	323.23
5	2	10	11	5	60.32	334.92	24.19	419.43
5	3	10	7	5	60.60	334.92	24.19	419.70
5	4	10	4	7	56.59	624.46	35.29	716.35
5	5	10	3	7	57.65	624.46	35.29	717.41
6	1	8	25	5	67.33	256.77	23.09	347.19
6	2	8	11	5	60.71	256.77	23.09	340.57
6	3	8	7	5	60.95	256.77	23.09	340.81
6	4	8	4	7	56.93	482.45	34.19	573.58
6	5	8	3	7	57.99	482.45	34.19	574.63
7	1	6	25	5	67.46	184.42	21.99	273.88
7	2	6	11	6	60.70	256.20	26.98	343.88
7	3	6	7	6	60.92	256.20	26.98	344.10
8	1	4	25	7	65.77	220.85	32.00	318.61

Using the required driving lane width of $\delta_x = 2\ bays$ and $\delta_y = 5\ rows$, we obtain the optimal layout in terms of the TL cycle time when $b_y = 7$ and $b_x = 1$ with the expected cycle time of

273.88 seconds. The travel, retrieval, and placement times are 67.46, 184.42, and 21.99 seconds, respectively, for this design. The depth of each block is 6 rows, and the length of each block is 25 bays with an average height of 5 tiers stacked. We show the eight best layout designs that give the eight lowest cycle times (Figure 5.14 and Figure 5.15) for this situation. Having multiple designs which all perform well is useful so that a human decision-maker can add other considerations and details to arrive at the final best design. There is also the important information of estimated cycle times for the various designs which demystifies the trade-offs amongst cycle times and decisions on blocking arrangements in the yard.



b_y=7 and b_x=1 with blocks of 6 rows and 25 bays (z=273.88 s)

b_y=8 and b_x=1 with blocks of 4 rows and 25 bays (z=318.61 s)

b_y=5 and b_x=1 with blocks of 10 rows and 25 bays (z=323.23 s)

b_y=6 and b_x=2 with blocks of 8 rows and 11 bays (z=340.57 s)

Figure 5.14. Four of the eight best layout configurations along with cycle times for $\delta_x = 2\ bay$ and $\delta_y = 5\ rows$

b_y =6 and b_x =3 with blocks of 8 rows and 7 bays (z =340.81 s)

b_y =7 and b_x =2 with blocks of 6 rows and 11 bays (z =343.88 s)

b_y =7 and b_x =3 with blocks of 6 rows and 7 bays (z =344.10 s)

b_y =6 and b_x =1 with blocks of 8 rows and 25 bays (z =347.19 s)

Figure 5.15. The remaining four best layout configurations along with cycle times for $\delta_x = 2\ bays$ and $\delta_y = 5\ rows$

For further analysis, we show the optimal layout for a narrower driving lane with $\delta_x = 1\ bay$ and $\delta_y = 3\ rows$, leaving other parameters the same. The optimal layout is obtained when $b_y = 10$ and $b_x = 2$ with an expected cycle time of 197.69 seconds. The travel, retrieval, and placement times are 59.27, 117.52, and 20.90 seconds, respectively, for this design. The depth of each block is 4 rows, and the length of each block is 13 bays with 5 tiers height (Figure 5.16). Note that this objective function value is better than that of the earlier example because the decrease in space allocated to driving lanes is used to form more blocks in the y-direction.

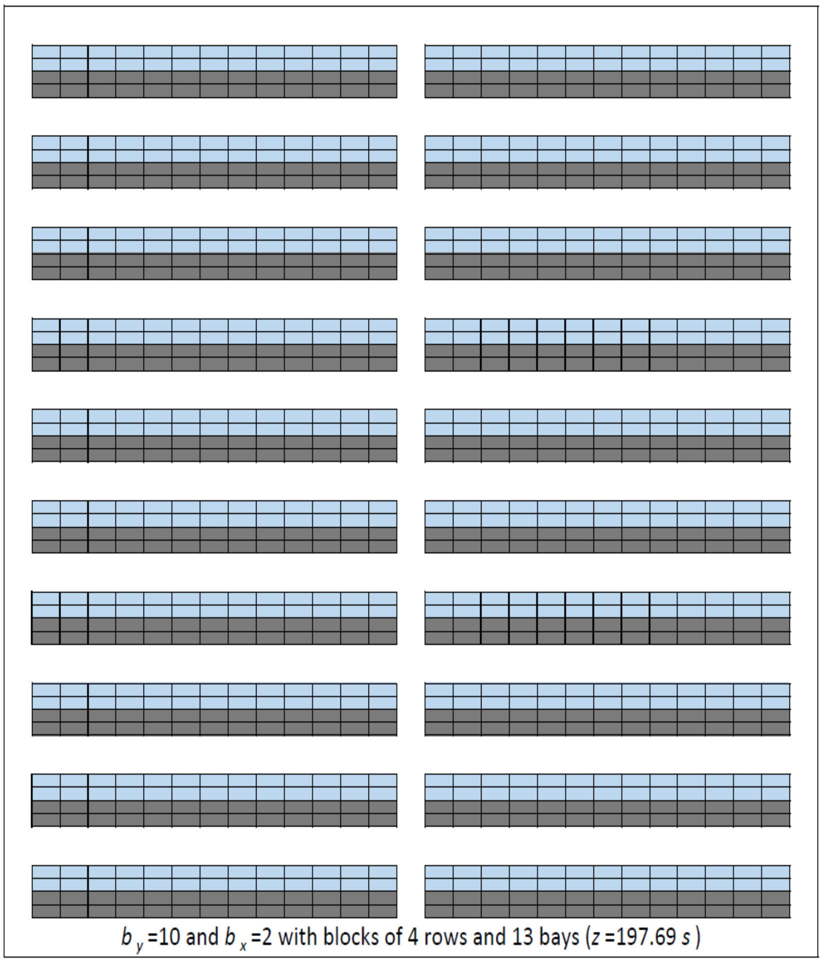


Figure 5.16. Optimal rectangular layout configuration for $\delta_x = 1\ bay$ and $\delta_y = 3\ rows$

5.7.1.1. Time Metrics Relations for Rectangular Shape

In this subsection, we observe the relations between the time metrics. We calculated the correlation coefficients between each time metric (travel, retrieval, placement, and cycle times) for the rectangular shape (Table 5.7). We observe that there is a strong positive correlation between retrieval, placement, and cycle times, as is expected.

Table 5.7. Correlation coefficient calculations for rectangular shaped layout

0	***tt***	***tr***	***tp***	***z***
tt	1.000000			
tr	0.691612	1.000000		
tp	0.585070	0.939670	1.000000	
z	0.693213	0.999995	0.940159	1.000000

5.7.2. Non-Rectangular Shape (*L*-shaped)

Numerical experiments are conducted to show the performance of the adopted model for non-rectangular (L-shaped) layouts. We use the "$L - ratio$" to refer to the ratios of YD^N/YD and YL^N/YL to create experimental instances with the given depth and length of the rectangular yard. We use equal ratios for YD^N/YD and YL^N/YL to make instances. However, ratios can be different from each other for depth and length. We use an $L - ratio$ of 0.4 in Figure 5.17 for both YD^N/YD and YL^N/YL, but these two ratios do not have to be equal. For instance, while YD^N/YD is 0.4, YL^N/YL does not have to be 0.4. If the length and depth of the yard are 174 m and 203 m, the length and the depth of the L-shape part (the unused part of the rectangular shape) will be 69.6 m and 81.2 m, respectively. We enumerate the $L - ratio$ ranging from 0 to 0.9 with an increment of 0.1. A ratio of 0 refers to a rectangular layout. An $L - ratio$ greater than 0.4 does not have any feasible solution since the capacity requirement violates the allowed stack height. We show results for an $L - ratio$ up to 0.4 along with the rectangular layout (Table 5.8 and Figure 5.18).

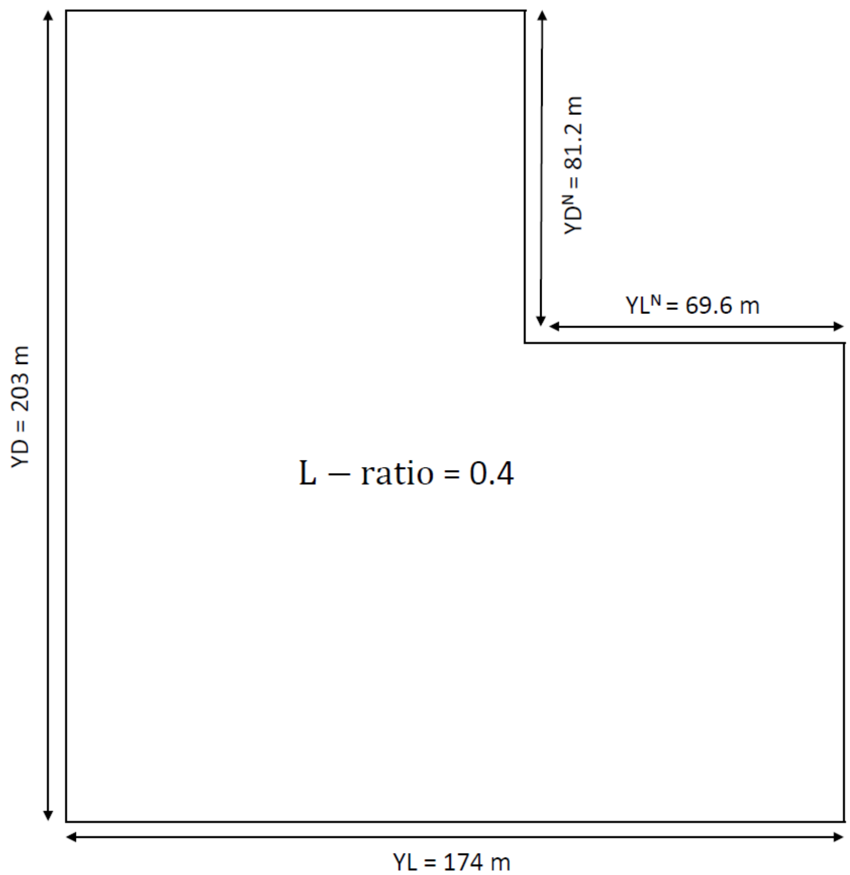


Figure 5.17. The calculation of $L - ratio$ = 81.2/203 = 69.6/174 = 0.4

We show the comparison of various $L - ratios$ for each time metric and the storage ground space for layout designs which give the minimum cycle times (Figure 5.18). We can conclude that when the yard area decreases, containers need to be stacked higher or at the same height T, which causes greater or equal placement and retrieval times. The required storage space is compensated for by an increase in the block height T or depth r, causing an increase in handling times. On the other hand, travel time decreases since the possible origin and destination locations are closer to each other.

Table 5.8. Optimal block configurations for various *L*-shaped layout sizes along with rectangular shaped layout

L-ratio	(b_y, b_x)	(r, l, T)	*tt (s)*	*tr (s)*	*tp (s)*	*z (s)*	(b_y^N, b_x^N)	*Storage Ground (TEU)*
0.0	(7, 1)	(6, 25, 5)	67.46	184.42	21.99	273.88	(0, 0)	1050
0.1	(7, 2)	(6, 11, 6)	58.50	256.20	26.98	341.68	(1, 1)	858
0.2	(7, 2)	(6, 11, 7)	56.97	348.22	33.09	438.29	(2, 1)	792
0.3	(7, 2)	(6, 11, 7)	56.20	348.22	33.09	437.52	(3, 1)	726
0.4	(6, 2)	(8, 11, 7)	56.02	482.45	34.19	572.67	(3, 1)	792

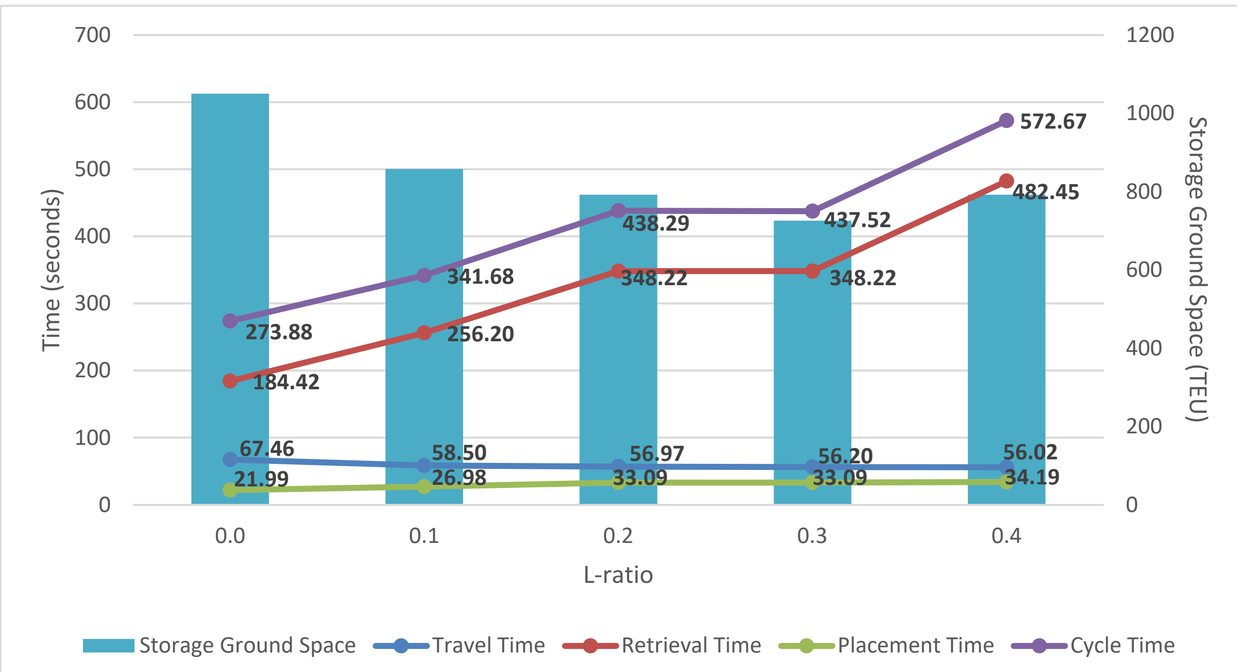


Figure 5.18. Comparison of various *L*-ratio (an *L*-ratio of 0 refers to a rectangular shape)

We also compare various *L*-ratios for each time metric when equalizing storage ground space (Table 5.9 and Figure 5.19). We show the comparison of various *L*-ratios for each time metric with an equal storage ground space of 880 TEUs except the rectangular shape which has 882 TEUs. There is no consistent pattern for the yard area and the cycle time relation if the storage ground space is around 880 TEUs. We can identify the same layout design for different *L*-ratios. For example, we get the same design for L-ratios of 0.2 and 0.3 which result in a cycle time of 440.5 s. Since we assume that the block sizes should be equal to apply our proposed model, the model cannot place another block unless there is enough space for another block. That is a limitation of our proposed model that could be relaxed in future studies.

Table 5.9. Time metrics for equal storage ground space (~880 TEUs) with various sizes of L-shaped layout along with rectangular shaped layout

L-ratio	*(b_y, b_x)*	*(r, l, T)*	*tt (s)*	*tr (s)*	*tp (s)*	*z (s)*	*(b_y^N, b_x^N)*	*Storage Ground (TEU)*
0.0	(7, 3)	(6, 7, 6)	60.92	256.20	26.98	344.10	(0,0)	882
0.1	(3, 4)	(20, 4, 6)	55.52	1102.15	34.66	1192.32	(1, 1)	880
0.2	(6, 2)	(8, 11, 6)	56.55	355.88	28.07	440.50	(2, 1)	880
0.3	(6, 2)	(8, 11, 6)	56.55	355.88	28.07	440.50	(2, 1)	880
0.4	(3, 2)	(20, 11, 6)	55.74	1102.15	34.66	1192.55	(2, 1)	880

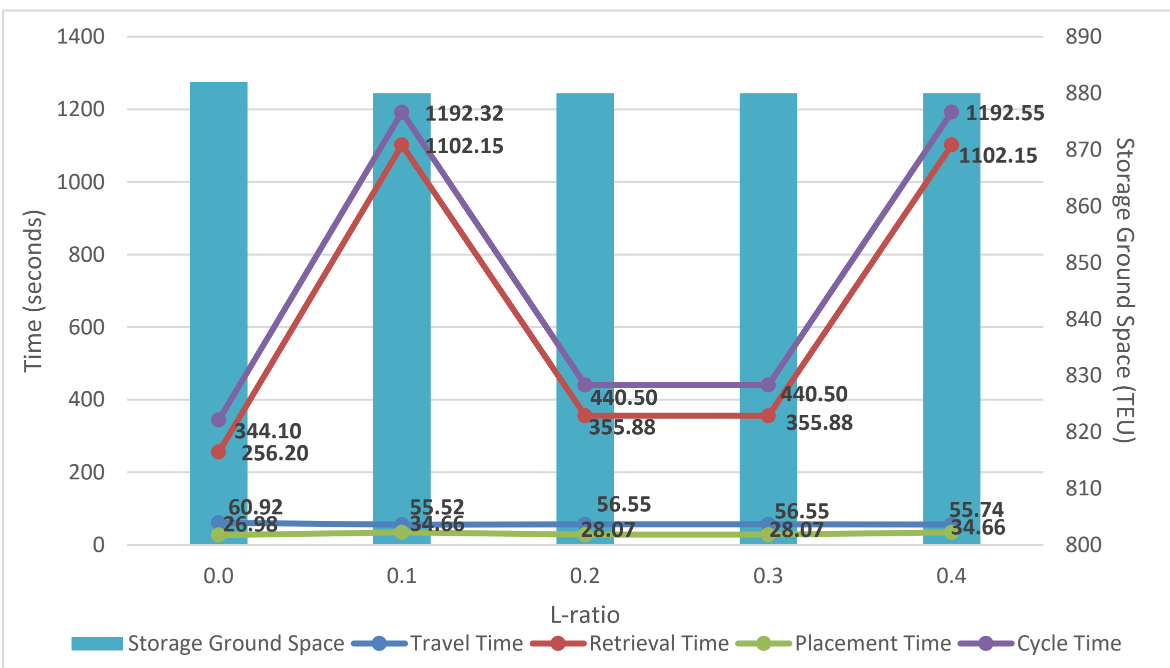


Figure 5.19. Comparison of the best layout for various L-ratios along for an equal storage ground space of 880 TEUs (an L-ratio of 0 refers to the rectangular shape)

We can conclude that the rectangular layout design is more efficient than L-shaped designs even when the minimum required capacities and the storage ground spaces are the same. Even though the travel times of the rectangular shape is greater than the L-shaped travels times, decreases in the relocation and placement times outweigh the benefit of the reduced travel time. Since the storage ground space is the same for all given designs, the average heights for a block are also the same which is 6 tiers of height. This causes a deeper block depth for L-shaped layouts which increases retrieval and placement times. Recall that the retrieval and placement times depend on the depth and the average height of a block. We see the same pattern when comparing the designs of L-ratios of 0.2 and 0.3 with the designs of L-ratios of 0.1 and 0.4. Since L-ratios of 0.1 and 0.4 result in deeper block depth than the L-ratios of 0.2 and 0.3, they have greater retrieval and placement times. Even though L-ratios of 0.1 and 0.4 layouts have smaller travel, their cycle times are greater.

5.7.2.1. Time Metrics Relations for Non-Rectangular Shape

We calculate the correlation coefficients for the same L-ratios (0.1, 0.2, 0.3, and 0.4) that were used in the previous subsection as shown in Table 5.10. The correlation coefficients between each time metric (travel, retrieval, placement, and cycle times) show that there is a strong positive correlation between retrieval, placement, and cycle times. Even though there is a positive correlation between travel time and placement time, this pair has the weakest correlation. Therefore, layout goodness is assessed primarily on retrieval times whereas placement and travel times are much less influential. Recall that we are not considering re-marshaling and if that were taking place, retrieval times would be relatively less.

Table 5.10. Correlation coefficient calculations of non-rectangular shapes for various L-ratios (0.1, 0.2, 0.3, and 0.4)

0.1	***tt***	***tr***	***tp***	***z***
tt	1.000000			
tr	0.695400	1.000000		
tp	0.571946	0.970363	1.000000	
z	0.695761	0.999999	0.970479	1.000000

0.2	***tt***	***tr***	***tp***	***z***
tt	1.000000			
tr	0.615086	1.000000		
tp	0.548207	0.957073	1.000000	
z	0.615941	0.999998	0.957418	1.000000

0.3	***tt***	***tr***	***tp***	***z***
tt	1.000000			
tr	0.515908	1.000000		
tp	0.424783	0.955713	1.000000	
z	0.516773	0.999998	0.956030	1.000000

0.4	***tt***	***tr***	***tp***	***z***
tt	1.000000			
tr	0.742625	1.000000		
tp	0.683586	0.980895	1.000000	
z	0.742971	1.000000	0.981001	1.000000

5.7.3. Summary Statistics

We show the summary statistics for all possible L-shaped designs along with a rectangular shape in Table 5.11. We can conclude that the standard deviation is high compared to the average value. In other words, the expected cycle times for various layout designs indicate that the results spread out over a large range of values which show the layout design decision importance for container yards. We can make the same conclusion based on the minimum and maximum values that are far away from each other.

Table 5.11. Summary statistics of cycle times in seconds for all possible designs for various L-ratios non-rectangular shapes along with the rectangular shape

Standard Deviation	2,237.11 s
Average	1,819.32 s
Minimum	273.88 s
Maximum	9,361.99 s

We also include the consideration of variability of retrieval times, the most important determinant of overall time, of various $L - ratios$ for designs that give the minimum cycle times (Table 5.12). As can be seen, retrieval times are highly variable with a coefficient of variation of near 100% for all layout configurations. Therefore, it can be valuable to consider the variability along with the expected value. These variability values for retrieval times can help decision-makers for yard layout design decisions. Since empty container depots have very high fluctuations depending on the seasonality and various shipment types such as individual and batch shipment, this is especially important in empty container depots.

Table 5.12. Standard deviations calculations for optimal block configurations for various L-shaped layout sizes along with rectangular shaped layout

L-ratio	*(b_y, b_x)*	*(r, l, T)*	*tr (s)*	*SD (tr)*	*z (s)*	*(b_y^N, b_x^N)*	*Storage Ground (TEU)*
0.0	(7, 1)	(6, 25, 5)	184.42	156.88	273.88	(0, 0)	1050
0.1	(7, 2)	(6, 11, 6)	256.20	222.19	341.68	(1, 1)	858
0.2	(7, 2)	(6, 11, 7)	348.22	306.68	438.29	(2, 1)	792
0.3	(7, 2)	(6, 11, 7)	348.22	306.68	437.52	(3, 1)	726
0.4	(6, 2)	(8, 11, 7)	482.45	420.77	572.67	(3, 1)	792

5.7.4. Computation Time

The computation time of the algorithm is less than a second to call the algorithm and enumerate all possible combinations of horizontal and vertical blocks. We show the elapsed time for each L-

shaped layout and the rectangular layout in Table 5.13. The search space is less than or equal to the multiplication of each number of horizontal and vertical blocks. In the case study, the largest search space is 100 (10*10) since we enumerate all possible combinations of horizontal and vertical blocks from 1 to 10.

Table 5.13. The elapsed time (seconds) for various *L*-ratios (0, 0.1, 0.2, 0.3, and 0.4)

L-ratio	0.0	0.1	0.2	0.3	0.4
Elapsed Time (seconds)	0.2992	0.2843	0.2870	0.2936	0.2794

5.8. Conclusions

This chapter proposes a method for determining the layout of container yards for both rectangular and non-rectangular designs. For evaluating layouts of a yard, the cycle time of TLs, including travel, retrieval, and placement times, is considered as the objective term subject to minimum storage capacity, maximum stacking height, and fixed yard size. A procedure for optimizing layouts of container yards is suggested.

For evaluating the objective function, this chapter proposes a method for estimating the cycle time considering the retrieval, placement, and travel times of TLs for the given layout of the yard. We also present formulas for estimating the expected travel distance of TLs for placement, retrieval, and reception in the given layout of a container yard.

This chapter proposed a novel and practical approach to be applicable to both rectangular and non-rectangular shapes of yards. We assume all blocks are the same size in terms of both length and depth. However, the approach could be extended to the problem of deriving the optimal layout of container yards for variable block sizes. We assume that blocks are perpendicular to the reception area, and the reception area is in the center of the depth side of the yard. Other orientations, such as locating the reception area in the corner of the yard or center of the length size of the yard instead of the center of the depth side of the yard, could be considered as well with a similar analysis as shown in this chapter. While we derive optimal block layouts according to cycle time, additional factors, such as truck travel times or various container size-types, can affect the best-detailed yard layout.

6. Conclusions and Future Research

This research proposes a layout optimization model for rectangular and non-rectangular container yards operated by top-lifters. Since most port container yards are operated by overhead access yard cranes, the majority of the studies in the literature focus on container yard layout optimization only operated by yard cranes. To the best of our knowledge, this is the first study that considers layout optimization for container yards operated by top-lifters. Top-lifters have different access and mobility from cranes therefore, container yards operated by top-lifters are different from other container yards studied in the literature for both handling and transfer of containers. Furthermore, the aspect of an *L*-shaped yard layout is an important realistic advance.

To enable the layout design optimization and as a stand-alone tool, we propose a Markov chain model to calculate the expected number of relocations for retrievals that allow simultaneous container arrivals for top-lifters and reach-stackers. These aspects are new to the literature. Our proposed model for the number of relocations contributes to the literature by providing an exact calculation method for the expected number of relocations. With this model, one can calculate all summary statistics for the number of relocations such as standard deviation, quartiles, and the mean values.

Our proposed Markov model assumes all arrivals and retrievals are random without any particular stacking or unstacking policy (other than containers are stacked at the most readily available slot). As a future research study, other stacking policies can be implemented for small size bay designs with advanced computer memory. We had some memory restrictions for the yard crane instances because of the large size of possible states and this may continue to be problematic for the Markov model. The expected time of retrieval and placement calculation methods can be extended with the availability of time studies for yard cranes and reach stackers to compare alternative layout designs with various handling equipment other than top-lifter based layouts.

Our proposed layout model uses enumeration to find the best layout design. A mixed-integer mathematical model approach can be implemented to solve more complicated layout structures with varying sizes throughout the yard, but such a model approach would be much more complex. In addition to that, a user-interface can be developed to be used by practitioners. Different container yard elements such as a reception area with alternative positions could then be evaluated without advanced knowledge of the approach. Furthermore, benefit-cost analysis can be made considering alternative resources such as reach stackers or yard crane instead of top-lifters, or differing numbers of the material handling resources and staffing levels.

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Appendix A. Supplementary Material for Chapter 3

Appendix A.1. Summary Statistics of the Numbers of Relocations

The following tables show the mean, standard deviation, and quartiles (1^{st}, 2^{nd}, 3^{rd}) of the computational results of the Markov chain model for each bay design for each material handling equipment type. Note that * means that this configuration's results could not be calculated due to memory overload.

Table A1. Expected number of relocations for the yard crane

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.500	1.000	1.500	2.000	2.500	3.000	3.500
2	0.000	0.375	0.750	1.126	1.503	1.881	2.261	2.641
3	0.000	0.319	0.643	0.971	1.302	1.635	1.969	2.305
4	0.000	0.286	0.584	0.888	1.195	1.505	1.816	2.128
5	0.000	0.265	0.547	0.835	1.128	1.424	1.721	2.020
6	0.000	0.250	0.521	0.799	1.082	1.369	1.657	1.946
7	0.000	0.239	0.501	0.773	1.049	1.329	1.610	1.893
8	0.000	0.231	0.486	0.752	1.024	1.298	1.575	1.853
9	0.000	0.224	0.475	0.736	1.004	1.274	1.547	1.821
10	0.000	0.218	0.465	0.723	0.987	1.255	1.524	*
11	0.000	0.213	0.457	0.712	0.974	1.239	1.506	*
12	0.000	0.209	0.450	0.703	0.963	1.225	*	*

Table A2. Standard deviation of the number of relocations for the yard crane

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.866	1.374	1.848	2.309	2.764	3.215	3.663
2	0.000	0.696	1.142	1.568	1.987	2.402	2.816	3.229
3	0.000	0.620	1.022	1.406	1.784	2.159	2.532	2.904
4	0.000	0.574	0.948	1.304	1.655	2.003	2.350	2.695
5	0.000	0.543	0.897	1.234	1.566	1.896	2.224	2.551
6	0.000	0.521	0.860	1.183	1.501	1.817	2.131	2.444
7	0.000	0.503	0.831	1.144	1.451	1.756	2.060	2.363
8	0.000	0.490	0.808	1.112	1.412	1.708	2.004	2.298
9	0.000	0.479	0.790	1.087	1.379	1.669	1.958	2.246
10	0.000	0.469	0.774	1.066	1.353	1.637	1.920	*
11	0.000	0.462	0.761	1.048	1.330	1.610	1.888	*
12	0.000	0.455	0.750	1.033	1.311	1.586	*	*

Table A3. 1st, 2nd and 3rd quartiles of number of relocations for the yard crane

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50
1	0.00	0.00	0.00	2.00	2.00	2.00	4.00	4.00
1	0.00	1.00	2.00	3.50	4.00	6.00	6.00	8.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
2	0.00	0.00	0.00	1.00	1.00	2.00	2.00	2.00
2	0.00	1.00	1.75	2.00	3.00	3.00	4.00	5.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
3	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
3	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
4	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
4	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
5	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
5	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
6	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
6	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
7	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
7	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
8	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
8	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
9	0.00	0.00	0.00	1.00	1.00	1.00	2.00	2.00
9	0.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*
10	0.00	0.00	0.00	1.00	1.00	1.00	2.00	*
10	0.00	1.00	1.00	2.00	2.00	3.00	3.00	*
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*
11	0.00	0.00	0.00	1.00	1.00	1.00	2.00	*
11	0.00	1.00	1.00	2.00	2.00	3.00	3.00	*
12	0.00	0.00	0.00	0.00	0.00	0.00	*	*
12	0.00	0.00	0.00	1.00	1.00	1.00	*	*
12	0.00	1.00	1.00	2.00	2.00	3.00	*	*

Table A4. Expected number of relocations for the top-lifter

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.500	1.000	1.500	2.000	2.500	3.000	3.500
2	0.500	1.500	2.500	3.500	4.500	5.500	6.500	7.500
3	1.000	2.500	4.000	5.500	7.000	8.500	10.000	11.500
4	1.500	3.500	5.500	7.500	9.500	11.500	13.500	15.500
5	2.000	4.500	7.000	9.500	12.000	14.500	17.000	19.500
6	2.500	5.500	8.500	11.500	14.500	17.500	20.500	23.500
7	3.000	6.500	10.000	13.500	17.000	20.500	24.000	27.500
8	3.500	7.500	11.500	15.500	19.500	23.500	27.500	31.500
9	4.000	8.500	13.000	17.500	22.000	26.500	31.000	35.500
10	4.500	9.500	14.500	19.500	24.500	29.500	34.500	39.500
11	5.000	10.500	16.000	21.500	27.000	32.500	38.000	43.500
12	5.500	11.500	17.500	23.500	29.500	35.500	41.500	47.500

Table A5. Standard deviation of the number of relocations for the top-lifter

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.866	1.374	1.848	2.309	2.764	3.215	3.663
2	0.866	1.848	2.764	3.663	4.555	5.444	6.331	7.217
3	1.374	2.764	4.110	5.444	6.774	8.102	9.428	10.754
4	1.848	3.663	5.444	7.217	8.986	10.754	12.520	14.286
5	2.309	4.555	6.774	8.986	11.195	13.403	15.610	17.816
6	2.764	5.444	8.102	10.754	13.403	16.051	18.699	21.346
7	3.215	6.331	9.428	12.520	15.610	18.699	21.787	24.875
8	3.663	7.217	10.754	14.286	17.816	21.346	24.875	28.403
9	4.110	8.102	12.078	16.051	20.022	23.992	27.962	31.932
10	4.555	8.986	13.403	17.816	22.228	26.639	31.050	35.460
11	5.000	9.870	14.727	19.581	24.434	29.285	34.137	38.988
12	5.444	10.754	16.051	21.346	26.639	31.932	37.224	42.516

Table A6. 1st, 2nd and 3rd quartiles of number of relocations for the top-lifter

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50
1	0.00	0.00	0.00	2.00	2.00	2.00	4.00	4.00
1	0.00	1.00	2.00	3.50	4.00	6.00	6.00	8.00
2	0.00	0.00	0.00	1.50	2.00	2.00	2.00	4.00
2	0.00	2.00	2.00	4.00	5.00	6.00	8.00	8.00
2	1.00	3.50	6.00	8.00	10.00	12.00	14.00	16.00
3	0.00	0.00	2.00	2.00	3.50	4.00	4.00	6.00
3	0.00	2.00	4.00	6.00	8.00	10.00	12.00	14.00
3	2.00	6.00	8.00	12.00	14.00	18.00	20.00	24.00
4	0.00	1.50	2.00	4.00	4.00	6.00	6.00	8.00
4	2.00	4.00	6.00	8.00	10.00	14.00	16.00	18.00
4	3.50	8.00	12.00	16.00	20.00	24.00	28.00	32.00
5	0.00	2.00	3.50	4.00	6.00	8.00	8.00	10.00
5	2.00	5.00	8.00	10.00	14.00	16.00	20.00	22.00
5	4.00	10.00	14.00	20.00	24.00	30.00	34.00	40.00
6	0.00	2.00	4.00	6.00	8.00	8.00	10.00	12.00
6	2.00	6.00	10.00	14.00	16.00	20.00	24.00	28.00
6	6.00	12.00	18.00	24.00	30.00	36.00	42.00	48.00
7	0.00	2.00	4.00	6.00	8.00	10.00	12.00	14.00
7	4.00	8.00	12.00	16.00	20.00	24.00	28.00	32.00
7	6.00	14.00	20.00	28.00	34.00	42.00	48.00	56.00
8	1.50	4.00	6.00	8.00	10.00	12.00	14.00	16.00
8	4.00	8.00	14.00	18.00	22.00	28.00	32.00	36.00
8	8.00	16.00	24.00	32.00	40.00	48.00	56.00	64.00
9	2.00	4.00	6.00	8.00	12.00	14.00	16.00	18.00
9	4.00	10.00	16.00	20.00	26.00	30.00	36.00	42.00
9	8.00	18.00	26.00	36.00	44.00	54.00	62.00	72.00
10	2.00	4.00	8.00	10.00	12.00	16.00	18.00	20.00
10	5.00	10.00	16.00	22.00	28.00	34.00	40.00	46.00
10	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00
11	2.00	4.00	8.00	10.00	14.00	16.00	20.00	22.00
11	6.00	12.00	18.00	26.00	32.00	38.00	44.00	50.00
11	10.00	22.00	32.00	44.00	54.00	66.00	76.00	88.00
12	2.00	6.00	8.00	12.00	16.00	18.00	22.00	24.00
12	6.00	14.00	20.00	28.00	34.00	42.00	48.00	56.00
12	12.00	24.00	36.00	48.00	60.00	72.00	84.00	96.00

Table A7. Expected number of relocations for the reach stacker

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.500	1.000	1.500	2.000	2.500	3.000	3.500
2	0.500	1.208	1.945	2.696	3.455	4.221	4.991	7.500
3	1.000	1.924	2.896	3.892	4.901	5.919	7.617	11.500
4	1.500	2.728	4.008	5.312	6.629	7.954	10.550	15.500
5	2.000	3.584	5.220	6.877	8.547	10.224	13.652	19.500
6	2.500	4.474	6.497	8.540	10.594	12.655	16.854	23.500
7	3.000	5.386	7.819	10.270	12.731	15.199	20.123	27.500
8	3.500	6.315	9.174	12.049	14.934	17.825	23.437	31.500
9	4.000	7.256	10.552	13.865	17.186	20.512	26.785	35.500
10	4.500	8.205	11.949	15.708	19.475	23.246	30.157	39.500
11	5.000	9.162	13.361	17.573	21.793	26.017	33.548	43.500
12	5.500	10.124	14.783	19.455	24.134	28.817	36.954	47.500

Table A8. Standard deviation of the number of relocations for the reach stacker

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.866	1.374	1.848	2.309	2.764	3.215	3.663
2	0.866	1.767	2.555	3.314	4.062	4.804	5.542	7.217
3	1.374	2.563	3.641	4.690	5.728	6.760	8.357	10.754
4	1.848	3.395	4.832	6.238	7.631	9.019	11.368	14.286
5	2.309	4.254	6.089	7.894	9.686	11.471	14.453	17.816
6	2.764	5.127	7.383	9.610	11.825	14.032	17.567	21.346
7	3.215	6.008	8.699	11.361	14.010	16.653	20.692	24.875
8	3.663	6.893	10.025	13.130	16.222	19.308	23.820	28.403
9	4.110	7.781	11.358	14.909	18.449	21.982	26.949	31.932
10	4.555	8.670	12.695	16.695	20.683	24.666	30.076	35.460
11	5.000	9.560	14.033	18.483	22.922	27.355	33.200	38.988
12	5.444	10.449	15.373	20.273	25.163	30.047	36.323	42.516

Table A9. 1st, 2nd and 3rd quartiles of number of relocations for the reach stacker

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50
1	0.00	0.00	0.00	2.00	2.00	2.00	4.00	4.00
1	0.00	1.00	2.00	3.50	4.00	6.00	6.00	8.00
2	0.00	0.00	0.00	0.00	0.00	0.00	2.00	4.00
2	0.00	0.00	2.00	2.00	2.00	4.00	4.00	8.00
2	1.00	2.00	4.00	4.50	6.00	8.00	8.00	16.00
3	0.00	0.00	0.00	0.00	0.00	2.00	2.00	6.00
3	0.00	2.00	2.00	2.00	4.00	4.00	6.00	14.00
3	2.00	4.00	6.00	6.00	8.00	10.00	14.00	24.00
4	0.00	0.00	0.00	2.00	2.00	2.00	4.00	8.00
4	2.00	2.00	2.00	4.00	4.00	6.00	10.00	18.00
4	3.50	6.00	8.00	10.00	11.50	14.00	20.00	32.00
5	0.00	0.00	2.00	2.00	2.00	2.00	4.00	10.00
5	2.00	2.00	4.00	6.00	6.00	8.00	12.00	22.00
5	4.00	7.50	10.00	12.00	14.00	18.00	26.00	40.00
6	0.00	2.00	2.00	2.00	2.00	4.00	6.00	12.00
6	2.00	4.00	6.00	8.00	8.00	10.00	16.00	28.00
6	6.00	8.50	12.00	16.00	20.00	22.00	34.00	48.00
7	0.00	2.00	2.00	2.00	4.00	4.00	6.00	14.00
7	4.00	6.00	8.00	10.00	10.00	14.00	20.00	32.00
7	6.00	10.00	16.00	20.00	24.00	28.00	40.00	56.00
8	1.50	2.00	2.00	4.00	4.00	6.00	8.00	16.00
8	4.00	6.00	8.00	12.00	14.00	16.00	24.00	36.00
8	8.00	12.00	18.00	24.00	28.00	34.00	48.00	64.00
9	2.00	2.00	2.00	4.00	6.00	6.00	10.00	18.00
9	4.00	8.00	10.00	14.00	16.00	20.00	28.00	42.00
9	8.00	14.00	22.00	28.00	34.00	40.00	54.00	72.00
10	2.00	2.00	4.00	4.00	6.00	6.00	12.00	20.00
10	5.00	8.00	12.00	16.00	20.00	22.00	32.00	46.00
10	10.00	16.00	24.00	32.00	38.00	46.00	62.00	80.00
11	2.00	2.00	4.00	6.00	6.00	8.00	14.00	22.00
11	6.00	10.00	14.00	18.00	22.00	26.00	38.00	50.00
11	10.00	18.00	28.00	36.00	44.00	52.00	68.00	88.00
12	2.00	4.00	4.00	6.00	8.00	10.00	16.00	24.00
12	6.00	10.00	16.00	20.00	24.00	30.00	42.00	56.00
12	12.00	20.00	30.00	40.00	48.00	58.00	74.00	96.00

Appendix A.2. Arrival Rate Effects on the Number of Relocations

Table A10. The expected number of relocations for 4 rows and 6 tiers bay design for different handling equipment with different arrival probabilities

Expected Number of Relocations			
Arrival Rates	**Crane**	**Top-lifter**	**Reach Stacker**
0	N/A	N/A	N/A
0.1	<0.01	0.12	0.12
0.2	<0.01	0.33	0.33
0.3	0.02	0.75	0.73
0.4	0.12	2.00	1.75
0.5	1.50	11.50	7.95
0.6	3.78	21.00	14.72
0.7	4.43	22.25	15.89
0.8	4.73	22.67	16.34
0.9	4.89	22.88	16.59
1	N/A	N/A	N/A

Appendix B. Supplementary Material for Chapter 4

The following tables show the mean, standard deviation, and the coefficient of variation of both retrieval and placement times in seconds for TLs for each bay design.

Table B1. Expected time of retrieval per container for TLs (seconds)

Tiers / Rows	1	2	3	4	5	6	7	8
1	12.60	20.15	29.08	40.28	54.67	73.13	96.57	125.88
2	20.74	36.81	56.79	82.95	117.52	162.74	220.85	294.06
3	30.11	55.77	87.70	129.42	184.42	256.20	348.22	463.98
4	40.69	77.12	122.11	180.42	256.77	355.88	482.45	641.20
5	52.49	100.88	160.10	236.13	334.92	462.39	624.46	827.07
6	65.51	127.07	201.71	296.63	419.00	575.94	774.60	1022.11
7	79.75	155.68	246.95	361.96	509.08	696.65	933.03	1226.55
8	95.21	186.73	295.83	432.12	605.18	824.57	1099.82	1440.51
9	111.89	220.21	348.35	507.14	707.34	959.73	1275.05	1664.06
10	129.78	256.13	404.53	587.01	815.57	1102.15	1458.72	1897.25
11	148.90	294.48	464.35	671.75	929.86	1251.84	1650.87	2140.10
12	169.23	335.27	527.83	761.36	1050.23	1408.82	1851.51	2392.64
13	190.78	378.50	594.96	855.83	1176.68	1573.09	2060.64	2654.88
14	213.56	424.16	665.75	955.17	1309.21	1744.66	2278.28	2926.84
15	237.55	472.26	740.18	1059.38	1447.83	1923.52	2504.42	3208.51
16	262.76	522.80	818.28	1168.46	1592.54	2109.69	2739.08	3499.91
17	289.19	575.77	900.03	1282.42	1743.33	2303.15	2982.26	3801.03
18	316.84	631.18	985.43	1401.25	1900.22	2503.93	3233.96	4111.89
19	345.70	689.03	1074.49	1524.95	2063.19	2712.01	3494.18	4432.48
20	375.79	749.32	1167.21	1653.52	2232.26	2927.39	3762.92	4762.81
21	407.09	812.05	1263.58	1786.97	2407.41	3150.09	4040.19	5102.88
22	439.62	877.21	1363.61	1925.29	2588.66	3380.09	4325.98	5452.69
23	473.36	944.81	1467.30	2068.49	2776.00	3617.41	4620.30	5812.25
24	508.32	1014.85	1574.64	2216.57	2969.43	3862.03	4923.14	6181.55
25	544.50	1087.32	1685.63	2369.51	3168.96	4113.97	5234.52	6560.59
26	581.91	1162.24	1800.29	2527.34	3374.58	4373.21	5554.42	6949.38
27	620.52	1239.59	1918.60	2690.03	3586.29	4639.77	5882.85	7347.91
28	660.36	1319.38	2040.57	2857.61	3804.10	4913.64	6219.81	7756.19
29	701.42	1401.60	2166.19	3030.05	4028.00	5194.82	6565.30	8174.22
30	743.70	1486.27	2295.47	3207.38	4257.99	5483.31	6919.32	8602.00
31	787.19	1573.37	2428.41	3389.57	4494.08	5779.11	7281.87	9039.52
32	831.91	1662.91	2565.00	3576.65	4736.26	6082.23	7652.95	9486.79
33	877.84	1754.89	2705.25	3768.60	4984.54	6392.66	8032.56	9943.82
34	924.99	1849.31	2849.16	3965.42	5238.91	6710.40	8420.70	10410.59
35	973.36	1946.16	2996.72	4167.12	5499.37	7035.45	8817.37	10887.11
36	1022.95	2045.46	3147.94	4373.70	5765.93	7367.82	9222.58	11373.37
37	1073.76	2147.19	3302.82	4585.15	6038.58	7707.50	9636.31	11869.39
38	1125.79	2251.36	3461.36	4801.48	6317.33	8054.50	10058.58	12375.16

Table B2. Standard deviation of the retrieval time for TLs (seconds)

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.00	11.31	19.83	30.72	45.43	65.27	91.50	125.31
2	11.61	26.37	44.15	67.88	99.99	142.82	198.67	269.81
3	20.02	42.60	70.48	107.43	156.88	222.19	306.68	413.65
4	29.08	60.65	99.62	150.69	218.31	306.88	420.77	564.32
5	39.02	80.67	131.72	197.88	284.63	397.41	541.63	722.70
6	49.92	102.71	166.86	249.10	355.96	493.92	669.45	889.01
7	61.82	126.78	205.06	304.39	432.35	596.47	804.30	1063.35
8	74.74	152.91	246.33	363.77	513.82	705.11	946.23	1245.75
9	88.67	181.11	290.70	427.25	600.42	819.87	1095.26	1436.26
10	103.64	211.38	338.18	494.86	692.15	940.76	1251.43	1634.88
11	119.64	243.72	388.76	566.61	789.03	1067.81	1414.75	1841.64
12	136.68	278.14	442.46	642.50	891.07	1201.03	1585.23	2056.56
13	154.76	314.65	499.28	722.54	998.28	1340.42	1762.90	2279.66
14	173.88	353.24	559.22	806.74	1110.67	1486.01	1947.76	2510.95
15	194.04	393.93	622.30	895.09	1228.25	1637.80	2139.84	2750.45
16	215.25	436.70	688.50	987.62	1351.02	1795.80	2339.13	2998.16
17	237.50	481.56	757.84	1084.31	1478.99	1960.02	2545.64	3254.10
18	260.80	528.51	830.31	1185.17	1612.16	2130.47	2759.40	3518.28
19	285.14	577.56	905.92	1290.21	1750.53	2307.14	2980.40	3790.71
20	310.53	628.70	984.66	1399.43	1894.12	2490.05	3208.65	4071.40
21	336.97	681.94	1066.55	1512.82	2042.92	2679.20	3444.16	4360.36
22	364.46	737.27	1151.57	1630.40	2196.94	2874.60	3686.93	4657.59
23	392.99	794.70	1239.74	1752.16	2356.18	3076.24	3936.98	4963.11
24	422.57	854.22	1331.05	1878.11	2520.64	3284.14	4194.30	5276.91
25	453.20	915.84	1425.50	2008.24	2690.32	3498.29	4458.90	5599.01
26	484.88	979.55	1523.09	2142.56	2865.24	3718.71	4730.79	5929.41
27	517.61	1045.37	1623.83	2281.07	3045.38	3945.38	5009.96	6268.12
28	551.39	1113.28	1727.71	2423.76	3230.74	4178.32	5296.43	6615.14
29	586.21	1183.29	1834.74	2570.65	3421.34	4417.53	5590.19	6970.48
30	622.09	1255.39	1944.92	2721.73	3617.18	4663.01	5891.25	7334.13
31	659.01	1329.60	2058.24	2877.00	3818.24	4914.75	6199.61	7706.12
32	696.98	1405.90	2174.70	3036.46	4024.55	5172.77	6515.28	8086.43
33	736.00	1484.30	2294.32	3200.11	4236.08	5437.07	6838.26	8475.07
34	776.07	1564.80	2417.08	3367.96	4452.86	5707.64	7168.54	8872.05
35	817.20	1647.40	2542.98	3540.00	4674.87	5984.49	7506.13	9277.37
36	859.37	1732.10	2672.04	3716.23	4902.12	6267.61	7851.04	9691.03
37	902.59	1818.90	2804.24	3896.67	5134.61	6557.02	8203.27	10113.03
38	946.85	1907.79	2939.59	4081.29	5372.34	6852.71	8562.81	10543.39

Table B3. Coefficient of variation of the retrieval time for TLs

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.561	0.682	0.763	0.831	0.893	0.948	0.995
2	0.560	0.716	0.777	0.818	0.851	0.878	0.900	0.918
3	0.665	0.764	0.804	0.830	0.851	0.867	0.881	0.892
4	0.715	0.787	0.816	0.835	0.850	0.862	0.872	0.880
5	0.743	0.800	0.823	0.838	0.850	0.859	0.867	0.874
6	0.762	0.808	0.827	0.840	0.850	0.858	0.864	0.870
7	0.775	0.814	0.830	0.841	0.849	0.856	0.862	0.867
8	0.785	0.819	0.833	0.842	0.849	0.855	0.860	0.865
9	0.793	0.822	0.835	0.842	0.849	0.854	0.859	0.863
10	0.799	0.825	0.836	0.843	0.849	0.854	0.858	0.862
11	0.804	0.828	0.837	0.843	0.849	0.853	0.857	0.861
12	0.808	0.830	0.838	0.844	0.848	0.853	0.856	0.860
13	0.811	0.831	0.839	0.844	0.848	0.852	0.856	0.859
14	0.814	0.833	0.840	0.845	0.848	0.852	0.855	0.858
15	0.817	0.834	0.841	0.845	0.848	0.851	0.854	0.857
16	0.819	0.835	0.841	0.845	0.848	0.851	0.854	0.857
17	0.821	0.836	0.842	0.846	0.848	0.851	0.854	0.856
18	0.823	0.837	0.843	0.846	0.848	0.851	0.853	0.856
19	0.825	0.838	0.843	0.846	0.848	0.851	0.853	0.855
20	0.826	0.839	0.844	0.846	0.849	0.851	0.853	0.855
21	0.828	0.840	0.844	0.847	0.849	0.851	0.852	0.854
22	0.829	0.840	0.845	0.847	0.849	0.850	0.852	0.854
23	0.830	0.841	0.845	0.847	0.849	0.850	0.852	0.854
24	0.831	0.842	0.845	0.847	0.849	0.850	0.852	0.854
25	0.832	0.842	0.846	0.848	0.849	0.850	0.852	0.853
26	0.833	0.843	0.846	0.848	0.849	0.850	0.852	0.853
27	0.834	0.843	0.846	0.848	0.849	0.850	0.852	0.853
28	0.835	0.844	0.847	0.848	0.849	0.850	0.852	0.853
29	0.836	0.844	0.847	0.848	0.849	0.850	0.851	0.853
30	0.836	0.845	0.847	0.849	0.850	0.850	0.851	0.853
31	0.837	0.845	0.848	0.849	0.850	0.850	0.851	0.852
32	0.838	0.845	0.848	0.849	0.850	0.850	0.851	0.852
33	0.838	0.846	0.848	0.849	0.850	0.851	0.851	0.852
34	0.839	0.846	0.848	0.849	0.850	0.851	0.851	0.852
35	0.840	0.846	0.849	0.850	0.850	0.851	0.851	0.852
36	0.840	0.847	0.849	0.850	0.850	0.851	0.851	0.852
37	0.841	0.847	0.849	0.850	0.850	0.851	0.851	0.852
38	0.841	0.847	0.849	0.850	0.850	0.851	0.851	0.852

Table B4. Expected time of placement per container for TLs (seconds)

Tiers / Rows	1	2	3	4	5	6	7	8
1	11.20	11.65	13.23	15.95	19.80	24.78	30.90	38.15
2	12.30	12.75	14.33	17.05	20.90	25.88	32.00	39.25
3	13.39	13.84	15.43	18.14	21.99	26.98	33.09	40.34
4	14.49	14.94	16.52	19.24	23.09	28.07	34.19	41.44
5	15.59	16.04	17.62	20.34	24.19	29.17	35.29	42.54
6	16.69	17.14	18.72	21.44	25.29	30.27	36.39	43.64
7	17.78	18.23	19.82	22.53	26.38	31.37	37.48	44.73
8	18.88	19.33	20.91	23.63	27.48	32.46	38.58	45.83
9	19.98	20.43	22.01	24.73	28.58	33.56	39.68	46.93
10	21.07	21.52	23.11	25.82	29.67	34.66	40.77	48.02
11	22.17	22.62	24.20	26.92	30.77	35.75	41.87	49.12
12	23.27	23.72	25.30	28.02	31.87	36.85	42.97	50.22
13	24.37	24.82	26.40	29.12	32.97	37.95	44.07	51.32
14	25.46	25.91	27.50	30.21	34.06	39.05	45.16	52.41
15	26.56	27.01	28.59	31.31	35.16	40.14	46.26	53.51
16	27.66	28.11	29.69	32.41	36.26	41.24	47.36	54.61
17	28.75	29.20	30.79	33.50	37.35	42.34	48.45	55.70
18	29.85	30.30	31.88	34.60	38.45	43.43	49.55	56.80
19	30.95	31.40	32.98	35.70	39.55	44.53	50.65	57.90
20	32.04	32.49	34.08	36.79	40.64	45.63	51.74	58.99
21	33.14	33.59	35.18	37.89	41.74	46.73	52.84	60.09
22	34.24	34.69	36.27	38.99	42.84	47.82	53.94	61.19
23	35.34	35.79	37.37	40.09	43.94	48.92	55.04	62.29
24	36.43	36.88	38.47	41.18	45.03	50.02	56.13	63.38
25	37.53	37.98	39.56	42.28	46.13	51.11	57.23	64.48
26	38.63	39.08	40.66	43.38	47.23	52.21	58.33	65.58
27	39.72	40.17	41.76	44.47	48.32	53.31	59.42	66.67
28	40.82	41.27	42.86	45.57	49.42	54.41	60.52	67.77
29	41.92	42.37	43.95	46.67	50.52	55.50	61.62	68.87
30	43.02	43.47	45.05	47.77	51.62	56.60	62.72	69.97
31	44.11	44.56	46.15	48.86	52.71	57.70	63.81	71.06
32	45.21	45.66	47.24	49.96	53.81	58.79	64.91	72.16
33	46.31	46.76	48.34	51.06	54.91	59.89	66.01	73.26
34	47.40	47.85	49.44	52.15	56.00	60.99	67.10	74.35
35	48.50	48.95	50.53	53.25	57.10	62.08	68.20	75.45
36	49.60	50.05	51.63	54.35	58.20	63.18	69.30	76.55
37	50.70	51.15	52.73	55.45	59.30	64.28	70.40	77.65
38	51.79	52.24	53.83	56.54	60.39	65.38	71.49	78.74

Table B5. Standard deviation of the placement time for TLs (seconds)

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.00	0.45	2.27	5.10	8.95	13.82	19.70	26.60
2	1.10	1.19	2.52	5.22	9.02	13.86	19.73	26.62
3	1.79	1.85	2.89	5.40	9.13	13.93	19.78	26.66
4	2.45	2.49	3.34	5.66	9.28	14.03	19.85	26.71
5	3.10	3.14	3.84	5.97	9.47	14.16	19.94	26.78
6	3.75	3.77	4.38	6.33	9.70	14.32	20.05	26.86
7	4.39	4.41	4.94	6.73	9.97	14.50	20.18	26.96
8	5.03	5.05	5.52	7.16	10.26	14.70	20.33	27.07
9	5.67	5.68	6.10	7.62	10.59	14.93	20.50	27.20
10	6.30	6.32	6.70	8.11	10.95	15.19	20.68	27.34
11	6.94	6.95	7.30	8.61	11.32	15.46	20.89	27.49
12	7.57	7.59	7.91	9.13	11.72	15.76	21.11	27.66
13	8.21	8.22	8.52	9.66	12.14	16.07	21.34	27.84
14	8.85	8.86	9.13	10.21	12.58	16.41	21.60	28.03
15	9.48	9.49	9.75	10.76	13.04	16.76	21.86	28.24
16	10.11	10.12	10.37	11.33	13.51	17.12	22.15	28.46
17	10.75	10.76	10.99	11.90	13.99	17.51	22.44	28.69
18	11.38	11.39	11.61	12.47	14.48	17.90	22.75	28.93
19	12.02	12.03	12.23	13.06	14.98	18.31	23.08	29.19
20	12.65	12.66	12.85	13.64	15.50	18.73	23.41	29.46
21	13.29	13.29	13.48	14.23	16.02	19.17	23.76	29.73
22	13.92	13.93	14.10	14.83	16.55	19.61	24.12	30.02
23	14.55	14.56	14.73	15.42	17.09	20.07	24.49	30.32
24	15.19	15.20	15.36	16.02	17.63	20.53	24.88	30.63
25	15.82	15.83	15.98	16.62	18.18	21.01	25.27	30.95
26	16.46	16.46	16.61	17.23	18.73	21.49	25.67	31.28
27	17.09	17.10	17.24	17.83	19.29	21.98	26.08	31.62
28	17.72	17.73	17.87	18.44	19.86	22.47	26.50	31.96
29	18.36	18.36	18.50	19.05	20.42	22.98	26.93	32.32
30	18.99	19.00	19.13	19.66	20.99	23.49	27.36	32.68
31	19.63	19.63	19.76	20.28	21.57	24.00	27.81	33.06
32	20.26	20.26	20.39	20.89	22.15	24.52	28.26	33.44
33	20.89	20.90	21.02	21.51	22.73	25.05	28.72	33.82
34	21.53	21.53	21.65	22.12	23.31	25.58	29.18	34.22
35	22.16	22.16	22.28	22.74	23.90	26.11	29.65	34.62
36	22.79	22.80	22.91	23.36	24.49	26.65	30.13	35.03
37	23.43	23.43	23.54	23.98	25.08	27.20	30.61	35.45
38	24.06	24.07	24.17	24.60	25.67	27.75	31.10	35.87

Table B6. Coefficient of variation of the placement time for TLs

Tiers / Rows	1	2	3	4	5	6	7	8
1	0.000	0.039	0.171	0.320	0.452	0.558	0.638	0.697
2	0.089	0.093	0.176	0.306	0.431	0.536	0.617	0.678
3	0.134	0.133	0.187	0.298	0.415	0.516	0.598	0.661
4	0.169	0.167	0.202	0.294	0.402	0.500	0.581	0.645
5	0.199	0.196	0.218	0.293	0.392	0.485	0.565	0.630
6	0.225	0.220	0.234	0.295	0.384	0.473	0.551	0.616
7	0.247	0.242	0.249	0.299	0.378	0.462	0.538	0.603
8	0.266	0.261	0.264	0.303	0.374	0.453	0.527	0.591
9	0.284	0.278	0.277	0.308	0.371	0.445	0.517	0.580
10	0.299	0.294	0.290	0.314	0.369	0.438	0.507	0.569
11	0.313	0.307	0.302	0.320	0.368	0.432	0.499	0.560
12	0.326	0.320	0.313	0.326	0.368	0.428	0.491	0.551
13	0.337	0.331	0.323	0.332	0.368	0.424	0.484	0.542
14	0.347	0.342	0.332	0.338	0.369	0.420	0.478	0.535
15	0.357	0.351	0.341	0.344	0.371	0.417	0.473	0.528
16	0.366	0.360	0.349	0.350	0.373	0.415	0.468	0.521
17	0.374	0.368	0.357	0.355	0.374	0.413	0.463	0.515
18	0.381	0.376	0.364	0.361	0.377	0.412	0.459	0.509
19	0.388	0.383	0.371	0.366	0.379	0.411	0.456	0.504
20	0.395	0.390	0.377	0.371	0.381	0.411	0.452	0.499
21	0.401	0.396	0.383	0.376	0.384	0.410	0.450	0.495
22	0.407	0.402	0.389	0.380	0.386	0.410	0.447	0.491
23	0.412	0.407	0.394	0.385	0.389	0.410	0.445	0.487
24	0.417	0.412	0.399	0.389	0.391	0.411	0.443	0.483
25	0.422	0.417	0.404	0.393	0.394	0.411	0.442	0.480
26	0.426	0.421	0.409	0.397	0.397	0.412	0.440	0.477
27	0.430	0.426	0.413	0.401	0.399	0.412	0.439	0.474
28	0.434	0.430	0.417	0.405	0.402	0.413	0.438	0.472
29	0.438	0.433	0.421	0.408	0.404	0.414	0.437	0.469
30	0.442	0.437	0.425	0.412	0.407	0.415	0.436	0.467
31	0.445	0.441	0.428	0.415	0.409	0.416	0.436	0.465
32	0.448	0.444	0.432	0.418	0.412	0.417	0.435	0.463
33	0.451	0.447	0.435	0.421	0.414	0.418	0.435	0.462
34	0.454	0.450	0.438	0.424	0.416	0.419	0.435	0.460
35	0.457	0.453	0.441	0.427	0.419	0.421	0.435	0.459
36	0.460	0.456	0.444	0.430	0.421	0.422	0.435	0.458
37	0.462	0.458	0.446	0.432	0.423	0.423	0.435	0.457
38	0.465	0.461	0.449	0.435	0.425	0.424	0.435	0.456

Appendix C. Supplementary Material for Chapter 5

We show the enumerated solutions for possible yard layout designs showing the number of vertical and horizontal blocks for various L-ratios from 0.1 to 0.4 and a rectangular shaped layout.

Columns tt, tr, $SD\ (tr)$, tp, and z show the time metrics in seconds regarding the given the number of horizontal blocks (b_y) and the number of vertical blocks (b_x) in each row. The $SD\ (tr)$ column shows the standard deviation of retrieval time for the given design in column (r, l, T) which refers to the depth, length, and average height of a block, respectively. In addition to the Table 6.6 variables, column (b_y^N, b_x^N) refers to the number of horizontal and vertical blocks in the non-used part of the L-shaped yard. The last column shows the number of storage ground spaces, excluding the unused ground space and driving lanes, in the TEU's metric.

The highlighted row in each table shows the best yard designs for its L-ratio. The best design refers to the yard design which gives the minimum cycle time as long as it has the minimum required capacity or larger.

Table C1. Time metrics of enumerated design parameters of rectangular shape (*s*-seconds)								
(b_y, b_x)	***(r, l, T)***	***tt (s)***	***tr (s)***	***SD (tr)(s)***	***tp (s)***	***z (s)***	***(b_y^N, b_x^N)***	***Storage Ground (TEU)***
(1, 1)	(72, 25, 3)	82.46	3147.94	2672.04	51.63	3282.03	(0, 0)	1800
(1, 2)	(72, 11, 4)	78.18	4373.70	3716.23	54.35	4506.23	(0, 0)	1584
(1, 3)	(72, 7, 4)	78.85	4373.70	3716.23	54.35	4506.90	(0, 0)	1512
(1, 4)	(72, 4, 5)	75.03	5765.93	4902.12	58.20	5899.15	(0, 0)	1152
(1, 5)	(72, 3, 5)	76.15	5765.93	4902.12	58.20	5900.28	(0, 0)	1080
(1, 6)	(72, 2, 6)	74.90	7367.82	6267.61	63.18	7505.90	(0, 0)	864
(2, 1)	(34, 25, 3)	66.31	900.03	757.84	30.79	997.13	(0, 0)	1700
(2, 2)	(34, 11, 4)	61.19	1282.42	1084.31	33.50	1377.11	(0, 0)	1496
(2, 3)	(34, 7, 4)	61.71	1282.42	1084.31	33.50	1377.63	(0, 0)	1428
(2, 4)	(34, 4, 5)	57.81	1743.33	1478.99	37.35	1838.50	(0, 0)	1088
(2, 5)	(34, 3, 5)	58.92	1743.33	1478.99	37.35	1839.60	(0, 0)	1020
(2, 6)	(34, 2, 7)	57.65	2982.26	2545.64	48.45	3088.36	(0, 0)	816
(3, 1)	(20, 25, 4)	67.15	587.01	494.86	25.82	679.99	(0, 0)	1500
(3, 2)	(20, 11, 4)	61.37	587.01	494.86	25.82	674.21	(0, 0)	1320
(3, 3)	(20, 7, 4)	61.77	587.01	494.86	25.82	674.61	(0, 0)	1260
(3, 4)	(20, 4, 6)	57.82	1102.15	940.76	34.66	1194.63	(0, 0)	960
(3, 5)	(20, 3, 6)	58.90	1102.15	940.76	34.66	1195.71	(0, 0)	900
(3, 6)	(20, 2, 7)	57.62	1458.72	1251.43	40.77	1557.12	(0, 0)	720
(4, 1)	(14, 25, 4)	66.26	361.96	304.39	22.53	450.75	(0, 0)	1400
(4, 2)	(14, 11, 5)	60.08	509.08	432.35	26.38	595.54	(0, 0)	1232
(4, 3)	(14, 7, 5)	60.41	509.08	432.35	26.38	595.87	(0, 0)	1176
(4, 4)	(14, 4, 6)	56.43	696.65	596.47	31.37	784.44	(0, 0)	896
(4, 5)	(14, 3, 6)	57.49	696.65	596.47	31.37	785.51	(0, 0)	840
(5, 1)	(10, 25, 4)	66.76	236.13	197.88	20.34	323.23	(0, 0)	1250
(5, 2)	(10, 11, 5)	60.32	334.92	284.63	24.19	419.43	(0, 0)	1100
(5, 3)	(10, 7, 5)	60.60	334.92	284.63	24.19	419.70	(0, 0)	1050
(5, 4)	(10, 4, 7)	56.59	624.46	541.63	35.29	716.35	(0, 0)	800
(5, 5)	(10, 3, 7)	57.65	624.46	541.63	35.29	717.41	(0, 0)	750
(6, 1)	(8, 25, 5)	67.33	256.77	218.31	23.09	347.19	(0, 0)	1200
(6, 2)	(8, 11, 5)	60.71	256.77	218.31	23.09	340.57	(0, 0)	1056
(6, 3)	(8, 7, 5)	60.95	256.77	218.31	23.09	340.81	(0, 0)	1008
(6, 4)	(8, 4, 7)	56.93	482.45	420.77	34.19	573.58	(0, 0)	768
(6, 5)	(8, 3, 7)	57.99	482.45	420.77	34.19	574.63	(0, 0)	720
(7, 1)	(6, 25, 5)	67.46	184.42	156.88	21.99	273.88	(0, 0)	1050
(7, 2)	(6, 11, 6)	60.70	256.20	222.19	26.98	343.88	(0, 0)	924
(7, 3)	(6, 7, 6)	60.92	256.20	222.19	26.98	344.10	(0, 0)	882
(8, 1)	(4, 25, 7)	65.77	220.85	198.67	32.00	318.61	(0, 0)	800

Table C2. Time metrics of enumerated design parameters when L-ratio is 0.1 (s-seconds)								
(b_y, b_x)	***(r, l, T)***	***tt (s)***	***tr (s)***	***SD (tr)(s)***	***tp (s)***	***z (s)***	***(b_y^N, b_x^N)***	***Storage Ground (TEU)***
(1, 2)	(72, 11, 7)	63.54	9222.58	7851.04	69.30	9355.41	(1, 1)	792
(1, 3)	(72, 7, 5)	68.27	5765.93	4902.12	58.20	5892.39	(1, 1)	1008
(1, 4)	(72, 4, 6)	67.89	7367.82	6267.61	63.18	7498.90	(1, 1)	864
(1, 5)	(72, 3, 6)	70.18	7367.82	6267.61	63.18	7501.19	(1, 1)	864
(1, 6)	(72, 2, 7)	70.12	9222.58	7851.04	69.30	9361.99	(1, 1)	720
(2, 1)	(34, 25, 6)	61.58	2303.15	1960.02	42.34	2407.07	(1, 1)	850
(2, 2)	(34, 11, 5)	56.56	1743.33	1478.99	37.35	1837.25	(1, 1)	1122
(2, 3)	(34, 7, 5)	57.72	1743.33	1478.99	37.35	1838.40	(1, 1)	1190
(2, 4)	(34, 4, 6)	54.89	2303.15	1960.02	42.34	2400.38	(1, 1)	952
(2, 5)	(34, 3, 6)	56.36	2303.15	1960.02	42.34	2401.85	(1, 1)	918
(2, 6)	(34, 2, 7)	55.54	2982.26	2545.64	48.45	3086.26	(1, 1)	748
(3, 1)	(20, 25, 5)	61.92	815.57	692.15	29.67	907.16	(1, 1)	1000
(3, 2)	(20, 11, 5)	57.57	815.57	692.15	29.67	902.81	(1, 1)	1100
(3, 3)	(20, 7, 5)	58.67	815.57	692.15	29.67	903.91	(1, 1)	1120
(3, 4)	(20, 4, 6)	55.52	1102.15	940.76	34.66	1192.32	(1, 1)	880
(3, 5)	(20, 3, 6)	56.91	1102.15	940.76	34.66	1193.71	(1, 1)	840
(4, 1)	(14, 25, 5)	61.17	509.08	432.35	26.38	596.63	(1, 1)	1050
(4, 2)	(14, 11, 5)	56.64	509.08	432.35	26.38	592.10	(1, 1)	1078
(4, 3)	(14, 7, 5)	57.68	509.08	432.35	26.38	593.14	(1, 1)	1078
(4, 4)	(14, 4, 6)	54.39	696.65	596.47	31.37	782.41	(1, 1)	840
(4, 5)	(14, 3, 7)	55.76	933.03	804.30	37.48	1026.26	(1, 1)	798
(5, 1)	(10, 25, 5)	62.69	334.92	284.63	24.19	421.80	(1, 1)	1000
(5, 2)	(10, 11, 6)	57.49	462.39	397.41	29.17	549.04	(1, 1)	990
(5, 3)	(10, 7, 6)	58.35	462.39	397.41	29.17	549.91	(1, 1)	980
(5, 4)	(10, 4, 7)	54.91	624.46	541.63	35.29	714.66	(1, 1)	760
(5, 5)	(10, 3, 7)	56.21	624.46	541.63	35.29	715.97	(1, 1)	720
(6, 1)	(8, 25, 5)	63.61	256.77	218.31	23.09	343.47	(1, 1)	1000
(6, 2)	(8, 11, 6)	58.15	355.88	306.88	28.07	442.11	(1, 1)	968
(6, 3)	(8, 7, 6)	58.95	355.88	306.88	28.07	442.90	(1, 1)	952
(6, 4)	(8, 4, 7)	55.43	482.45	420.77	34.19	572.07	(1, 1)	736
(7, 1)	(6, 25, 6)	64.32	256.20	222.19	26.98	347.49	(1, 1)	900
(7, 2)	(6, 11, 6)	58.50	256.20	222.19	26.98	341.68	(1, 1)	858
(7, 3)	(6, 7, 6)	59.19	256.20	222.19	26.98	342.37	(1, 1)	840

Table C3. Time metrics of enumerated design parameters when L-ratio is 0.2 (s-seconds)								
(b_y, b_x)	***(r, l, T)***	***tt (s)***	***tr (s)***	***SD (tr)(s)***	***tp (s)***	***z (s)***	***(b_y^N, b_x^N)***	***Storage Ground (TEU)***
(1, 2)	(72, 11, 7)	63.54	9222.58	7851.04	69.30	9355.41	(1, 1)	792
(1, 3)	(72, 7, 5)	68.27	5765.93	4902.12	58.20	5892.39	(1, 1)	1008
(1, 4)	(72, 4, 6)	67.89	7367.82	6267.61	63.18	7498.90	(1, 1)	864
(2, 1)	(34, 25, 6)	61.58	2303.15	1960.02	42.34	2407.07	(1, 1)	850
(2, 2)	(34, 11, 5)	56.56	1743.33	1478.99	37.35	1837.25	(1, 1)	1122
(2, 3)	(34, 7, 5)	57.72	1743.33	1478.99	37.35	1838.40	(1, 1)	1190
(2, 4)	(34, 4, 6)	54.89	2303.15	1960.02	42.34	2400.38	(1, 1)	952
(2, 5)	(34, 3, 7)	54.77	2982.26	2545.64	48.45	3085.48	(1, 2)	816
(3, 1)	(20, 25, 5)	61.92	815.57	692.15	29.67	907.16	(1, 1)	1000
(3, 2)	(20, 11, 5)	57.57	815.57	692.15	29.67	902.81	(1, 1)	1100
(3, 3)	(20, 7, 5)	58.67	815.57	692.15	29.67	903.91	(1, 1)	1120
(3, 4)	(20, 4, 6)	55.52	1102.15	940.76	34.66	1192.32	(1, 1)	880
(3, 5)	(20, 3, 7)	55.60	1458.72	1251.43	40.77	1555.10	(1, 2)	780
(4, 1)	(14, 25, 5)	61.17	509.08	432.35	26.38	596.63	(1, 1)	1050
(4, 2)	(14, 11, 5)	56.64	509.08	432.35	26.38	592.10	(1, 1)	1078
(4, 3)	(14, 7, 5)	57.68	509.08	432.35	26.38	593.14	(1, 1)	1078
(4, 4)	(14, 4, 6)	54.39	696.65	596.47	31.37	782.41	(1, 1)	840
(4, 5)	(14, 3, 7)	54.55	933.03	804.30	37.48	1025.06	(1, 2)	756
(5, 1)	(10, 25, 7)	60.84	624.46	541.63	35.29	720.59	(2, 1)	750
(5, 2)	(10, 11, 6)	56.00	462.39	397.41	29.17	547.56	(2, 1)	880
(5, 3)	(10, 7, 6)	57.03	462.39	397.41	29.17	548.59	(2, 1)	910
(5, 4)	(10, 4, 7)	53.96	624.46	541.63	35.29	713.71	(2, 1)	720
(6, 1)	(8, 25, 7)	61.22	482.45	420.77	34.19	577.87	(2, 1)	800
(6, 2)	(8, 11, 6)	56.55	355.88	306.88	28.07	440.50	(2, 1)	880
(6, 3)	(8, 7, 6)	57.62	355.88	306.88	28.07	441.57	(2, 1)	896
(7, 1)	(6, 25, 7)	62.07	348.22	306.68	33.09	443.39	(2, 1)	750
(7, 2)	(6, 11, 7)	56.97	348.22	306.68	33.09	438.29	(2, 1)	792
(7, 3)	(6, 7, 7)	57.95	348.22	306.68	33.09	439.27	(2, 1)	798

Table C4. Time metrics of enumerated design parameters when L-ratio is 0.3 (s-seconds)								
(b_y, b_x)	***(r, l, T)***	***tt (s)***	***tr (s)***	***SD (tr)(s)***	***tp (s)***	***z (s)***	***(b_y^N, b_x^N)***	***Storage Ground (TEU)***
(1, 2)	(72, 11, 7)	63.54	9222.58	7851.04	69.30	9355.41	(1, 1)	792
(1, 3)	(72, 7, 5)	68.27	5765.93	4902.12	58.20	5892.39	(1, 1)	1008
(2, 1)	(34, 25, 6)	61.58	2303.15	1960.02	42.34	2407.07	(1, 1)	850
(2, 2)	(34, 11, 5)	56.56	1743.33	1478.99	37.35	1837.25	(1, 1)	1122
(2, 3)	(34, 7, 5)	57.72	1743.33	1478.99	37.35	1838.40	(1, 1)	1190
(2, 4)	(34, 4, 7)	53.44	2982.26	2545.64	48.45	3084.15	(1, 2)	816
(2, 5)	(34, 3, 7)	54.77	2982.26	2545.64	48.45	3085.48	(1, 2)	816
(3, 1)	(20, 25, 5)	61.92	815.57	692.15	29.67	907.16	(1, 1)	1000
(3, 2)	(20, 11, 5)	57.57	815.57	692.15	29.67	902.81	(1, 1)	1100
(3, 3)	(20, 7, 5)	58.67	815.57	692.15	29.67	903.91	(1, 1)	1120
(3, 4)	(20, 4, 7)	54.21	1458.72	1251.43	40.77	1553.70	(1, 2)	800
(3, 5)	(20, 3, 7)	55.60	1458.72	1251.43	40.77	1555.10	(1, 2)	780
(4, 2)	(14, 11, 6)	55.40	696.65	596.47	31.37	783.42	(2, 1)	924
(4, 3)	(14, 7, 6)	56.40	696.65	596.47	31.37	784.41	(2, 1)	980
(5, 1)	(10, 25, 7)	60.84	624.46	541.63	35.29	720.59	(2, 1)	750
(5, 2)	(10, 11, 6)	56.00	462.39	397.41	29.17	547.56	(2, 1)	880
(5, 3)	(10, 7, 6)	57.03	462.39	397.41	29.17	548.59	(2, 1)	910
(6, 1)	(8, 25, 7)	61.22	482.45	420.77	34.19	577.87	(2, 1)	800
(6, 2)	(8, 11, 6)	56.55	355.88	306.88	28.07	440.50	(2, 1)	880
(6, 3)	(8, 7, 6)	57.62	355.88	306.88	28.07	441.57	(2, 1)	896
(7, 2)	(6, 11, 7)	56.20	348.22	306.68	33.09	437.52	(3, 1)	726
(7, 3)	(6, 7, 7)	57.18	348.22	306.68	33.09	438.50	(3, 1)	756

Table C5. Time metrics of enumerated design parameters when L-ratio is 0.4 (s-seconds)								
(b_y, b_x)	***(r, l, T)***	***tt (s)***	***tr (s)***	***SD (tr)(s)***	***tp (s)***	***z (s)***	***(b_y^N, b_x^N)***	***Storage Ground (TEU)***
(1, 2)	(72, 11, 7)	63.54	9222.58	7851.04	69.30	9355.41	(1, 1)	792
(2, 1)	(34, 25, 6)	61.58	2303.15	1960.02	42.34	2407.07	(1, 1)	850
(2, 2)	(34, 11, 5)	56.56	1743.33	1478.99	37.35	1837.25	(1, 1)	1122
(2, 3)	(34, 7, 6)	56.79	2303.15	1960.02	42.34	2402.29	(1, 2)	952
(2, 4)	(34, 4, 7)	53.44	2982.26	2545.64	48.45	3084.15	(1, 2)	816
(3, 2)	(20, 11, 6)	55.74	1102.15	940.76	34.66	1192.55	(2, 1)	880
(4, 2)	(14, 11, 6)	55.40	696.65	596.47	31.37	783.42	(2, 1)	924
(4, 3)	(14, 7, 7)	55.31	933.03	804.30	37.48	1025.82	(2, 2)	784
(5, 2)	(10, 11, 7)	55.30	624.46	541.63	35.29	715.05	(3, 1)	770
(6, 2)	(8, 11, 7)	56.02	482.45	420.77	34.19	572.67	(3, 1)	792