NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
DIVISION OF SHIP DESIGN AND MARITIME TRANSPORT

CONTAINER TERMINAL EMISSIONS: A SIMULATION BASED APPROACH TO REDUCING CO2 FOOTPRINT

DIPLOMA THESIS

JULY 2018

Author : Alexandros Lamprou
Supervisor : Nikolaos Ventikos, Associate Professor, NTUA
Commitee : Lambros Kaiktsis, Professor, NTUA
Ioannis Prousalidis, Professor, NTUA

Acknowledgements

The present Diploma Thesis is the pinnacle of graduate studies at the School of Naval Architecture and Marine Engineering of National Technical University of Athens. Thus, I seize the chance to express my sincere gratitude to a number of people whose contribution where valuable for the accomplishment of this work and of my studies. First of all, I would like to thank my supervising Professor N. Ventikos for his guidance and support during the preparation of this thesis. His deep and wide knowledge in the field of port facilities and combined transportations provided me with the required background to overcome the difficulties encountered during this study. Furthermore, he gave me inspiration and encouragement during that educational as well as perceptive journey. Another special thank would be to my supervisor PhD student K. Louzis for the constant assistance, support and thoroughness he showed examining this Diploma Thesis. Also, I would like to thank my co student A. Priovolos for his tips in the art of programming. Last but not least, I would like to thank my family, and my friends as without their help, support and understanding it would be very difficult to finish my studies.

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ΠΕΡΙΛΗΨΗ

Οι τερματικοί εμπορευματοκιβωτίων παγκοσμίως τείνουν στην υιοθέτηση πρακτικών που αποσκοπούν στη δραστική μείωση των εκπομπών διοξειδίου του άνθρακα. Προκειμένου να επιτευχθεί ο στόχος για «πράσινους» λιμένες, ο κατάλληλος σχεδιασμός των τερματικών και η αποδοτική χρήση του διαθέσιμου εξοπλισμού είναι καθοριστικής σημασίας. Στην παρούσα διπλωματική εργασία προτείνεται μια μέθοδος αντιμετώπισης του προβλήματος ανακατανομής και ανάκτησης εμπορευματοκιβωτίων. Αφού εξετάστηκαν διάφοροι παράγοντες που επηρεάζουν το πρόβλημα, αναπτύχθηκε μια ευρετική λύση για την ελαχιστοποίηση των μη παραγωγικών κινήσεων των γερανών του τερματικού. Η αποτελεσματικότητα της ευρετικής λύσης αντιπαρατέθηκε με άλλες μεθόδους που προτείνονται σε δημοσιευμένες εργασίες. Στη συνέχεια, δημιουργείται ένα μοντέλο προσομοίωσης ενός τερματικού εμπορευματοκιβωτίων προκειμένου να καθοριστεί η βέλτιστη διάταξη του τερματικού, ανάλογα με την αναμενόμενη ετήσια διακίνηση εμπορευματοκιβωτίων και το διαθέσιμο μήκος αποβάθρας, με στόχο την ελαχιστοποίηση των εκπομπών CO_2. Εξετάζονται δύο δημοφιλείς στην πράξη τύποι διάταξης τερματικών. Στο πρώτο τύπο οι στοίβες εμπορευματοκιβωτίων στοιχίζονται παράλληλα με την αποβάθρα, ενώ στο δεύτερο τύπο στοιχίζονται κάθετα στην αποβάθρα. Για κάθε διάταξη, εξετάζεται το βέλτιστο μήκος, πλάτος και ύψος της στοίβας εμπορευματοκιβωτίων, καθώς και ο βέλτιστος αριθμός σειρών και στηλών από στοίβες. Όλες οι κύριες λειτουργίες που πραγματοποιούνται σε ένα τερματικό προσομοιώνονται στο μοντέλο. Αυτό περιλαμβάνει τη φόρτωση και εκφόρτωση πλοίων, τη μεταφορά εμπορευματοκιβωτίων μεταξύ της αποβάθρας και του χώρου στοιβασίας, τον χειρισμό των εμπορευματοκιβωτίων, την ανάκτηση και την αποθήκευση τους στο χώρο στοιβασίας, καθώς και την εξυπηρέτηση αιτημάτων παραλαβής και ανάκτησης εμπορευματοκιβωτίων από φορτηγά που καταφθάνουν από την ενδοχώρα. Οι ενεργειακές καταναλώσεις κατά τη διάρκεια των εργασιών υπολογίζονται για τους γερανούς στοιβασίας, τους γερανούς αποβάθρας, τους μεταφορείς, τα φορτηγά και τα πλοία. Αφού ικανοποιηθούν ορισμένες απαιτήσεις, όπως η επίτευξη κάποιων ελάχιστων επιτρεπόμενων επιπέδων απόδοσης και η μη υπέρβαση του μέγιστου επιτρεπόμενου κόστους επένδυσης και λειτουργίας για τον τερματικό εμπορευματοκιβωτίων, το μοντέλο δίνει τη βέλτιστη λύση σχεδίασης διάταξης. Τα αποτελέσματα του μοντέλου προσομοίωσης συγκρίνονται με τα αποτελέσματα αναλυτικού μοντέλου σε δημοσιευμένη εργασία. Τέλος, το μοντέλο προσομοίωσης εφαρμόστηκε για να βρεθεί η βέλτιστη δυνατή σχεδίαση σε διάφορα πραγματικά τερματικά εμπορευματοκιβωτίων, συμπεριλαμβανομένου του Piraeus Container Terminal (PCT) στο λιμάνι του Πειραιά.

ABSTRACT

Container terminals globally are adopting practices aiming to reduce CO_2 emissions drastically. In order to achieve 'greener' port status, proper terminal layout design and efficient machinery equipment usage is key. This study proposes a method to address the container reallocation and retrieval problem. After examining various factors affecting the problem, a heuristic is developed to minimize unproductive yard crane moves. The effectiveness of the heuristic is tested with other methods proposed in published papers. Then, a simulation model of a container terminal is created in order to establish the optimal container yard layout, depending on the expected annual throughput and the available quay length, with aim to minimize CO_2 emissions. Two popular types of yard layout in practice are examined. In the first one container blocks are laid out parallel to the quay, and in the second blocks are laid out perpendicular to the quay. For each layout, the optimal block length, width and height is examined, as well as the optimal number of rows and columns of blocks. All main operations taking place in a container terminal are simulated. This includes loading and unloading berthed vessels, container transportation between the yard and the quay, container handling, retrieving and storing in the yard, and handling container delivery and retrieval requests from highway trucks arriving from the mainland. Yard cranes, quay cranes, terminal transporters, highway freights and vessels energy consumptions are estimated. After a certain set of constrictions is met, including achieving minimum allowed performance standards and not exceeding a maximum allowed investment and operational cost, the optimal layout design solution is established. The simulation model results are compared to analytical model results found in a published paper. Finally, the simulation model is applied to find the optimal yard design in several real-world container terminals, including Piraeus Container Terminal (PCT) in Piraeus, Greece.

1. INTRODUCTION

Container terminals are the focal points of containerized transport, containing the necessary facilities for receiving, delivering, storing, maintaining, and repairing containers, as well as handling commercial and customs procedures. They serve as the most important and essential links in inter-modal transportation logistic chains, ensuring fast, efficient and secure management and transfer of containerized goods around the world.

The main goal of terminals around the world is the development of strategies with the aim to offer better services to users and lead to acquiring a competitive position in the shipping industry. Therefore, it is clear that maintaining a certain level of performance in the container terminal and attempting to optimize key functions and factors of the operations conducted on a daily basis is of the outmost importance for the continuous advancement and growth of the port as a whole.

In a world where maritime trade dominates and occupies the largest part of world trade in products, with increasing trends year by year, the role of ports and more specifically of container terminals is becoming more and more important. In this context, as their yearly work cycle is steadily rising, the need to transform terminals into eco-friendly structures is more evident than ever. Terminals around the world rally to this cause integrating more and more low consumption and emission technologies to their operations.

The purpose of this section is to propose solutions and strategies to decrease container terminal emissions aligning with the global trend for 'greener' terminals.

1.1 TERMINAL OPERATIONS

In order to propose solutions for better terminal performance, one must first and foremost understand the way terminals operate. Below we introduce the main activities and operations occurring in container terminals.

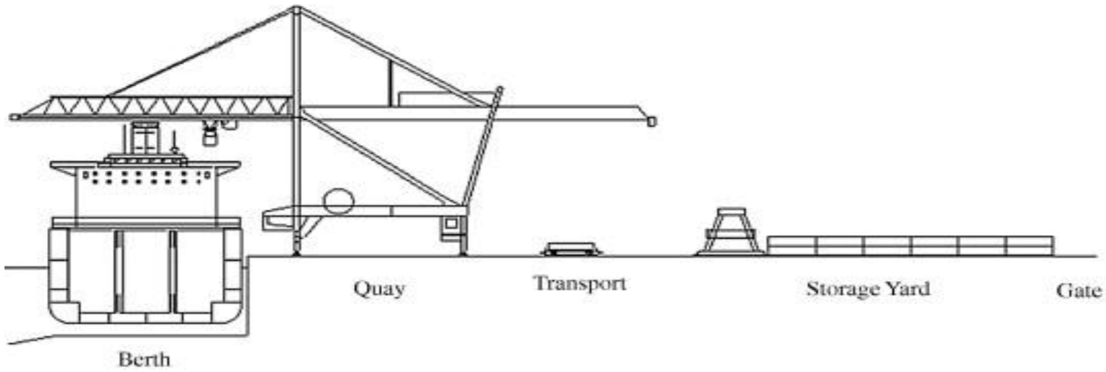

*Figure 1. The chain of the main activities taking place in a container terminal. (*Vis and Koster, 2003)

According to Koh, Goh and Ng (1994) the operations shown in Figure 1 can be broken down into the following categories:

1.1.1 Berth operation

The berth operation revolves around the schedules of incoming vessels and therefore the allocation of dock area and quay crane resources to service the vessels. The focal point of the berthing operation is to supply quay area accessibility for all incoming ships while aiming to reduce their waiting and turn-around and times. Vessel arrival and terminal service processes typically vary significantly resulting in important handling delays and resource underutilization. Thus, terminal management policies have to deal with managing such traffic variances and optimizing the usage of available berth slots.

1.1.2 <u>Quay operation</u>

Figure 2. STS cranes operating on a container ship (Liebherr).

Figure 2 shows operations involving discharging and loading of containers onboard the vessel. Upon mooring, vessels are unloaded by one or more quay cranes according to an unloading plan. Quay cranes begin to unload containers from the ship to terminal transporters dedicated to delivering containers to the yard. Depending on their destination, containers might be transshipped to another vessel, or dispatched via the terminal gates for transport by trucks or trains after being inspected. Terminal transporters also provide quay cranes with containers from the yard to be loaded onto ships according to a stowage plan. In order to maintain a high level of crane efficiency, the flow of containers to and from the dock must be managed properly in order to avoid crane idle times as much as possible. Quay cranes can operate either in single or double cycle patterns. In the first case quay cranes are divided into two groups each one dedicated only to loading or discharging operations, while in the second case quay cranes, also referred to as Ship to Shore Cranes (STSC) can attain both types of ship operations.

1.1.3 <u>Yard operation</u>

Figure 3. Terminal yard in Manila International Container Terminal (ICTSI).

Figure 3 shows operations taking place in a container yard. These operations involve discharging and loading containers from and to terminal transporters, discharging and loading containers from and to highway trucks and managing containers in the yard with the aim to minimize the idle time of transporters and trucks waiting to be serviced by the yard cranes operating. As yard operations are the main focus of the current section, they will be reviewed extensively in the next segment.

1.1.5 Gate operation

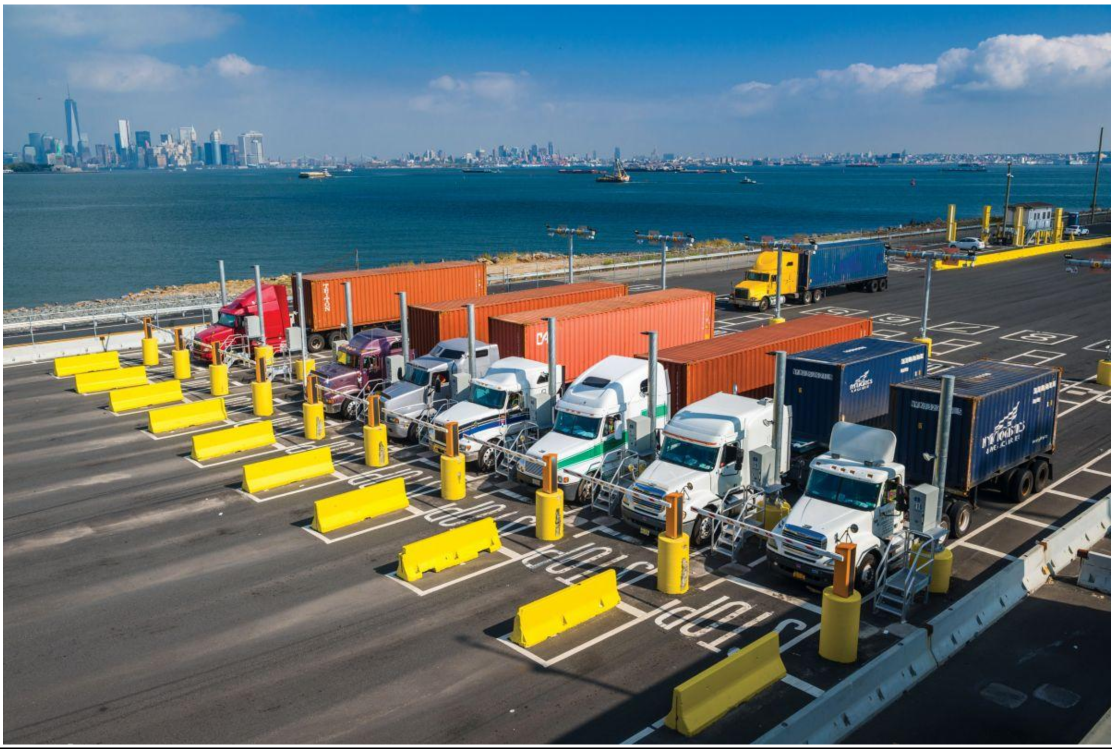

Figure 4. Highway freights arriving at a container terminal (Global Terminals).

Figure 4 shows external heavy duty trucks entering a container terminal, carrying delivery containers. Two main activities are involved in gate operations, namely export delivery where the freights bring in export containers to the yard or to be loaded onto the vessels, and import receiving, where the trucks receive containers from the yard to bring into the mainland. These activities can also involve railway trains incoming with containers instead of highway trucks.

1.1.6 Scheduling

Scheduling ensures all available resource tools in the terminal are utilized properly given the variables and constrains emerging in various situations. Storage yard scheduling, focusing especially on yard crane dispatching, will be the focus of this paper as we attempt to propose strategies to reduce energy consumption and emissions in terminals operations.

2. YARD OPERATIONS

2.1 Layout

According to Carlo, Vis, Roodbergen (2014) a typical yard layout consists of multiple rectangular blocks. Yard cranes (YCs) serve one or multiple blocks. A block is composed of several bays of containers placed in row. Containers can be stacked in blocks up to a maximum height depending on the height of YCs operating in the yard. There are two main yard layout set ups, as shown in Figure 5. The main differences between them lie in the location of the input/output (I/O) point, which is where vehicles and the yard crane exchange containers, the relative positioning of the blocks to the quay(parallel or perpendicular) and the level of automation used.

The first layout, which is most common in non-automated storage yards, places yard blocks parallel to the quay. Typically, one or more rows in each block are reserved as truck lanes. Terminal transporters and highway trucks travel in the lanes until they reach the bay associated with the storage or retrieval request they are serving. This kind of layout is quite common in large Asian terminals. Hence, it is referred to as the Asian layout.

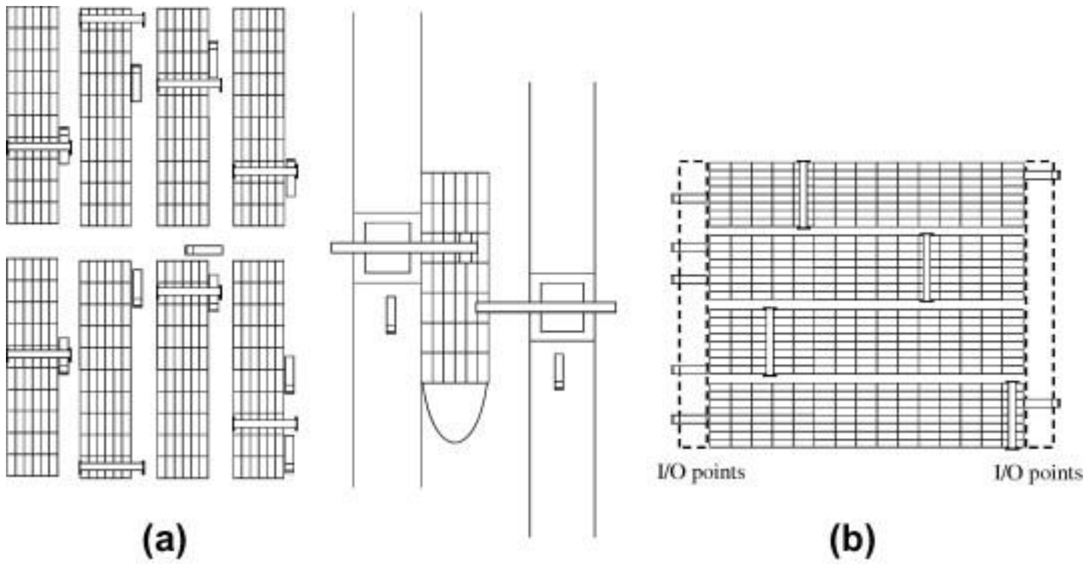

Figure 5. . Asian (a) and European (b) storage yard layout. (Carlo, Vis, Roodbergen, 2014)

The second set up, commonly used in automated yards, places yard block perpendicular to the quay. The I/O points are located at both ends of the storage blocks to respectively handle storages and requests from the seaside and landside. Terminal transporters exchange containers at the seaside I/Os, while highway freights transact with YCs at the landside I/Os. This layout configuration was first implemented in large European container terminals. Henceforth, it is referred to as the European layout.

Lee & Kim (2010) compare the two layouts. They find that blocks in the Asian model must be longer and less wide than the European. They observe that in both models the smallest possible height enhances efficiency. Also, they observe that with increasing the speed of the cranes the optimal size of the blocks is accordingly increased.

Lee & Kim (2012) examine again the two layouts and come up with the following conclusions. For Asian layouts, they suggest adopting terminals with fewer blocks but with a larger block width than is usually the case in practice. For European layouts, they propose blocks with larger width and shorter length than in common practice. In general, they emphasize the beneficial effects of increasing the width of blocks in terminal efficiency, but point out that it should be taken into account that greater width leads to larger slower cranes operating. This could lead to reduction in efficiency and increase in energy consumption. Finally, they conclude that in terms of cost reduction, the Asian model is better than the European one.

Finally, Petering (2006) studies how terminal yard efficiency is affected by the width of blocks. Examining block widths ranging from 2 to 15 stacks resulted in the following. The optimal width of blocks ranges from 6 to 12 stacks depending on the size, shape and throughput of the terminal. Secondly, the optimal block width decreases when more equipment is developed. Finally, overall performance improves as the shape of the terminal becomes squarer.

2.2 Operations

The main operations taking place in a container yard are storage of incoming containers from the quayside or landside and retrieving outgoing containers in order to deliver them to their respective transportation means. When it comes to conducting yard operations, various decision making problems occur. The main problems a terminal operator has to address are yard crane and terminal transporter dispatching, and managing container allocation and retrieval within the yard.

When it comes to container management the approaches used in practice are the following. One method to address this problem is the consignment or remarshalling strategy. Consignment is the process in which containers bound to the vessel are directly delivered and allocated by vehicles in the same storage area within the yard. Using the consignment strategy will require more storage space since a dedicated storage assignment policy is applied to reserve block areas for specific vessels, resulting in lower storage space utilization in contrast to random allocating policies. (De Koster, Le-Duc, & Roodbergen, 2007).

Remarshalling is the process of repositioning containers to a dedicated area within the yard instead for the same reasons the consignment strategy is used. An area within the block is reserved for containers bound to the same vessel, repositioning containers to this area is referred to as remarshalling (Saanen & Dekker, 2011). While remarshalling is a good process when it comes to lowering container delivery times to TTs and reducing YC cycle times, it has downsides as well. First of all, the ability to conduct this process depends heavily on getting timely notice for ship calls and at the same time facing low enough operation volume so as for cranes and transporters to have enough idle time in order to remarshall. In other words this option is not always available. Also, from an energy standpoint remarshalling is relatively costly as extra energy must be spent from transporters and cranes to assemble containers that are scattered in the yard, and restack them all in the same bays.

Another phenomenon found in storage yards is reshuffling, also known as reallocating. Reallocations are unproductive moves required to gain access to a desired container that is blocked with other containers over it and they are performed during retrieval operations. Another operation, which is actually not performed ahead of retrieval operations but during available crane idle time throughout container retrievals, is premarshalling. When container retrieval sequence is given, yard cranes perform reallocations during their idle time in order to better utilize their workload and serve retrieval tasks faster.

When it comes to yard crane set ups, the most common ones utilized in practice are the following. The simplest set up is assigning one yard crane per block. According to Carlo, Vis, Roodbergen (2014), in order to increase the throughput of storage yards, multiple gantry cranes may be used in collaboration. There are two types of gantry crane arrangements, passing and non-passing gantry cranes. The passing cranes arrangement, also known as double or dual, uses one crane that is larger than the other. This allows for the smaller crane to pass under the larger crane. The non-passing gantry cranes arrangement is composed of two identical gantry cranes (twin GC) that must maintain a minimal safety distance from each other (Klein, 2011) and typically serve one area of the yard (Saanen, 2011). Also, there is a triple set up which essentially consists of a twin set up which has a third crane larger than the other two. Finally, a popular set up in Asian terminals is to utilize freely moving yard cranes among blocks in the same row instead of dedicating them to specified blocks.

Figures 6, 7 summarize the various yard crane set ups and container reshuffling strategies used in practice. In the current section we will examine the ‘single block Twin RMGC’ set up for European layouts and the ‘multiple blocks freely moving RMGCs’ set up for Asian layouts. When it comes to allocating strategies, the current section will examine the ‘Sequencing retrievals and reshuffling operations for a known retrieval sequence’ operation.

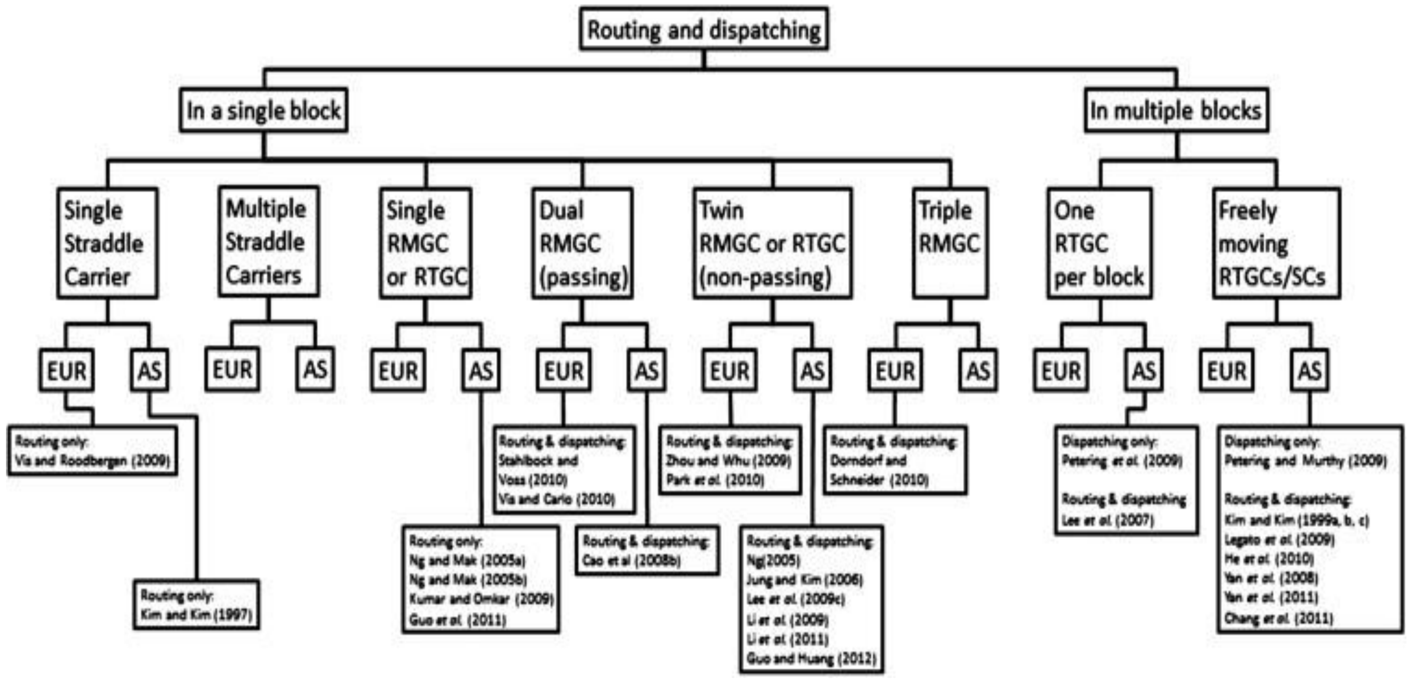

Figure 6. Categorization of various YC routing and dispatching set ups and the papers addressing them (Carlo, Vis, Roodbergen, 2014)

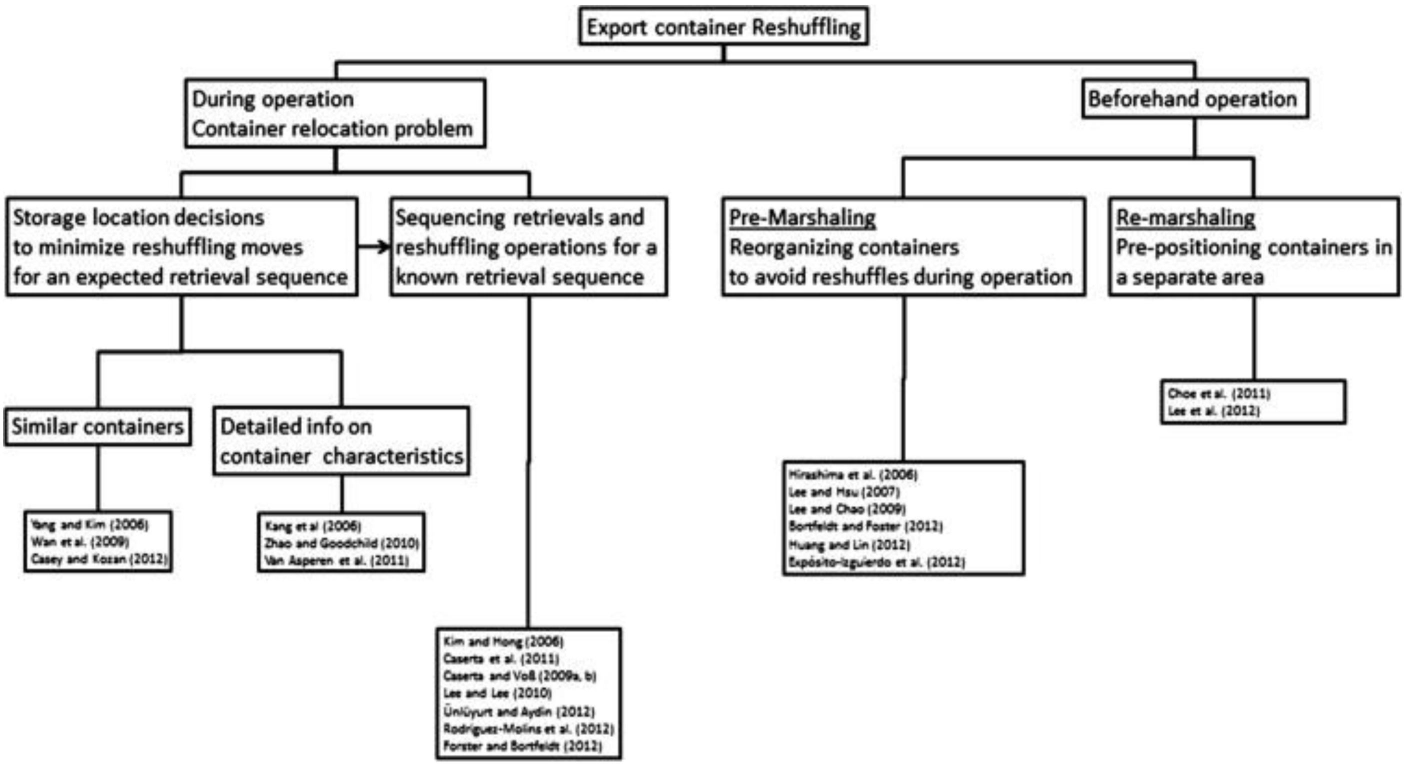

Figure 7. Categorization of various container reshuffling strategies and the papers addressing them (Carlo, Vis, Roodbergen, 2014)

2.3 Optimizing reallocation operations for a known retrieval sequence

In order to achieve the best possible performance in a container terminal, the cranes operating in the container yard must do so efficiently, something that can be achieved by reducing unproductive reallocations moves. Choosing the optimal reallocation receiving stack is necessary in order to reduce reallocations.

On this issue, Kim & Hong (2006) propose an algorithm to minimize the number of reallocations. In particular, a heuristic is proposed with a feasible starting point for the expected number of containers added in each stack due to reallocations which results in a probabilistic formula for finding the appropriate reallocation receiving stack. The algorithm concludes in finding a number of reallocations needed to empty a bay from containers in a given order of priority. No containers are added to the block, containers are only retrieved from the block or moved between the stacks of the block. The problem is solved only for single bay block instances. Finally, they compare the performance of their heuristic to a Branch & Bound algorithm.

Lee & Lee (2010) propose a three-step heuristic optimization. Their goal is to minimize the total number of reallocations done by the yard crane. The first step finds a feasible initial recovery sequence assuming that reallocations are made to the closest stack having an available slot (given a maximum stack height defined by the height of the yard crane used). In the second step, the number of reallocations in the initial sequence decreases with the repeated production and resolution of a binary integer program. Then, by using a mixed integer program, the work sequence is repeatedly adjusted to reduce the completion time of the project from the yard crane without increasing the number of reallocations.

Bian & Jin (2013) present a three-phase hybrid algorithm to solve the problem. After creating an initial feasible recovery sequence with heuristic rules, the second phase acquires various alternative recovery sequences utilizing various methods. The third phase constructs a shorter path problem and produces the optimal sequence using dynamic programming.

2.4 Equipment types

There are two main types of equipment used in storage yards. The first type is Yard Cranes (YC). YCs are machinery used to handle retrieval, delivery, storage and reallocation tasks in the yard blocks. These cranes are divided into two major categories, Railed Mounted Gantry Cranes (RMGC) and Rubber Tired Gantry Cranes (RTGC). The second type is Terminal Transporters (TT). TTs serve as means of transportation in the yard delivering containers from vessels to storage blocks and vice versa.

2.4.1 Yard cranes

Railed Mounted Gantry Cranes

Figure 8. Railed Mounted Gantry Cranes (Lincolnmes)

Figure 8 shows RMGCs operating on a container block. As implied by their name, these cranes operate mounted on rails fixed on the ground and their gantry can only move forward or backward on these rails. RMGCs can operate fully automated following a task sequence plan provided by port planners, and this is the reason why they are popular among automated European terminals. RMGCs are fully electrified cranes. Their main power supply and data transmission is managed by dedicated and highly dynamic motor driven cable reels. RMG cranes are typically wider and higher than RTG cranes. Fully automated RMG cranes are known as Automated Stacking Cranes (ASC). ASCs can operate fully automated following a task sequence plan provided by port planners, and this is the reason why they are popular among automated European terminals.

Rubber Tired Gantry Cranes

Figure 9. Rubber Tired Gantry Crane (Apcdisplay)

Figure 9 shows an RTGC. RTG cranes are operated by onboard drivers, unlike the automated RMG cranes. Typically RTGCs span 5-8 containers in width and 3-5 in height. Standard RTG cranes are equipped with diesel engines to provide power for travel and lifting. Unlike RMGCs, RTGCs can freely roam in the yard and handle tasks among different blocks. RTGCs are able to rotate the tires 90° to perform orthogonal moves known as cross gantrying. RTGCs are mostly popular among Asian terminals as their high flexibility and ability to roam fits the style of operations performed in such terminals.

2.4.2 <u>Terminal transporters</u>

There are four basic transporter means used in modern container terminals around the world. These are Straddle Carriers (SC), Automatic Guided Vehicles (AGV) and Automatic Guided Vehicles-Lift (AGV-Lift). In the following segment the operational function of each transporter and the positive and negative aspects they come with are presented.

<u>Straddle Carriers</u>

Figure 10. Straddle Carrier (Konecranes)

Straddle Carriers (Figure 10) are a really popular means of transport in container terminals all around the world. They are fast diesel powered vehicles that have the ability to pick up containers from the ground and or even containers stacked at tier 2 or 3 height (depending on the SC model). They can also stack containers upon others at the same height. Given this extremely useful function in their operational capabilities SCs can provide the yard a really fast and effective transportation system connecting STSCs and YCs.

First of all, a SC transportation system gives the STSCs the ability to minimize idle times and operate relatively unaffected by transporter arrival times. STSCs can freely unload containers on the quay ground without waiting for a SC arrival, due to SC's ability to pick up containers. In terminals operating with other transportation systems STSCs are bound to wait for transporters to unload containers onto and this has a direct effect on their productivity. Transporter idle times in the quay are also reduced when using SCs because they can leave a container to the ground for the STSC to pick up instead of facing significant amounts of idle time waiting to be unloaded by the STSC. The same advantages can be gained in the storage yard as well. Despite their significant advantages, they come with major drawbacks as well, as shown below and in Figure 13.

Advantages:

a) Low idle and waiting times – high utilization
b) Increase YC and STS utilization
c) High travelling speed

Disadvantages:

- Diesel Powered-Energy Intensive
- High energy and maintenance cost
- More accidents due to high speed

Automatic Guided Vehicles

Figure 11. Automatic Guided Vehicle (VIL)

Automatic Guided Vehicles (Figure 11) are extremely popular among northern European terminals. They are fully automatic transportation means that can be loaded and unloaded with containers by YCs and STSCs. They are relatively slow travelling vehicles and their delivery times are directly linked to YC and STSC cycle times. In an AGV operating system AGVs have to wait under the STSC or YC to be serviced and correspondingly the YCs and STSCs are directly affected by AGV arrival times both in loading and unloading operations.

Despite their disadvantages, AGVs come with significant advantages as well. They are safe, reliable, cost and energy effective pieces of equipment, as shown Figure 13.

Automatic Guided Vehicle-Lift

Figure 12. Lift Automatic Guided Vehicle (Konecranes)

These vehicles are a modified version of the automatic guided vehicle. They have the ability to lift and carry containers from specially designed platforms in buffer zones on which they are deposited by YCs, as shown in Figure 12. They can also unload containers onto these platforms for YCs to pick up. In this way they provide shorter waiting times and increase YC productivity than AGVs. On the other hand such platforms cannot be set under STSC working space for various practical reasons and thus the operation of the AGV-Lift is the same with that of the AGV when it comes to interacting with STSCs.

To conclude, AGV-Lifts are somewhere in between SCs and AGVs in respect to advantages and disadvantages achieving less waiting times than AGVs but more than TTs, and being less cost and energy intensive than SCs but more correspondingly more to AGVs (Figure 13).

Type of vehicle	AGV (diesel-electric/ battery-electric) Source: TPS	Lift AGV (diesel-electric/ battery-electric) Source: TPS	ALV (diesel-electric) Source: TPS
Vehicle weight	26t / 26t	31t / 31t	52t
Fuel / energy consumption per hour	7.5 L / hour or 17 kW / hour (equivalent to 1.9 L / hour)	12.0 L / hour or 27 kW / hour (equivalent to 2,5 L / hour)	17 L / hour
CO_2 emission per hour	19.3 kg / h or 4.9 kg / h	30.9 kg / h or 6.4 kg / h	43.6 kg / h
Energy cost per move	1.25 € / 0.43 €	1.33 € / 0.45 €	1.70 €

Note: 2.6 kg CO_2 per L diesel, or 0.24 kg per kWh electricity.

Figure 13. AGV, Lift AGV and SC(ALV) comparison (Saanen 2016)

2.4.3 <u>STS Cranes</u>:

Figure 14. Ship to Shore Cranes operating on vessels (Liebherr)

The STS Cranes, shown in Figure 14, unload import and transshipment containers from ships and load export and transshipment containers onto ships. They interact with TTs. TTs deliver export and transshipment containers to the STSCs and receive import and transshipment containers from them. Containers are loaded and unloaded one by one by the STSCs. Loading operations are performed with a strict priority sequence derived from the Ship's Stowage Plan. The STSCs load containers in the exact order these are being delivered to them, so it comes upon the yard system (RMGCs-TTs) to supply them with containers in the correct order. The Ship’s SP can be determined and affected by various factors. The Stowage Plan is considered predetermined for all purposes and intent and is not an object of research in the current paper.

2.5 Container Types

Containers are standard-sized metal boxes containing goods which can be easily transferred between different modes of transportation, such as ships, trains and trucks. The most common container used container is the twenty-foot equivalent unit container also known as a TEU. Special types of container, which include reefer, out-of-gauge, dangerous, empty and 40-ft equivalent unit containers are not considered in this study.

The standard dimensions of the TEU unit are presented below.

Length	Width	Height	Volume
20 ft (6.1 m)	8 ft (2.44 m)	8 ft 6 in (2.59 m)	1,172 cu ft (33.2 m^3)

Table 1. TEU size container dimensions

There are two ways of classifying containers handled in port container terminals. In the first way of the classification, containers can be classified into three groups according to the container flow paths: import containers, export containers, and transshipment containers. Import containers are those discharged from vessels and delivered to trucks. Export containers are those received from trucks to be loaded onto vessels. Transshipment containers are discharged from a vessel and then loaded onto another vessel. In the second way of the classification, containers can be classified into two groups according to their destination, outbound containers and inbound containers. Export and transshipment containers are classified as outbound containers because they leave the storage yard through the quay, while import containers as inbound containers because they leave the storage yard through the gate.

3. KEY PERFORMANCE INDICATORS

Now that the basic terminal operations have been established, the key performance indicators given below can be better understood. According to Thomas and Monie (2000), performance indicators can be broken down to four basic categories, each of which contains KPIs addressing the whole chain of operations presented above.

3.1 Production Indicators

Production indicators reflect the level of activity of the terminal. Throughput measures indicate the amount of containers moved through various terminal areas per unit of time.

Throughput measures include:

• ***Quay throughput***: Measures the number of containers loaded and discharged to and from vessels in a given time period.

• ***Container yard throughput***: Measures the number of containers stored and transferred through the storage yard in a given time period.

• ***Gate throughput***: Measures the number of containers incoming and leaving through the landside in a given time period.

3.2 Productivity Indicators

Productivity indicators measure the ratio of output to input and are particularly important to terminal operators as they are key indicators of terminal efficiency. There are seven different productivity measures:

• ***Ship productivity***: Measures the time taken to service a vessel in relation to the amount of containers loaded and discharged.

• ***Crane productivity***: Crane productivity measures the amount of container lifts per unit of time a crane performs.

• ***Quay productivity***: Measures the number of containers moved through the quay in an annual basis in regard to the total terminal quay length.

• ***Terminal area productivity***: Similar to the quay productivity indicator is the measure of terminal area productivity, which applies to the entire terminal and expresses the ratio between terminal production and total terminal area for a given unit time.

• ***Equipment productivity***: The value that is of interest is the number of container movements made per working hour, either for terminal transporters or yard cranes.

• ***Labour productivity***: Measures the productivity per man-hour, more important in non automated terminals.

• ***Cost effectiveness***: Measures the total cost, operational and investment, per container handled in the terminal.

3.3 Utilization Indicators

Utilization indicators allow management to determine how intensively the production resources are being used. The most common and most relevant utilization indicators are:

• ***Quay utilization***: This measure reflects the amount of time that the available berth slots were occupied out of the total time available.

• ***Storage utilization***: Measures the ratio of storage slots occupied at a given time to the total number of available slots according to the yard's design capacity plan.

• ***Gate utilization***: Measure the traffic level produced by highway trucks at the gate at a given time.

• ***Equipment utilization***: The utilization of any type of equipment is defined as the ratio of time that it was effectively deployed over a specified period.

3.4 Services Indicators

These indicators measure the level of services provided to the terminal customers. The principal external service measures include:

• ***Ship turnaround time***: This is the total time, spent by the vessel in port, during a given call. It is the sum of waiting time, plus berthing time, plus service time. Ideally, ship turnaround should be only marginally longer than ship's time at berth and thus waiting time in particular should be as near to zero as possible.

• ***Road vehicle turnaround time***: For trucking companies the most important measure of a terminal's service quality is the time required to collect a container from the terminal or deliver one.

• ***Rail service measures***: Train turnaround time is a useful measure for the service performance of a container terminal to the rail.

4. A HEURISTIC FOR THE CONTAINER RETRIEVING PROBLEM

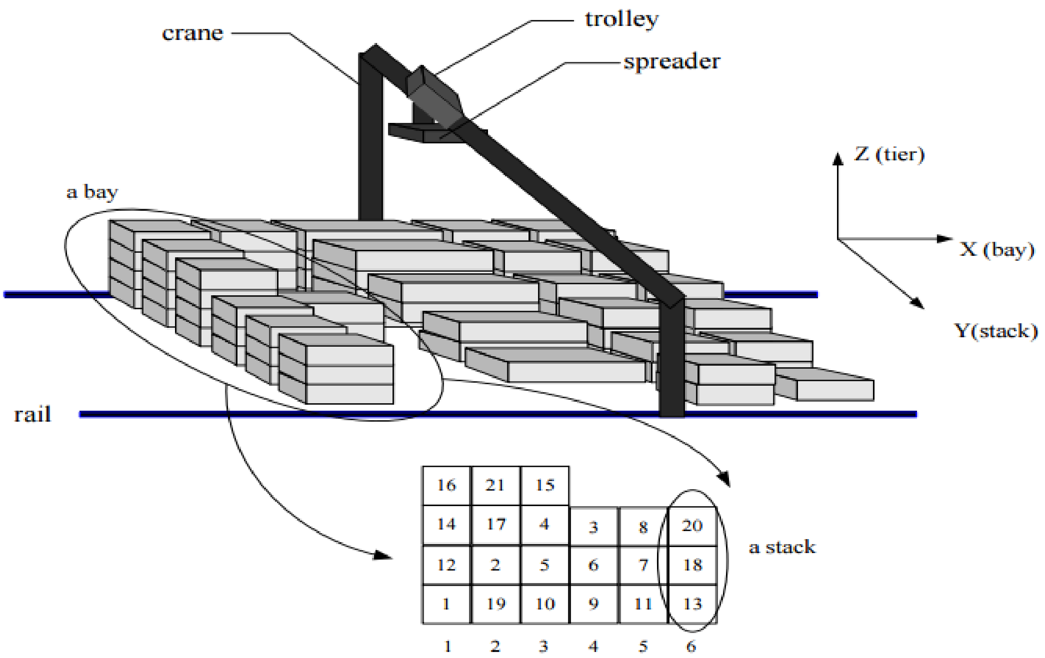

*Figure 15. Container yard block with an RMG crane operating (*Bian & Jin 2013)

As indicated in Figure 15, a yard block consists of multiple bays of containers placed in a row and each bay consists of several stacks. The containers stacked in the blocks are picked up by yard cranes (YCs) and are loaded onto terminal transporters (TTs) or highway freights. Yard cranes can move containers in three dimensions. They can lift or lower a container using their spreader in Z-dimension. They can move a container across Y-dimension using their trolley and finally they can also transport it in the X-dimension, as the cranes move forwards and backwards on their rails or tires depending on the YC type.

As shown in the image above containers are given a certain priority number that represents the order in which containers must be delivered by YCs to TTs or trucks. That is either because there is a certain stowage plan for loading a ship that demands containers to be loaded at a certain order or because in the case of highway trucks, after they arrive at the port each one of them is bound to receive the specific container assigned to it.

It immediately becomes clear that containers in the yard are not stacked in the proper order so as to be lifted one by one by the crane, given the fact that a crane can only lift a container being on top of a stack. Containers are given a priority number which indicates the order in which they must be removed from the yard from the lowest to the highest number. So in this example number 1 must be loaded first and number 21 last. In order for the YC to perform this task, it has to reallocate any container preventing it from reaching the container with the lowest priority at the block at a given time. Reallocating is the act of a YC picking up a container on top of a stack and laying it on top of another stack instead of delivering it to a transporter.

Reallocations are unproductive crane movements and increase YC delivery times and energy consumption. In this section a heuristic is proposed to minimize the amount of these unproductive movements during delivery operations. By minimizing reallocations, several KPIs introduced in the previous segment of this paper can be drastically improved. These KPIs are:

-*Crane productivity*:

By reducing the amount of unproductive moves the crane needs to do its ability to handle more containers in the same amount of time is improved thus increasing its productivity. There might even be a decrease the number of cranes needed to handle a certain amount of containers.

-*Equipment productivity*:

The yard cranes are part of the total equipment force of the terminal and thus increasing their productivity increases equipment productivity. Also, by reducing the amount of unproductive moves by the crane we increase the productivity of other types of equipment as well. For example, we reduce the time spent by TTs and trucks waiting to be loaded/unloaded by the cranes and thus increasing equipment productivity even more.

-*Terminal area productivity*:

It becomes clear that by increasing the productivity of a certain terminal activity we increase the productivity of the terminal as a whole.

-*Equipment utilization*:

By increasing the efficiency of the tasks conducted by our equipment we can utilize our equipment better in order to perform more tasks in a given time period.

-*Storage utilization*:

By handling containers faster and thus decreasing the amount of time they spend in the yard we can assure to keep the yard’s capacity levels under control.

-*Cost effectiveness*:

By increasing the productivity and utilization of certain aspects of the terminal we attain an increase in cost effectiveness.

4.1 HEURISTIC PROPOSAL

1. The goal of the heuristic is to minimize the amount of reallocations required to discharge every container off a yard block, given the priority number of each container.
2. No containers are being added to the block. The initial layout of the block contains a certain number of containers that can only be reallocated from stack to stack or loaded to a truck until the block is empty.

A yard crane is forced to reallocate a container when it blocks the access of the crane to the container with the minimum priority number (*PN*) currently in the block. The container with the minimum *PN* is the one that must be discharged from the block to a transporter. Hence if it is not placed on top of its stack, the YC is forced to reallocate the container currently placed on top of that stack in order to reach the *min(PN)* container.

While reallocating the container to another stack solves the problem temporarily, it might cause further future interference and force the YC to reallocate the same container again if the reallocation stack is chosen randomly. This will increase the number of moves required to clear the bay of blocks and lead to a severe YC productivity drop. In order to solve this problem a set of criteria must be established, indicating how 'good' of a candidate is each stack as a possible reallocation receiver.

1. Let *S* be the indicator of each possible receiver stack, where *S*=1,2…,*n*, where n the number of stacks
2. Let *R* be the *PN* of the container to be reallocated
3. Let C_s be the indicator of each container in a stack from bottom to top position, where C_s=1,2…,H_s, where H_s is the number of containers in stack *S*
4. Let X_s be the number of containers with $PN<R$ in stack *S*
5. Let W_s be the container with *min(PN)* in stack *S*
6. Let E_s be the container with $min(PN)>R$ in stack *S*
7. Let *L* be the container with *min(PN)* in the block
8. Let *M* be the maximum number of containers per stack, for all stacks in the block

The best receiver candidate would be a stack that does not have containers with $PN<R$, meaning a stack with $X_s=0$. This indicates that container *R* will not have to be reallocated again as it is the first container out of this stack to be discharged from the block. If no such stack exists then a stack with as few containers with $PN<R$ as possible should be chosen. In other words, a reallocation move should cause further YC access interference to as few containers as possible.

If two or more stacks tie at the same *min*(X_s) value, then a tie breaker criterion must be implemented in order to determine the optimal stack among them. If *min*(X_s)>0, then the reallocation of container *R* will cause access interference to a number of containers to whichever of the tying stacks it is moved to. The worst case scenario is to reallocate container *R* to a stack containing *PN=L+1*, which means *R* will be reallocated again right after *L* is discharged from the block. So, since access interference cannot be avoided, we try to postpone it as much as possible. Thus, the stack with *max*(W_s) value out of the tying ones is chosen, as the W_s value of a stack indicates how soon a container will have to be retrieved from the stack.

If *min*(X_s)=0, then the reallocation will not cause access interference to whichever of the tying stacks it is moved to. In this case we try to group containers with close by priority numbers in the same stacks as much as possible. Ideally, containers would be stacked in the block according to their exact priority sequence and no reallocation actions would be required. So, containers with close by *PN*s should be stacked in the same stacks as much as possible in order to establish a better retrieving sequence for the YC. Thus, the stack with *min*(E_s) value out of the tying ones is chosen. The heuristic function is showcased using a flow chart in Figure 16.

Bian & Jin (2013) propose a similar initial heuristic in their three-phase hybrid algorithm to solve the problem. The authors suggest the most important parameter to consider when reallocating a container is to avoid causing any further interference. The best receiver candidate would be a stack that does not have containers with *PN<R*, meaning $X_s=0$. If more than one stacks tie in the above criterion they suggest selecting the stack among them with *min*(E_s). Also, they suggest that if there are containers, other than *R*, on top of stacks and the following set of criteria (*SOC*) are met:

SOC:

- its *PN* is greater than *R*
- it blocks the access to a container in its current stack
- its *PN* is lesser than *min*(E_s)
- there is more than one empty slot in the stack with *min*(E_s)

then the container with *max(PN)* ,among the ones satisfying *SOC*, is reallocated to the stack with *min*(E_s) instead of *R* in order to improve the retrieval sequence even more.

If, however, there are no containers satisfying $X_s=0$ then the optimal reallocation stack chosen is the one with *max*(W_s).

To sum up, the main differences between the heuristic proposed in the current segment and the one suggested by Bian & Jin (2013) are the following:

- The first criterion of the Bian & Jin heuristic examines only if there are any containers blocked in a receiving stack by a possible reallocation move. The current heuristic takes into consideration not only if there are any containers blocked by a reallocation move, but also how many containers are blocked by this reallocation move. The difference between the two heuristics is showcased below.

Bian & Jin: If min(Xs)>0 choose the stack with max(Ws) out of all the stacks.

Current: If min(Xs)>0 and there is only one stack with min(Xs), choose that stack. If min(Xs)>0 and there are more than one stacks tieing at min(Xs), then choose the stack with max(Ws) out of the tieing ones.

- The current heuristic does not implement the *SOC* criteria.

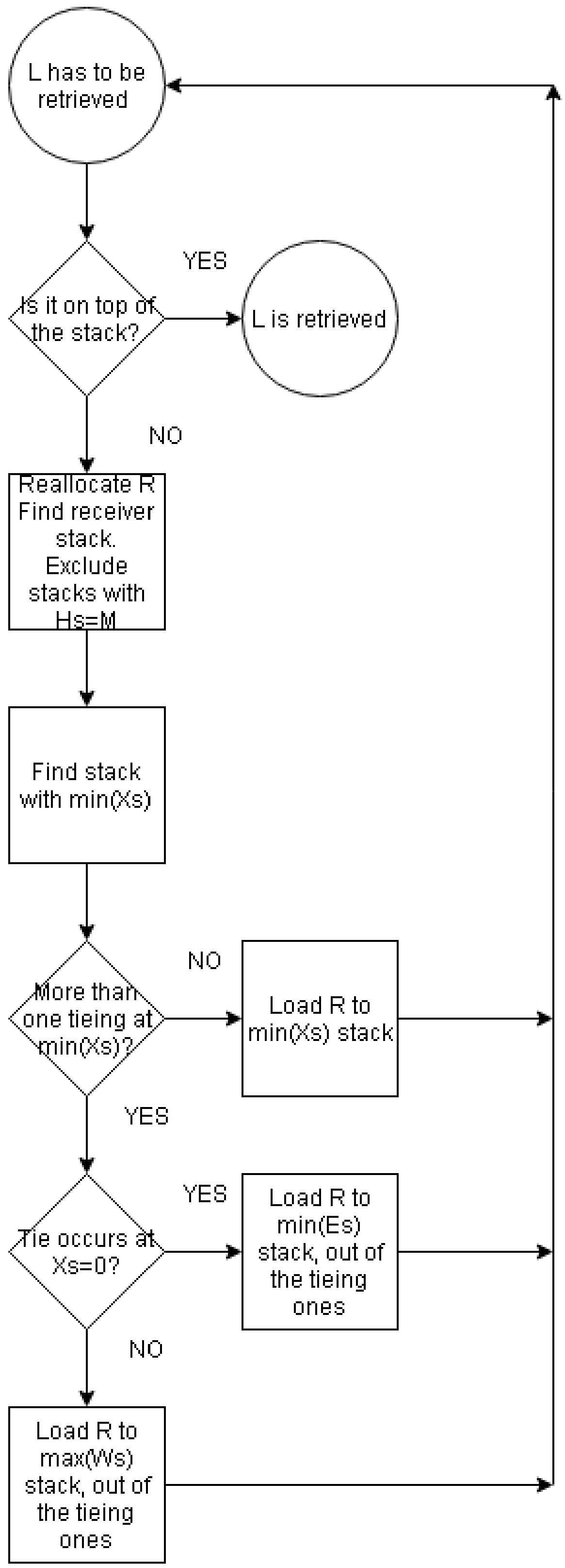

Figure 16. Heuristic flow chart

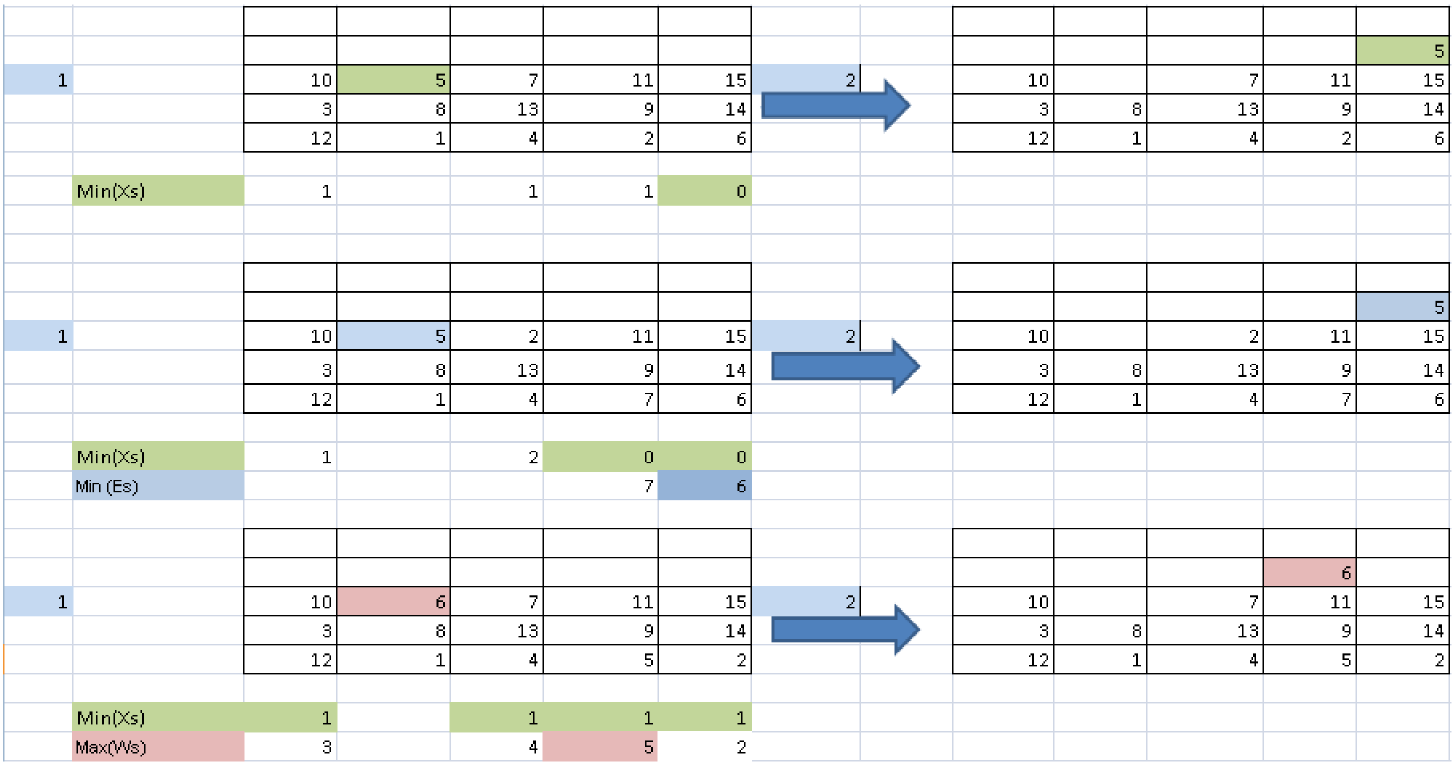

Figure 17. Heuristic implementation example

Figure 17 presents an implementation example of the heuristic on simple container layouts. In the first case container No.5 has to be reallocated in order to retrieve container No.1. Out of all possible receiver stacks the one with the lowest *Xs* value is chosen as the optimal stack. In the second case, more than one stacks tie at *min(Xs).* As explained before if the tie occurs at *min(Xs)=0,* then the stack with *min(Es)* value is chosen as the optimal one. In the third case, more than one stacks tie at *min(Xs)* again. Only this time the tie occurs at *min(Xs)=1,* hence the stack with *max(Ws)* is chosen as the optimal one.

4.2 HEURISTIC TESTS

The papers that we tested our method against are the following:

1. A heuristic rule for relocating blocks, Kim & Hong 2006
2. A heuristic for retrieving containers from a yard, Lee & Lee 2010
3. Optimization on retrieving containers based on multi-phase hybrid dynamic programming, Bian & Jin 2013

We compared our results with the ones from the above papers on exactly the same container block instances, which can all be found here: *https://sites.google.com/site/smallcontainerworld/*

Every instance is given a certain ID number which indicates its characteristics. For example, ID R011606_0070_001 means that this block has 1 bay (01), with 16 stacks (16) and a maximum stack height of 6 containers (06). The number of containers in the block is 70 (0070) and finally the last number (001) indicates the instance's id as there more block instances with exactly the same characteristics but with different distribution of container priority numbers among the block. The comparison in block instances with more than one bay does not include Kim&Hong(2004) because this paper addressed only single bay instances.
In each instance the result given is the total number of moves (loading containers to trucks and reallocating them) required to empty the bay off containers. Also, the last column (Lower bound) indicates the theoretical lowest number of moves that is possible to be achieved in each instance. The Lower bound is calculated by adding up the moves required to empty each stack separately assuming there are no other stacks in the block. (Lee & Lee, 2010)

The results are presented in the tables below:

ID	Kim&Hong (2004)	Lee&Lee (2010)	Bian&Jin (2013)	Bian&Jin heuristic (2013)	Current Paper	Lower Bound
R011606_0070_001	173	118	107	108	107	100
R011606_0070_002	174	117	110	109	108	104
R011606_0070_003	176	110	104	108	109	104
R011606_0070_004	182	158	108	118	118	108
R011606_0070_005	184	124	112	112	110	106
R011608_0090_001	303	190	143	152	156	143
R011608_0090_002	253	191	139	152	153	139
R011608_0090_003	315	216	142	155	162	142
R011608_0090_004	283	178	143	151	152	143
R011608_0090_005	283	182	143	150	153	143

Table 2. NUMBER OF MOVES REQUIRED TO CLEAR THE BLOCK FOR EACH HEURISTIC (SINGLE BAY)

ID	Kim&Hong (2004)	Lee&Lee (2010)	Bian&Jin heuristic (2013)	Bian&Jin (2013)	Lower Bound
R011606_0070_001	38%	9%	1%	0%	-7%
R011606_0070_002	38%	8%	1%	2%	-4%
R011606_0070_003	38%	1%	-1%	-5%	-5%
R011606_0070_004	35%	25%	0%	-9%	-9%
R011606_0070_005	40%	11%	2%	2%	-4%
R011608_0090_001	49%	18%	-3%	-9%	-9%
R011608_0090_002	40%	20%	-1%	-10%	-10%
R011608_0090_003	49%	25%	-5%	-14%	-14%
R011608_0090_004	46%	15%	-1%	-6%	-6%
R011608_0090_005	46%	16%	-2%	-7%	-7%
AVERAGE	41.84%	15%	-1%	-5.70%	-7.52%

Table 3. MOVEMENT REDUCTION ACHIEVED BY THE CURRENT PAPER IN COMPARISON TO THE OTHER HEURISTICS (SINGLE BAY)

	Lee&Lee (2010)	Bian&Jin (2013)	Bian&Jin heuristic (2013)	Current Paper	Lower Bound
R021606_0140_001	228	208	227	210	208
R021606_0140_002	224	197	219	199	197
R021606_0140_003	247	223	219	215	211
R021606_0140_004	235	219	230	226	219
R021606_0140_005	217	210	220	212	210
R041606_0280_001	502	439	509	455	439
R041606_0280_002	450	423	473	428	423
R041606_0280_003	450	419	436	423	415
R041606_0280_004	430	426	474	426	426
R041606_0280_005	439	431	462	431	431
R061606_0430_001	765	660	700	661	660
R061606_0430_002	695	670	704	654	654
R061606_0430_003	698	656	709	657	656
R061606_0430_004	699	648	691	649	648
R061606_0430_005	701	660	685	662	660
R081606_0570_001	924	869	945	869	869
R081606_0570_002	930	874	925	874	874
R081606_0570_003	981	891	1022	891	891
R081606_0570_004	952	871	962	874	871
R081606_0570_005	940	873	983	873	873
R101606_0720_001	1163	1107	1171	1107	1107
R101606_0720_002	1132	1085	1179	1085	1085
R101606_0720_003	1225	1102	1152	1102	1102
R101606_0720_004	1168	1100	1132	1085	1081
R101606_0720_005	1158	1085	1188	1085	1085
R021608_0190_001	423	305	348	321	305
R021608_0190_002	359	309	374	320	309
R021608_0190_003	373	311	321	319	302
R021608_0190_004	351	303	313	307	303
R021608_0190_005	333	310	339	314	310
R041608_0380_001	830	602	697	618	602
R041608_0380_002	804	617	777	630	617
R041608_0380_003	684	603	662	614	603
R041608_0380_004	755	614	694	625	614
R041608_0380_005	773	617	685	628	617
R061608_0570_001	1143	904	1018	911	904
R061608_0570_002	1353	897	1019	936	897
R061608_0570_003	1139	913	982	916	913
R061608_0570_004	1242	910	1043	918	902
R061608_0570_005	1333	914	1018	927	914

Table 4. NUMBER OF MOVES REQUIRED TO CLEAR THE BLOCK FOR EACH HEURISTIC (MULTIPLE BAYS)

ID	Lee&Lee (2010)	Bian&Jin heuristic (2013)	Bian&Jin (2013)	Lower Bound
R021606_0140_001	8%	7%	-1%	-1%
R021606_0140_002	11%	9%	-1%	-1%
R021606_0140_003	13%	2%	4%	-2%
R021606_0140_004	4%	2%	-3%	-3%
R021606_0140_005	2%	4%	-1%	-1%
R041606_0280_001	9%	11%	-4%	-4%
R041606_0280_002	5%	10%	-1%	-1%
R041606_0280_003	6%	3%	-1%	-2%
R041606_0280_004	1%	10%	0%	0%
R041606_0280_005	2%	7%	0%	0%
R061606_0430_001	14%	6%	0%	0%
R061606_0430_002	6%	7%	2%	0%
R061606_0430_003	6%	7%	0%	0%
R061606_0430_004	7%	6%	0%	0%
R061606_0430_005	6%	3%	0%	0%
R081606_0570_001	6%	8%	0%	0%
R081606_0570_002	6%	6%	0%	0%
R081606_0570_003	9%	13%	0%	0%
R081606_0570_004	8%	9%	0%	0%
R081606_0570_005	7%	11%	0%	0%
R101606_0720_001	5%	5%	0%	0%
R101606_0720_002	4%	8%	0%	0%
R101606_0720_003	10%	4%	0%	0%
R101606_0720_004	7%	4%	1%	0%
R101606_0720_005	6%	9%	0%	0%
R021608_0190_001	24%	8%	-5%	-5%
R021608_0190_002	11%	14%	-4%	-4%
R021608_0190_003	14%	1%	-3%	-6%
R021608_0190_004	13%	2%	-1%	-1%
R021608_0190_005	6%	7%	-1%	-1%
R041608_0380_001	26%	11%	-3%	-3%
R041608_0380_002	22%	19%	-2%	-2%
R041608_0380_003	10%	7%	-2%	-2%
R041608_0380_004	17%	10%	-2%	-2%
R041608_0380_005	19%	8%	-2%	-2%
R061608_0570_001	20%	11%	-1%	-1%
R061608_0570_002	31%	8%	-4%	-4%
R061608_0570_003	20%	7%	0%	0%
R061608_0570_004	26%	12%	-1%	-2%
R061608_0570_005	30%	9%	-1%	-1%
AVERAGE	11%	8%	-1%	-1%
TOTAL AVERAGE	**12%**	**6%**	**-2%**	**-3%**

Table 5. MOVEMENT REDUCTION ACHIEVED BY THE CURRENT SECTION IN COMPARISON TO THE OTHER HEURISTICS (MULTIPLE BAYS). The total average includes single and multiple bays instances.

The results show that the heuristic introduced in the current section:

<u>In single bay instances:</u>

1. Outperforms Kim & Hong(2004) by a large margin in all instances achieving an average cut down in moves of 41.3%
2. Outperforms Lee & Lee(2010) in all instances achieving an average movement reduction of 15%
3. Underperforms to Bian & Jin(2013) heuristic averaging 1% more moves
4. Underperforms to Bian & Jin(2013) averaging 5.7% more moves
5. Averages 7.5% more moves than the lower bound

<u>In multiple bay instances:</u>

1. Outperforms Lee & Lee(2010) in all instances achieving an average movement reduction of 11%
2. Outperforms Bian & Jin(2013) heuristic in all instances achieving an average movement reduction of 8%
3. Underperforms to Bian & Jin(2013) averaging 1% more moves
4. Averages 1% more moves than the lower bound

<u>In total average:</u>

1. Outperforms Lee & Lee(2010) in all instances achieving an average movement reduction of 12%
2. Outperforms Bian & Jin(2013) heuristic achieving an average movement reduction of 6%
3. Underperforms to Bian & Jin(2013) averaging 2% more moves
4. Averages 3% more moves than the lower bound

5.3 Number of moves per container

Figures 18, 19 indicate the number of moves per container needed to clear the block for each method. In the first graph results for instances with maximum height of 6 containers per stack are presented, while in the second one results for maximum height of 8 containers are showcased. The average number of moves per container needed to clear the block is derived from the formula below (Kim 1997):

$$N = \frac{(M - 1)}{4} + \frac{(H + 1)}{(8 \times St)} + 1$$

Where M is the maximum stack height, H is the average stack height which can be formulated as

$$H = \frac{N_{con}}{(B \times St \times M)}$$

Where N_{con} is the number of containers in the block, B is the number of bays and St is the number of stacks per bay.

The first part of the formula $\frac{(M - 1)}{4} + \frac{(H + 1)}{(8 \times St)}$, represents the number of reallocations needed per container. Adding 1 to that, results to the total number of moves required. Kim's equation shows that the number of reallocations is sensitive to the maximum and average height of stacks and to the number of stacks per bay. Increasing the height of stacks raises the number of moves required to reach the desired container while on the opposite hand increasing the number of stacks has a positive effect on reducing reallocations. A larger number of stacks provides more restacking options each time a container has to be reallocated, thus decreasing the chance of the container reallocated to block another container in its new stack and force the crane to reallocate it again later on.

Another issue needed to be addressed is the fact that in both graphs the average number of moves is a steady function, while the lower bound fluctuates slightly. This fluctuation is not sensitive to the number of containers, but to the distribution of priority numbers among containers in each of the block instances examined. The priority sequence impacts the number of reallocations directly and due to this fact the lower bound is not solely sensitive to block size variables (*M, H, B, St*), in contrast to Kim's formula.

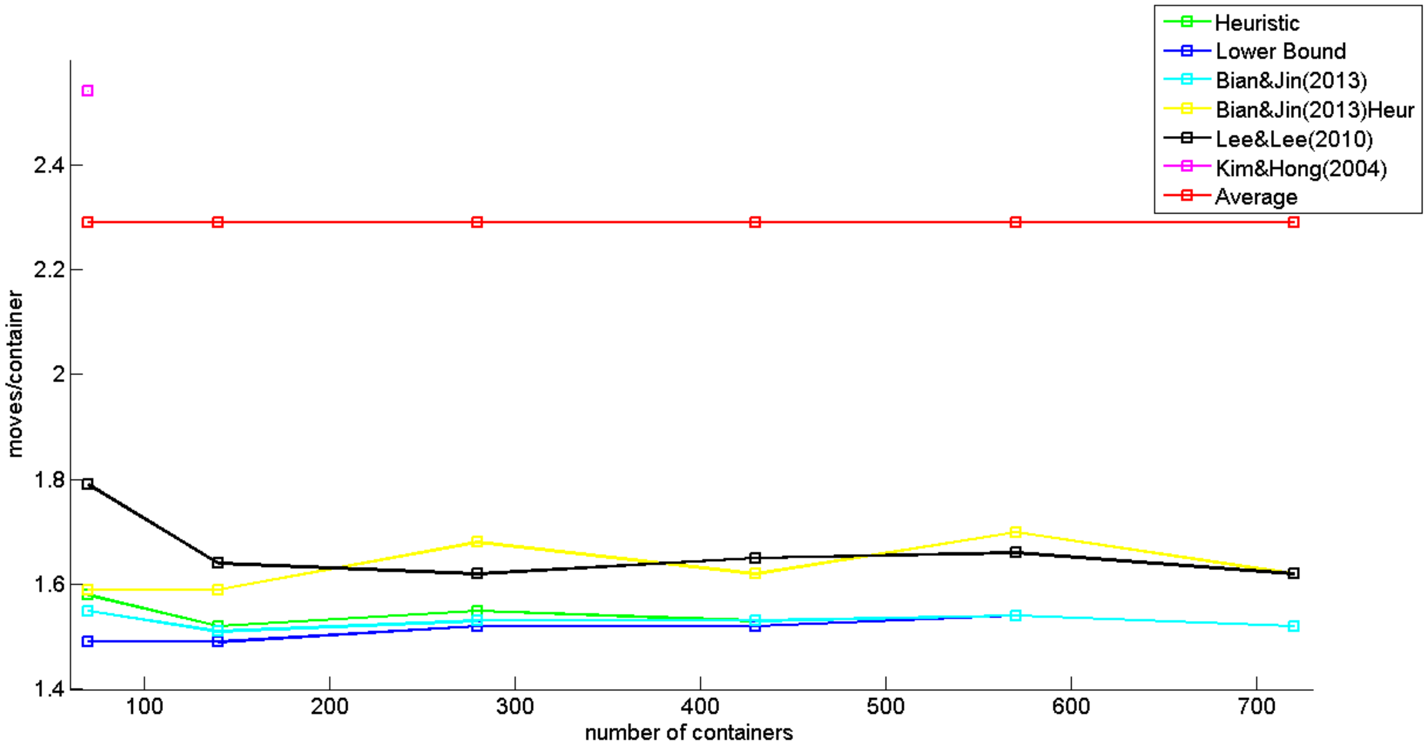

Figure 18. Number of moves/container required to clear a block of containers in relation to the number of containers in the block, for M=6.

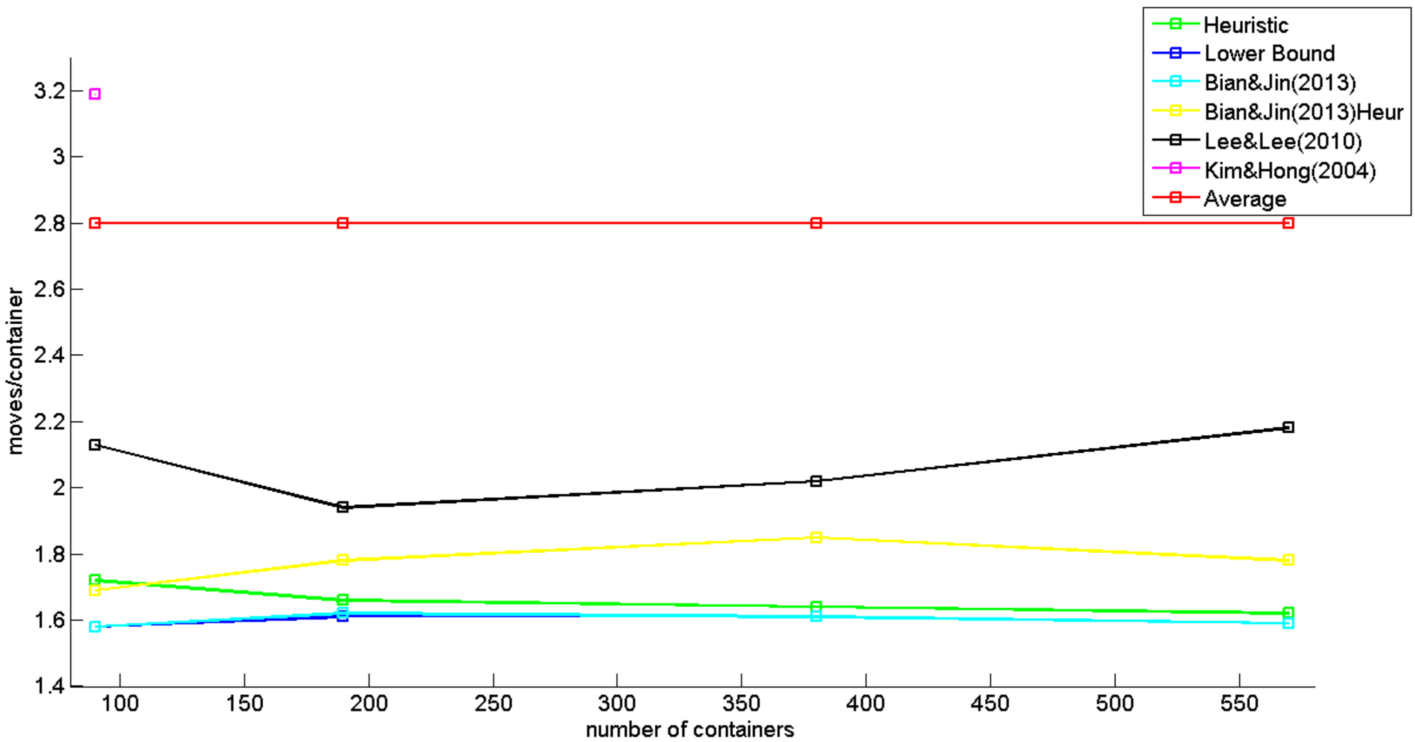

Figure 19. Number of moves/container required to clear a block of containers in relation to the number of containers in the block, for M=8.

5. SIMULATION MODEL

The model is a simulation based approach to determining the optimal layout for container yards. The optimization goal is to minimize the energy consumption and emissions produced by all the main operation clusters taking place in a terminal regarding the handling of containers.

The model requires as the main input variables:

A. The *annual throughput* handled by the container terminal
B. The *quay length* of the terminal (the quay length can optionally be derived from data of container terminals relating the average quay length with the annual throughput and thus only the latter will be required as an input variable)

Given the above input variables the model proceeds to find the optimal layout subject to certain constrains. These constrains are:

1. A maximum allowed average transporter turnaround time in the Yard.
2. A maximum allowed average highway truck turnaround time in the Yard.
3. A minimum allowed available storage capacity in the Yard.
4. A maximum allowed investment and operational cost.

So the problem can be formulated as:

MIN(EMISSIONS) , Subject to constrains : 1,2,3,4

5.1 Yard Layouts Examined

The model examines 2 different yard layouts. In the first layout the blocks are positioned parallel to the quay wall. This type of container yard layout is called 'Asian' because of its popularity among South East Asian terminals. In the second layout the blocks are positioned perpendicular to the quay wall. This type of container yard layout is called 'European' because of its popularity among major Northern European terminals.

In the Asian layout each block in the yard is dedicated to either inbound (import) or outbound (export and transshipment) containers. The number of blocks and YCs, out of the total available, dedicated to handling and storing inbound or outbound containers is proportionate to the percentage of each type of container out of the total annual throughput. Export and transshipment containers are bound to exit the terminal through the quay where they will be loaded onto a ship, and thus are called outbound, while Import containers leave the terminal through the gate via highway trucks, and are called inbound.

In the European layout blocks are not dedicated to one type of container, unlike the Asian layout. Each block is divided into an inbound and an outbound side. The side facing the quay handles outbound containers while the side facing the gate handles the inbound ones. Because in the European layout the transporters connecting the quay with the yard and the highway trucks connecting the gate with the yard do not travel among blocks, which is the opposite case of what takes place in the Asian layout, outbound containers are being delivered from trucks in the inbound side (gate side) while inbound containers from terminal transporters are being discharged in the outbound side (quay side). Thus, a problem emerges in which the containers delivered in the wrong side must be repositioned to the correct one.

In order to examine each layout, the key parameters defining their operational function are established.

5.1.1 <u>Asian yard layouts parameters</u>

In this type of layout, YCs can travel from one block to another. Road trucks and transporters travel through vertical and horizontal aisles to transport containers. The following additional assumptions are introduced for defining the problem (Lee & Kim 2012):

1. The entire layout of a container terminal is of rectangular shape, which is the most popular type in practice.

2. The number of YCs per row of blocks in the yard is given and the same for all the rows.

3. Interference among YCs is treated in the manner presented below. Each YC operates within a given range depending on the number of YCs per row of blocks, the number of blocks in each row and the type of handling operations each YC is assigned to. Given the above, a fixed and defined range of operations is considered for each YC. This range extends to and from the limits of operation of the adjacent cranes for each YC. In this manner there are no situations of interference

4. The number of YCs deployed to each type of the operation (outbound or inbound) is proportional to the number of handling operations of the type.

5. Some blocks are dedicated only to inbound containers, while the others are dedicated only to outbound containers. Blocks are divided into two classes, one for inbound containers and the other for outbound containers, following the ratio that is proportional to the numbers of inbound and outbound containers to be stored in the yard.

6. The blocks for inbound and loading (outbound) containers are uniformly mixed in the yard. There are cases where loading container blocks are located in a confined area in the yard, while inbound container blocks are located at the other area, for example, near to the gate. It must be an important problem to determine the allocation of blocks to different types of containers and the problem is worth being analyzed as another independent study. Because this is not the main issue of this paper, it was assumed that blocks for inbound and loading containers are uniformly distributed across the yard.

7. The sizes of blocks (number of bays per block, number of stacks per bay, maximum height of stacks) are the same within the entire yard.

8. The gate is located at the middle of the landside of the rectangular yard.

9. Transporters deliver containers between the yard and a vessel in double command cycles, which means that a transporter moves a container in one direction and moves back loaded. The transporter delivering a container to an STS crane will wait until it receives a container from the STS crane or will pick up one that has already been unloaded (only Straddle Carriers can perform a pick up move). The same procedure takes place at the yard as well.

10. Transporters are considered 'dedicated' to an STS crane, which is the most common method used in practice (Kim, Park, Jin 2007). This means that each time multiple STS cranes operate simultaneously each crane has a certain number of transporters dedicated to its operations and these transporters cannot be assigned to another STS crane. This dedication applies only for STS cranes, transporters can be assigned to any YC at a given operation cycle.

5.1.2 European yard layouts parameters

In this layout, the YCs cannot move from one block to another and the traffic areas for trucks and transporters are separated. Many automated container terminals use this type of yard layout because of its simple traffic control. The following assumptions are introduced for defining the problem (Lee & Kim 2012):

1. The entire layout of a container terminal is of a rectangular shape, which is the most popular type in practice.

2. The number of rows of blocks is always equal to one. Only the number of columns can vary and thus the number of blocks is equal to the number of

columns of blocks in the yard. The number of YCs per block is fixed at two YCs per block which is the most common arrange used in practice.

3. Interference among YCs is treated in the manner presented below. In European layouts, YCs are required to operate in a dynamic space span. Thus, a decision making plan is proposed to address the issue so as to avoid collision situations and minimize crane idle times caused by interference as much as possible. This heuristic is presented in the corresponding section later on.

4. In perpendicular layouts outbound and inbound containers are mixed in the same blocks and each block is divided in two sides, one to store outbound and one to store inbound containers. This mixing method is a byproduct of the European layout design, in which transporter and truck movements do not take place among the blocks and thus it is left upon the blocks and the YCs operating on them to work as a transfer system between the quay and the gate. Export containers delivered by trucks at the gateside must be transferred through the blocks at the quayside and accordingly import containers follow the opposite route.

5. Gateside YCs are deployed to inbound operations and quayside YCs to outbound operations.

6. The sizes of blocks (number of bays per block, number of stacks per bay, maximum height of stacks) are the same within the entire yard.

7. The gate is located at the middle of the landside of the rectangular yard.

8. Transporters deliver containers between the yard and a vessel in double command cycles, exactly as mentioned above in the parallel layout section.

9. Transporters are considered ‘dedicated’ to an STS crane, exactly as mentioned above in the parallel layout section.

5.2 Simulation Model Input and Output Parameters

All the input constants, variables, dependent variables and finally model output variables are presented collectively in the following matrices.

	CONSTANTS
l_v	Average length of a vessel (m).
l_b	Length of a bay (m). Consists of the length of a TEU size container plus a spacing distance between bays.
l_h	Height of a container (m)
w_r	Width of a stack (m). Consists of the width of a TEU size container plus a spacing distance between stacks.
w_h	Width of a horizontal aisle between adjacent blocks in the layout including the width of a lane for driving (m).
w_v	Width of a vertical aisle between adjacent blocks in the layout including the width of a lane for driving (m).
h_T	Total working time per year (min).
c_{QC}	Average cycle time of a QC. (min/move)
n_{QC}	Average number of QCs allocated to a vessel.
u	Average utilization of storage space ($0 \leq u \leq 1$). Where $u=H/M$. The value of u can be estimated from historical data of other terminals already in operation. This parameter is a function of a storage requirement and the storage space provided. The space utilization significantly influences not only the space requirement but also the efficiency of the handling operation in the yard. However, this study does not attempt to determine how much space should be provided but attempts to determine the layout of the yard under the condition that the space is provided to satisfy a predetermined utilization and the storage requirement.
v_l	Travel speed of a loaded transporter(m/min).
v_e	Travel speed of an empty transporter(m/min).
v_b	Travel speed of a YC gantry. It is the speed at which the YC travels among bays in the block (m/min).
v_s	Travel speed of a YC trolley. It is the speed at which the trolley of the YC travels among rows in the block (m/min).
v_{hl}	Travel speed of the loaded spreader of a YC. It is the speed at which the spreader travels up or down when it is loaded with a container. (m/min).
v_{he}	Travel speed of the empty spreader of a YC. It is the speed at which the spreader travels up or down when it is not loaded with a container. (m/min).
T_p	Time required by the spreader to pick up or release a container. (sec)
GT	Average gross tonnage of incoming vessels (gt)
kwhCO2f	Kwh to CO2 conversion factor
DieselCO2f	Diesel to CO2 conversion factor

MDOCO2f	Marine Diesel Oil to CO2 conversion factor
u_{QC}	Average utilization of a QC ($0 \leq u_{QC} \leq 1$). Indicates the number of berths slots being used, out of the total available, at a given moment.
δ	Peak ratio for arriving containers by road trucks ($0 < \delta < 1$). Road trucks do not arrive at the terminal uniformly over 7 days a week and 24 h a day. There are fluctuations in the arrival rate of road trucks during the arrival period of outbound containers and the retrieval period of inbound containers, and even during the different time periods in a day. The container handling system must have a capacity enough to accommodate the fluctuation in the handling requirement.
QC_{sim}	The sum of containers loaded and discharged per STSC during the simulation.

Table 6. Simulation model constants

	VARIABLES
l_q	Length of the quay/terminal (m).
R	Number of rows of blocks.
C	Number of columns of blocks.
B	Number of bays per block.
St	Number of stacks per bay.
M	Stack maximum height
Ex	Number of containers moving from the hinterland to vessels (outbound containers) during a year.
Tr	Number of containers discharged from a vessel and then loaded onto another vessel (transshipment containers) during a year.
Im	Number of containers discharged from a vessel and then moved to the hinterland (inbound containers) during a year.
n_{YC}	Number of YCs installed at each row of blocks in the layout.
D_{Ex}	Average dwell time (in working time) of outbound containers at the yard (mins).
D_{Tr}	Average dwell time (in working time) of transshipment containers at the yard (mins).
D_{Im}	Average dwell time (in working time) of inbound containers at the yard (mins).

Table 7. Simulation model variables

	DEPENDENT VARIABLES		
w_q	Max width of terminal (m).	l_q	Lee & Kim 2012
w_{qA}	Width of Asian terminal (m).	$R \times St \times w_r + (R+1) \times w_h$	Lee & Kim 2012
w_{qE}	Width of European terminal (m).	$B \times l_b + 2 \times w_h$	Lee & Kim 2012
l_{qA}	Length of Asian terminal (m).	$C \times B \times l_b + (C+1) \times w_v$	Lee & Kim 2012
l_{qE}	Length of European terminal (m).	$C \times St \times w_r + (C+1) \times w_v$	Lee & Kim 2012
N_A	Number of blocks Asian terminal	$R \times C$	Lee & Kim 2012
N_E	Number of blocks European terminal	C	Lee & Kim 2012
s_O	Average storage space requirement (TEU) for loading containers, which can be evaluated as .	$\frac{(Ex \times D_{Ex} + Tr \times D_{Tr})}{(u \times h_T)}$	Lee & Kim 2012
s_I	Average storage space requirement (TEU) for inbound containers, which can be represented by .	$\frac{(Im \times D_{Im})}{(u \times h_T)}$	Lee & Kim 2012
f_G	Construction cost of the ground space equivalent to a square meter, which is converted to the equivalent annual cost. This includes the investment capital cost for the land and the construction of the ground. (Korean Won)	$28890 \times Ground\ Space$	Lee & Kim 2012
f_{YC}	Fixed overhead cost of a YC per year. This is related to the investment capital cost for purchasing a YC. (Korean Won)	$(116000000 + (St + 2 \times M) \times 1380000) \times (No.\ of\ YCs)$	Lee & Kim 2012
c_{YC}	Operating cost per minute of a YC including labor, fuel, maintenance, and overhead costs. This explains the cost term which increases as the operation time of YCs increases.(Korean Won)	$569 \times YC\ operational\ time$	Lee & Kim 2012
f_{TR}	Fixed overhead cost of a transporter per minute. (Korean Won)	$19.29 \times .017 \times TT\ operational\ time$	Lee & Kim 2012
c_{TR}	Operating cost per minute of a transporter including labor, fuel, maintenance,	$481 \times TT\ operational\ time$	Lee & Kim 2012

	and overhead costs(Korean Won)		
Cost	Total annual cost (Korean Won)	$f_G+f_{YC}+c_{YC}+f_{TR}+c_{TR}$	Lee & Kim 2012
	EURO	ASIAN	
Ground Space	$l_q \times w_{qE}$	$l_q \times w_{qA}$	Lee & Kim 2012
TT operational time	$1.1\times\left\{\begin{matrix}\left(\frac{T_{scE}}{2}+CU+\frac{WO}{2}\right)\times(Im+Tr)\\+\left(\frac{T_{scE}}{2}+CL+\frac{WO}{2}\right)\times(Ex+Tr)\end{matrix}\right\}$	$1.1\times\left(\begin{matrix}\left(\frac{T_{scA}}{2}+CR+\frac{WO}{2}+CU+WI\right)\times(Im+Tr)\\+\left(\frac{T_{scA}}{2}+CL+\frac{WO}{2}\right)\times(Ex+Tr)\end{matrix}\right)$	Lee & Kim 2012
YC operational time	$\left(\begin{matrix}CL\times(Ex+Tr)+CR\times Ex\\+CD\times Im+CU\times(Im+Tr)\end{matrix}\right)$	$\left(\begin{matrix}CL\times(Ex+Tr)+CR\times(Ex+Tr)\\+CD\times Im+CU\times Im\end{matrix}\right)$	Lee & Kim 2012
No. of Ycs	$n_{YC}\times C$	$n_{YC}\times R$	Lee & Kim 2012
N_{QC}	Total number of STCs operating at a given moment.	$n_{QC}\times u_{QC}\times\frac{l_q}{l_v}$	Lee & Kim 2012
YCkwh =	Yard cranes energy consumption. (kwh)	*2kwh/move +0.0206 kwh/m*	He,Huang & Yan 2015
STSkwh =	Ship to shore cranes energy consumption. (kwh)	*6kwh/move*	Geerlings & Van Duin 2011
SCl =	Straddle carriers energy consumption. (litres)	*12.3l/h*	Kalmar
AGVkwh =	Automated guided vehicles energy consumption. (kwh)	*17kw/h*	Saanen 2016
TRl =	Highway trucks energy consumption. Consists of the total diesel oil consumption of all highway trucks entering the terminal, calculated within the limits of the terminal. (litres)	*1.2kg/km(EURO5), 1.7kg/km(EURO3)*	Zamboni 2013
SHl =	Ships energy consumption. The consumption is calculated only for the time ships spend at berth and not for the time spent entering and leaving the port. (litres)	$0.7\times2.9kg\times(\frac{GT}{1000})/h$	Winnes& Parsmo 2016

ah =	Arrival rate of road trucks for receiving and delivery containers, incorporating the peak arrivals, per minute.	$(1+\delta)\times\frac{(Ex+Im)}{h_T}$	Lee & Kim 2012
T_{scE}=	Average round-trip travel time of transporters in European layouts	$\frac{\left(2\times\frac{l_q}{3}+2\times w_h\right)}{v_l}$	Lee & Kim 2012
T_{scA}=	Average round-trip travel time of transporters in Asian layouts	$\frac{\left(\frac{(2\times C^2+3\times C+1)}{(3\times C^2)}\times l_q+(w_r\times St+w_h)\times R+w_h\right)}{v_l}$	Lee & Kim 2012
D_{trE}=	Average round-trip travel distance of trucks in European layouts	$\frac{l_q}{2}+2\times w_h$	Lee & Kim 2012
D_{trA}=	Average round-trip travel distance of trucks in Asian layouts	if *C* is even $D_{trA}=\frac{(C+2)}{(2\times C)}\times l_q+(w_r\times St+w_h)\times R+w_h$ else $D_{trA}=\frac{(C+1)^2}{(2\times C^2)}\times l_q+(w_r\times St+w_h)\times R+w_h$	Lee & Kim 2012
$Ship_{sim}$	The sum of containers loaded and discharged on vessels during the simulation. The numbers of loaded and discharged containers are considered equal.	$QC_{sim}\times N_{QC}$	
$Load_{sim}$	The number of containers loaded by each STSC during the simulation.	$\frac{Ship_{sim}}{2}$	
Dis_{sim}	The number of containers discharged by each STSC during the simulation.	$\frac{Ship_{sim}}{2}$	
$Truck_{sim}$	The number of trucks arriving in the terminal during the simulation	*f(ah)*	
Del_{sim}	The number of trucks arriving to deliver a container during the simulation.	$Tr_{sim}\times\frac{Ex}{(Im+EX)}$	

Rec_{sim}	The number of trucks arriving to receive a container during the simulation.	$Tr_{sim} \times \frac{Im}{(Im + EX)}$

Table 8. Simulation model dependent variables

	OUTPUT
Conkwh =	Electrical energy spent per container handled. (kwh/container)
Conl =	Diesel oil spent per container handled. (litres/container)
ConCO2 =	Amount of CO2 produced per container handled. (kg/container)
CR% =	CO2 percentage produced due to YC and STS crane operations.
TT% =	CO2 percentage produced due to TT operations.
SH% =	CO2 percentage produced due to ships.
TR% =	CO2 percentage produced due to highway trucks.
CR =	Average YC cycle time for receiving an export container from trucks and transshipment container from TTs (Asian) or export container from trucks (European). (min).
CD =	Average YC cycle time for delivering an import container to trucks. (min).
CL =	Average YC cycle time for delivering an export or transshipment container to TTs. (min).
CU =	Average YC cycle time for receiving an import container from TTs (Asian) or import and transshipment container from TTs (European). (min).
WO =	Average service waiting time for a transporter or truck by an outbound YC . (min).
WI=	Average service waiting time for a transporter or truck by an inbound YC . (min).
R	Number of rows of blocks.
C	Number of columns of blocks.
B	Number of bays per block.
St	Number of stacks per bay.
M	Stack maximum height

Table 9. Simulation model output

*<u>On *TT operational time*</u>:

The *TT operational time* function presented above is different than the one showcased in Lee & Kim 2012 because it addresses a double cycle operational policy instead of a single cycle one. Under double cycle policy transporters deliver export and transshipment containers from STSCs to YCs and return back to STSCs loaded with import and transshipment containers. The 1.1 factor in the function is used because even in double cycle operational policies there are an extra 10% of single cycle routes required to be made.

5.3 Solution procedure

Given all the necessary input the model proceeds to find all the possible layouts that satisfy a certain number of constrictions. First of all, the layout variables in the models are:

ASIAN	EUROPEAN
R = number of rows of blocks	
C = number of columns of blocks	*C = number of columns of blocks*
B = number of bays per block	*B = number of bays per block*
St = number of stacks per bay	*St = number of stacks per bay*
M = maximum height of stacks	*M = maximum height of stacks*

Table 10. Asian and European layout variables

With these principle variables given we can design the layout of a container terminal. Below we establish the procedure steps that lead to finding the optimal layout solution.

1. At step 1 the model finds all possible *R, C, B, St, M* combinations that satisfy certain constrictions. At first we determine the range of the above variables. All variables are given a certain value range considering the common practice experience from container terminals around the world. These value ranges are $B \in (20,60)$, $St \in (6,16)$, $M \in (4,7)$, $R \in (1,10)$, $C \in (1,10)$ (Asian) or $C \in (1,50)$ (European) .

   The space required for each layout combination cannot exceed the given terminal space. As stated before the terminal is considered a rectangular space with X-dimension = l_q and Y-dimension = w_q. The length and the width of the layout produced by each combination are formulated as shown in the dependent variable matrix:

w_{qA}	Width of Asian terminal (m).	$R \times St \times w_r + (R+1) \times w_h$
w_{qE}	Width of European terminal (m).	$B \times l_b + 2 \times w_h$
l_{qA}	Length of Asian terminal (m).	$C \times B \times l_b + (C+1) \times w_v$
l_{qE}	Length of European terminal (m).	$C \times St \times w_r + (C+1) \times w_v$

Table 11. Storage yard dimensions

   Also there must be enough storage space in the yard so as to satisfy the storage space requirements considering the average throughput rates and the average dwell times of different kinds of containers being handled in the terminal and the utilization of storage space. The storage space requirement can be formulated as:

$$S_{req} = s_O + s_I = \frac{\left(Im \times D_{Im} + Ex \times D_{Ex} + Tr \times D_{Tr}\right)}{\left(u \times h_T\right)} \text{ (No. of containers)}$$

The storage space outputted by each layout combination can be formulated as:

$S_{out} = N \times B \times St \times M \times u$, where N is the number of blocks

Concluding, step 1 can be formulated as:

Find(R,C,B,St,M) subject to: l_{gA} *or* $l_{gE} < l_g$, w_{gA} *or* $w_{gE} < w_g$, $S_{out} > S_{req}$

2. At step 2 the model proceeds to disqualify all the combinations derived from step 2 that are by default inferior to their counterparts and will lead to higher energy consumption and emissions. A layout combination is regarded by default inferior to another combination and is disqualified from entering the simulation if one of the following cases occur:

ASIAN LAYOUT

a. Out of all layouts that have equal *R, C, St, M* variables only the one with the minimum *B* value is qualified.
b. Out of all layouts that have equal *R, C, St, B* variables only the one with the minimum *M* value is qualified.
c. Out of all layouts that have equal *R, St, M, B* variables only the one with the minimum *C* value is qualified.

PROOF:

The 5 energy consuming units taken into consideration in the simulation model are YCs, STSCs, TTs, ships and trucks. In this segment each energy consuming unit is going to be expressed as function of the 5 layout variables in order to prove that an increase in variables *B, C, M* , under all other variables equal, can only increase the energy consumption in Asian layouts.

1. *YCkwh= 2kwh/move +0.0206 kwh/m*

   YCkwh= f(moves, gantry distance travelled)

   Moves=f(reallocations)=f(M,St^{-1}*)* ,(Kim 1997)

   Gantry distance travelled =f(l_{qA}*)=f(C,B)*

Finally, *YCkwh= f(M,C,B,* St^{-1}*)*

2. *TTkwh= f(TT operational time) =f(TscA, CT, WT), CT= YC cycle times, WT= TT waiting times*

   TscA= f(C,R,St)

   Given the flows of incoming containers to the yard from the quay and the gate are the same for all layouts, YC cycle times become sensitive only to the number of YCs available and to the productivity they output.

   CT=f(reallocations, (No. of YCs)$^{-1}$*, YC gantry/trolley/spreader distance travelled)*

   Reallocations =f(M,St^{-1}*)*

   No. of YCs= f(R)

   Gantry=f(lqA)=f(C,B)

   Trolley= f(St)

   Spreader= f(M)

   WT= f(CT)

   Finally TTkwh=f(C,B,M,R,St^{-1}*,* R^{-1}*)*

3. *TRkwh= f(truck distance travelled)=f(C,R,St)*
4. STSC energy consumption is a function of *Im, Ex, Tr* and is not sensitive in any way to the layout variables
5. Ship MDO consumption is a function of the time spent to conclude unloading and loading operations. This is a function of the STSCs deployed to each ship, which is considered fixed, and also a function of STSC cycle time, also considered fixed. Only in cases of container delivery delay to STSCs, ship MDO consumption becomes a function of CT.

   Finally *SHlit= f(CT)= f(C,B,M,R,*St^{-1}*,* R^{-1}*)*

Out of all the above we conclude that *St, R* variables can impact the energy consumption in both positive and negative ways, while an increase in *C, B, M* under all other variables being equal can only increase the energy consumption.

EUROPEAN LAYOUT

a. Out of all layouts that have equal *C, St, M* variables only the one with the minimum *B* value is qualified.
b. Out of all layouts that have equal *C, St, B* variables only the one with the minimum *M* value is qualified.

<u>PROOF:</u>

A corresponding analysis to the one done for the Asian layout above, leads to the conclusion that an increase in *B, M* under all other variables being equal can only increase the energy consumption. Variable *C* can have both a positive and a negative impact energy wise because *No. of YCs=f(C)* in the European layout.

3. At step 3 all combinations left after step 2 are run through a simulation model which determines which one of them is better energy wise and produces the least amount of emissions. All layouts have to match certain constrictions If any of the above combinations fails to match the constrictions established by the end of the simulation it is disqualified.
   These constrictions are:

$$Max(CR+CL+WO,CD+WI,CU+WI) < TCST \ \& \ Cost < TCost$$

   Out of all layouts matching the above restrictions, the layout with *MIN(emissions)* is the winner.

5.4 SIMULATION

Each layout derived at step 4 is tested and evaluated through the simulation model. The model examines the operational efficiency of each layout under certain parameters. To analyze the function of the simulation model we will break it down to its basic components and proceed to analyze each component's function for European and Asian layouts. The components used in each layout are YCs, TTs, STSCs, trucks and containers.

5.4.1 Containers

The simulation begins assuming a certain number of berth slots in the terminal are occupied by vessels, and loading and discharging operations are about to commence on all of them. A fixed number of STSCs operating per vessel is set and also, a fixed number of containers loaded and discharged by each STSC is set. As the quay operations take place highway freights arrive through the gate at a given rate seeking to deliver or receive a container. The simulation ends when all tasks set for each STSC are completed.

The simulation model assumes that containers bound to be loaded onto arriving highway trucks and vessels are already in the yard prior to the arrival. Ships are not loaded with containers that arrive at the yard while they are already under berth operations. In fact all containers bound to be loaded on a ship must already be at the yard a few days prior to its arrival (Lee & Kim 2012). Accordingly, a truck arriving at the yard does not retrieve an import container that is being unloaded by the ship at the time of the truck's arrival. This policy ensures a smooth flow of containers in the yard and minimizes vessel's berth time and truck turnaround time.

The simulation model also assumes all containers in the yard are given a sequential priority number stating the order in which each container should be loaded onto a ship according to the stowage plan, or onto a truck according to the truck arrival schedule. Yard cranes are faced with the task of delivering containers stacked in yard blocks to transporters and trucks given that sequential priority as fast and effective as possible.

Based on these priority numbers given to containers the heuristic determines the optimal task handling sequence in order to minimize reallocations, as well as transporter and truck waiting times at the yard. As far as handling containers discharged from vessels and trucks is concerned, the priority number given to these containers is higher than the priority number of every container already stacked in the yard. As stated earlier, they will be retrieved by vessels and freights in a future time and thus are treated as lower priority containers by the heuristic. No remarshalling operation is considered before the start of the simulation. Containers bound to be loaded onto vessels are randomly distributed among yard blocks.

5.4.2 Heuristic alteration for the real scale problem

In the previous section, where the decision heuristic with regard to minimizing container reallocations was introduced, there were certain assumptions made that do not apply to the real scale operations taking place in the storage yard. In order for the heuristic to be applicable in realistic operation instances there are certain features that need to be addressed and altered.

ISSUE NO.1

Heuristic alteration

The goal of the heuristic presented was to minimize the amount of moves required by a YC to deliver all containers to transporters until the block was empty of containers and assuming no containers where being added in the block during the process. In real scale storage yard operations containers are constantly being added to and removed from the block.

Containers delivered to the yard block are given higher priority numbers than the priority number of every container already stacked in the yard as stated earlier. So, the *min(Xs)* criterion is rendered pointless since all containers in the yard have a *PN<D*, where *D* is the priority number of the container delivered to the block. Hence, the heuristic for choosing the optimal stack for delivered containers only (for reallocation purposes it remains the same) becomes the following:

Deliver the container to the stack with *max(Ws)*

ISSUE NO.2

Heuristic alteration

The second major issue regarding the heuristic is that its goal is to minimize the amount of moves needed to clear the block off containers without taking into account the time and energy cost of the reallocation movements performed. For example, the optimal stack for a given reallocation move under the heuristic could be 20 bays away from the bay of origin. In a real case scenario such a movement would be extremely costly time and energy wise for a YC to perform, despite the fact that it is the best one with regard to minimizing the total amount of reallocations. Given this, it becomes obvious that the optimal Search Space Range (*SSR*) of the heuristic for finding the optimal stack should be examined in order to establish the right tradeoff between minimizing the amount of reallocations and the amount of crane gantry movements.

In order to determine the optimal *SSR* value a simulation trial is performed. In the course of this trial several yard block layouts are examined (*B, St, M*). For each layout a sensitivity analysis of the layout to the *SSR* is performed. The *SSR* value varies from *0* to

B-1. An *SSR* value of zero *(0)* means that reallocations can only be performed within the same bay. An *SSR* value of one *(1)* means that reallocations can be performed to adjacent bays as well, increasing the number of available bays to *3*. The *SSR* value reaches up to *B-1* in which case all bays in the block become available reallocation options.

In order to establish the optimal *SSR* value we perform simulation tests for several block dimensions. The block dimension values examined were *B=(10,20,30), St=(6,11,16), M=(4,7)*. That leads to a total of *18* layout combinations the results of which are presented in Figures 20, 21, 22. Only YC energy consumption is calculated in the simulation tests.

It becomes clear that most curves present a rising trend as the *SSR* value increases, especially as *St* and *M* values increase as well, and thus the optimal value of *SSR* is *0*. Hence, the *SSR* value will be set to *0* for all layouts examined in the simulation, meaning reallocations will be only performed within the same bay. In situations where all stacks within the same bay happen to be maxed out, *SSR* value will be increased by *1* until feasible reallocations stacks are found.

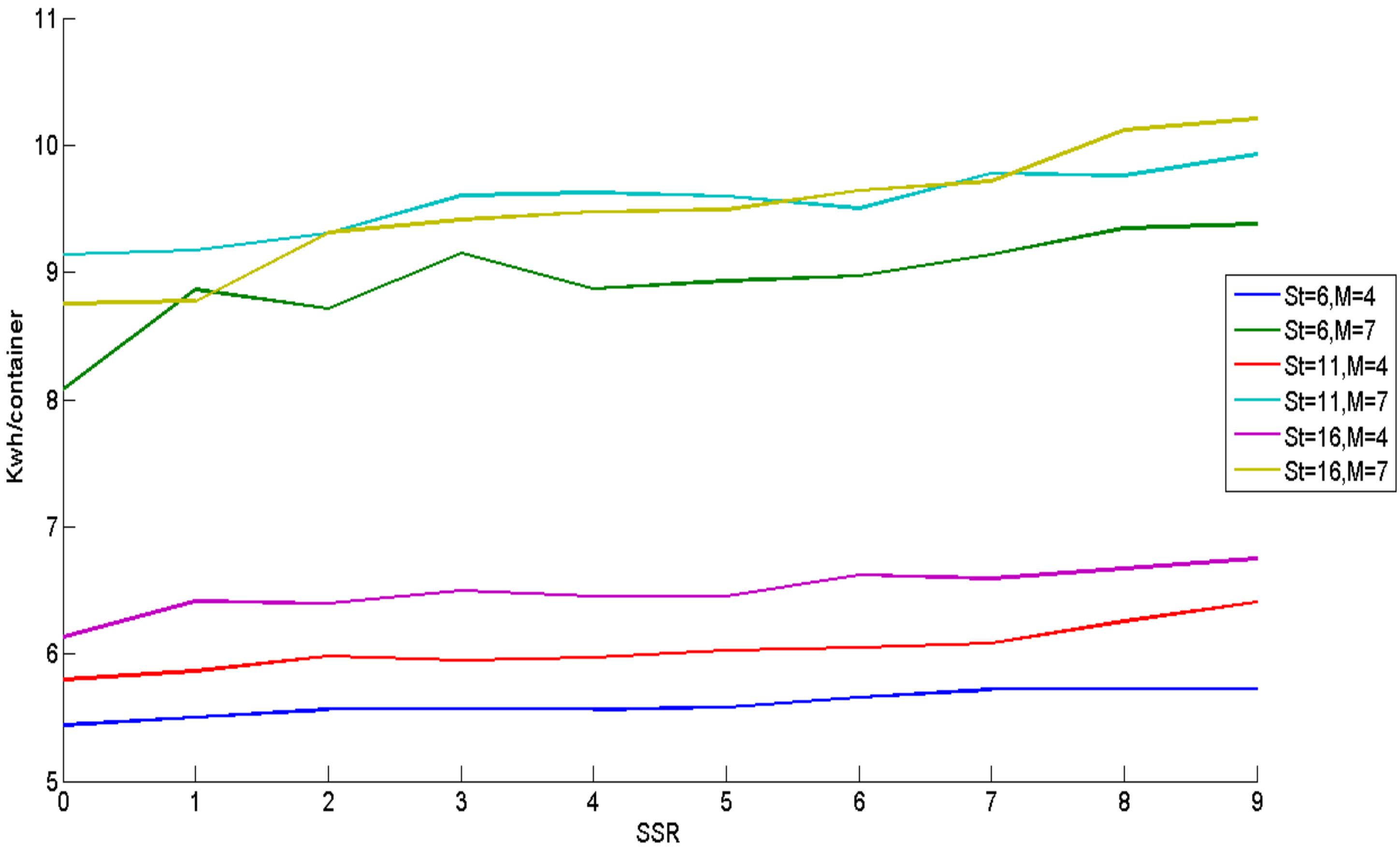

Figure *20. Kwh/container relation to SSR value for B=10 and for various St, M values.*

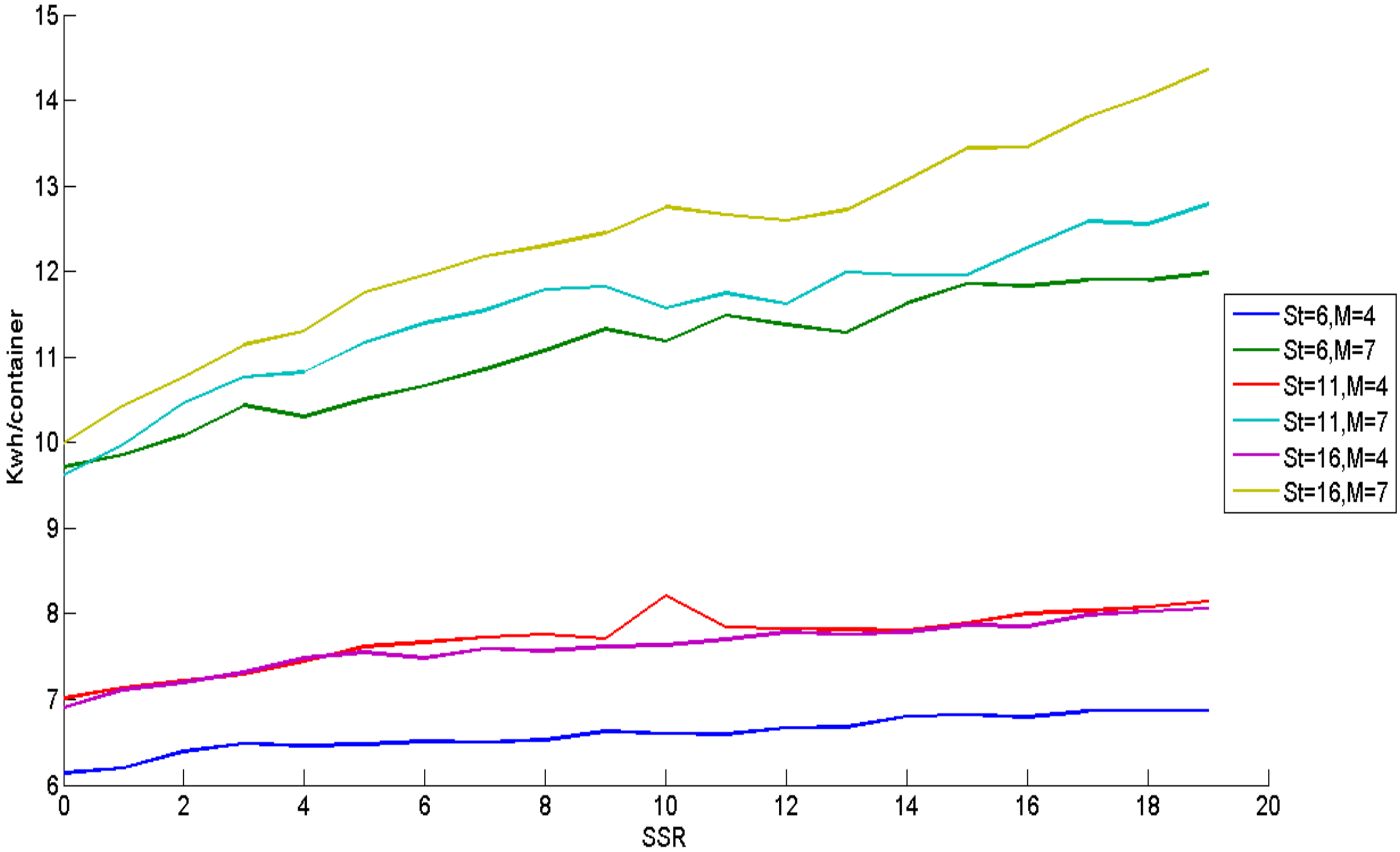

Figure 21. Kwh/container relation to SSR value for B=20 and for various St, M values.

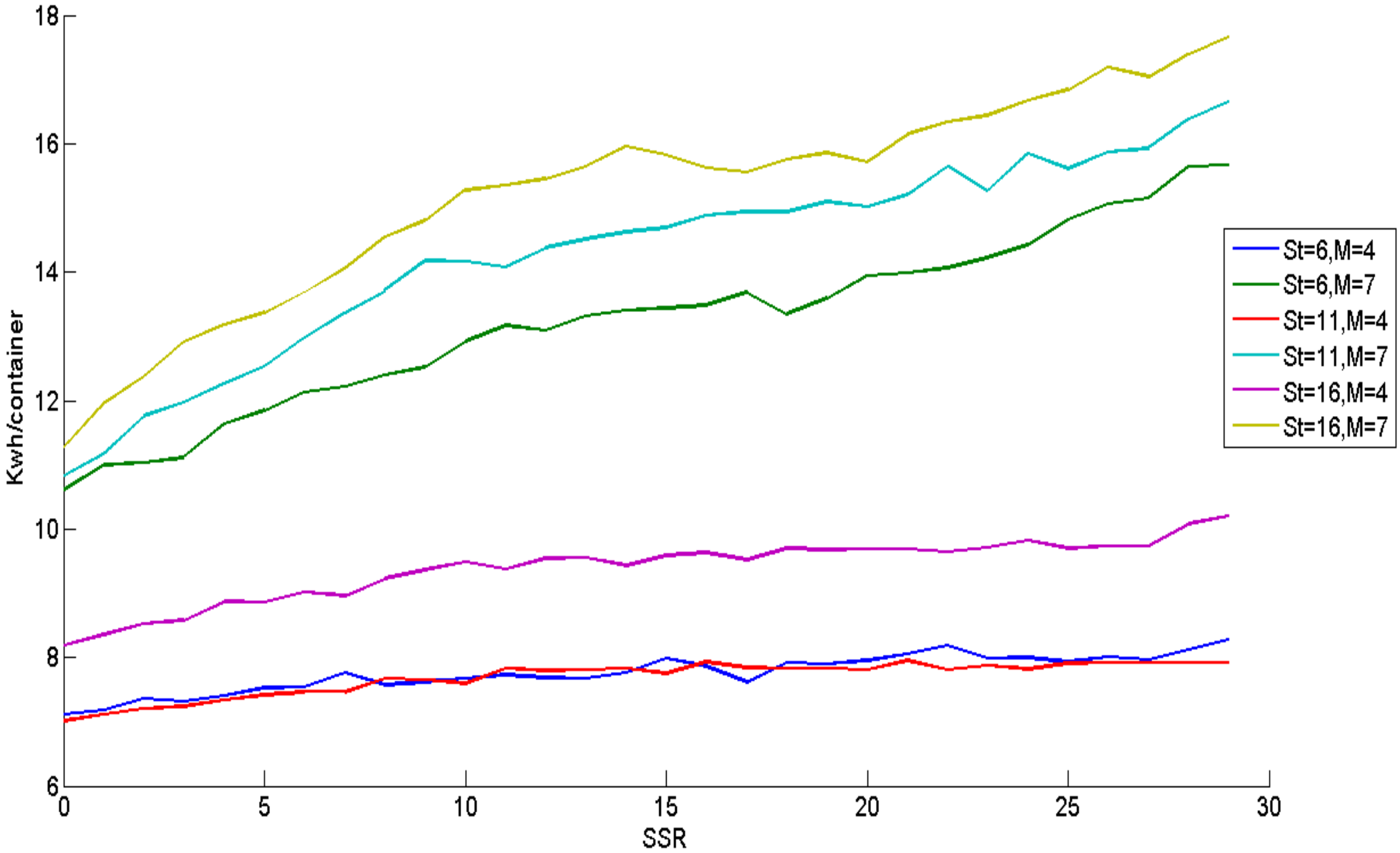

Figure 22. Kwh/container relation to SSR value for B=30 and for various St, M values.

5.4.3 STS CRANES

The simulation scenario begins assuming a certain amount of berth slots is occupied by ships and unloading operations by STSCs are about to commence. An average ship length l_v is estimated for container ships arriving at the terminal and all ships are considered to be of this average size. Dividing the available quay length l_q with the average ship length l_v gives as the number of available berth slots. The number of STSCs working per berth slot p_{QC} is considered fixed. The total number of STSCs available in the terminal is estimated by multiplying the number of berth slots with p_{QC}.

The cranes begin loading and unloading ships under double cycle operation policy (Figure 23).

STSCs work under the double cycle method as follows:

Containers bound to be unloaded in the same port are usually stacked in the same bays on the ship. For example, if a ship is to unload 500 containers at a given port and each bay has a capacity of 100 containers, then 5 bays are considered fully stowed with containers bound to be discharged at the same port. For the simulation scenario it is assumed that every ship bay planned to be unloaded will be fully unloaded and then reloaded with the same amount of containers.

In order for STSCs to completely unload and reload a certain ship bay the following process is used. The STSC fully unloads the first stack of the bay delivering the unloaded containers to TTs. After the first stack is unloaded, TTs supply the STSC with loading containers as well as delivering unloaded ones, operating in double cycle policy, and one by one, stacks are emptied and refilled until the bay is fully reloaded.

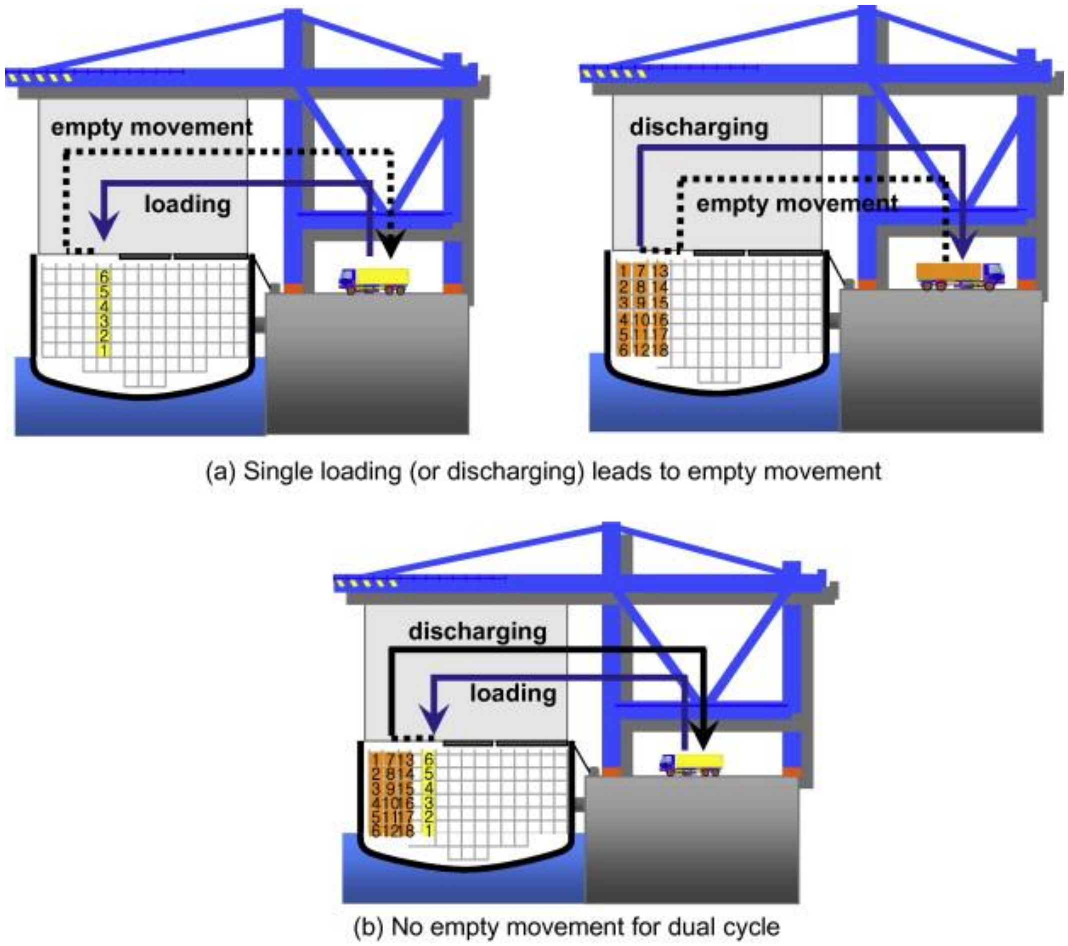

Figure 23. Single cycle versus dual(double) cycle STSC operations (Zhang & Kim 2009)

5.4.4 Terminal Transporters

TTs operate under double cycle policy connecting YCs and STSCs. Transporters are considered 'dedicated' to an STS crane, which is the most common method used in practice (Kim,Park,Jin 2007). This means that each time multiple STSCs operate simultaneously each crane has a certain number of transporters dedicated to its operations and these transporters cannot be assigned to other STS cranes. This dedication applies only for STSCs, transporters can be assigned to any YC at a given operation cycle.

TTs operating under double cycle policy are unloaded by YCs or STSCs and wait in I/O points until they are reloaded by the same crane. In European layouts (Figure 25), TTs carrying a container unloaded by an STSC, deliver the container to the yard block containing the next container to be delivered back to the same STSC (Figure 25). In this way TTs can be unloaded and reloaded in the same block. In Asian layouts however this process can only be done when TTs are delivering transshipment containers to the yard. Import containers are stacked in different blocks than outbound (export and transshipment) containers and thus when TTs deliver import containers to the yard they arrive at a different block to the one they will be reloaded to. In order to make the extra travel distance as small as possible TTs deliver import containers to the nearest block to the one they will be reloaded to (Figure 24).

In a previous chapter the advantages and disadvantages of AGVs, Lift-AGVs and SCs as means of container transportation within the terminal were analyzed. In the current simulation AGVs are chosen as terminal transporters (TTs) due to their low energy consumption. The number of AGVs dedicated to each STSC is set to 4.

5.4.5 Highway Trucks

A highway truck arrives at the terminal either to deliver an export container or receive an import container. In the first case the freight arrives at a random outbound block while in the latter the truck arrives at the inbound block containing the container bound to be received by the specific truck. The simulation scenario assumes a specified truck arrival rate with a normal distribution variance included.

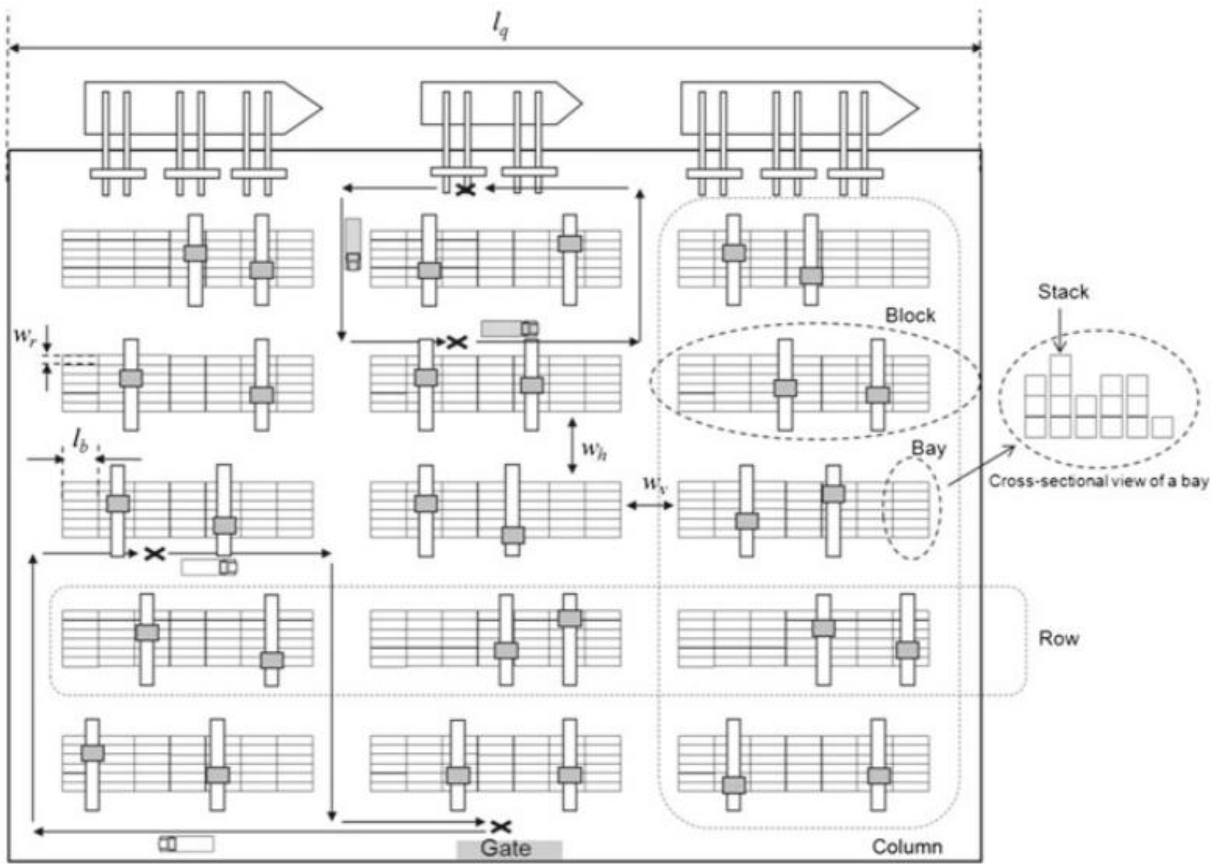

Figure 24. Terminal Transporter and Highway Trucks routes in Asian terminals.(Lee & Kim 2012)

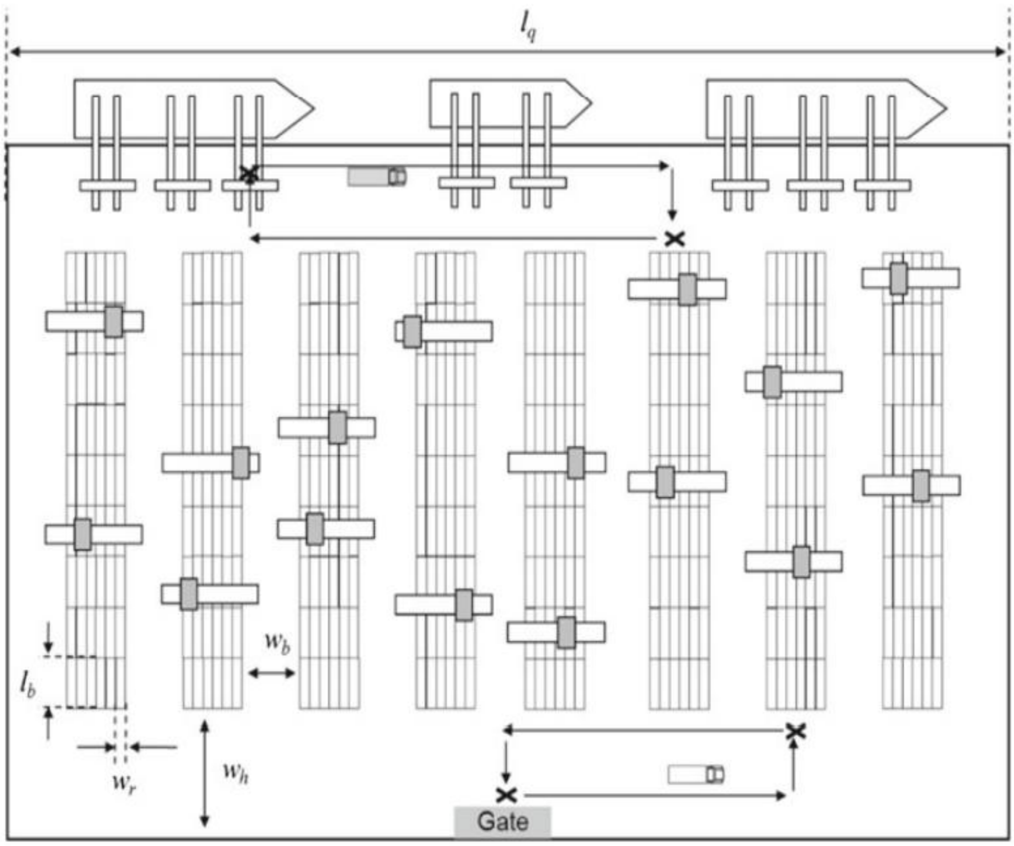

Figure 25. Terminal Transporter and Highway Trucks routes in European terminals. (Lee & Kim 2012)

5.4.6 Yard Cranes

Yard crane operations will be examined separately for each layout. For both layouts RMGC type cranes are used.

ASIAN

OUTBOUND RMGCs:

The RMGCs handling outbound containers, that is export and transshipment containers, are faced with the tasks below:

1. Load an outbound container from the block to a TT
2. Unload an outbound container from a TT to the block (transshipment containers only)
3. Unload an outbound container from a highway truck to the block (export containers only)
4. Reallocate

So each time the RMG has to attain a task, the TT can be in three different states with regard to the RMGC:

TT: AWAY-LOADED-EMPTY

While the truck can be in two different states:

TR: AWAY-LOADED

LOADED: There is a TT or Truck stand by in the driving lane next to the block waiting to be unloaded by the RMGC.

EMPTY: There is a TT stand by in the driving lane next to the block waiting to be loaded by the RMGC.

AWAY: There is no TT or Truck stand by in the driving lane waiting to be serviced.

From the above is concluded that every time the RMGC has to handle a task it is faced with a 2X3 matrix of possible situations. These situations are presented below and the decision making that comes along with them is presented below. The RMG reassesses the situation and the state of the matrix after every single move it does and proceeds on the next move accordingly.

1. TT=AWAY, TR= AWAY
   RMGC= if the container with the highest priority in the outbound side of the block is not on top of its stack, reallocate the container on top of its stack according to the heuristic. If the container with the highest priority is on top of

its stack implement the same procedure on the container with the next highest priority and so on.

2. TT=AWAY, TR=LOADED
   RMGC= unload the truck and load the container onto the block according to the heuristic.

3. TT=LOADED, TR=LOADED
   RMGC= as the minimization of the ship berth time and the TT waiting time is much more important to the terminal than the minimization of truck turnaround time, priority is given to the TT and the RMGC unloads the TT and loads the container onto the block according to the heuristic.

4. TT= EMPTY, TR= LOADED
   RMGC= as the minimization of the ship berth time and the TT waiting time is much more important to the terminal than the minimization of truck turnaround time, priority is given to the TT and If the container with the highest priority in the outbound side of the block is on top of its stack load the container to the TT. If the container with the highest priority in the outbound side of the block is not on top of its stack reallocate the container on top of its stack according to the heuristic.

5. TT=EMPTY,TR=AWAY
   RMGC= If the container with the highest priority in the outbound side of the block is on top of its stack load the container to the TT. If the container with the highest priority in the outbound side of the block is not on top of its stack reallocate the container on top of its stack according to the heuristic.

6. TT=LOADED,TR=AWAY
   RMGC= unload the TT and load the container onto the block according to the heuristic.

<u>INBOUND RMGCs:</u>

The RMGCs handling inbound/import containers are faced with the tasks below:

1. Load an inbound container from the block to a Truck
2. Unload an inbound container from a TT to the block (import containers only)
3. Reallocate

So each time the RMG has to attain a task, the TT can be in three different states with regard to the RMGC:

TT: AWAY-LOADED

While the truck can be in two different states:

TR: AWAY-EMPTY

From the above is concluded that every time the RMGC has to handle a task it is faced with a 2X2 matrix of possible situations. These situations are presented below and the decision making that comes along with them is presented below. The RMG reassesses the situation and the state of the matrix after every single move it does and proceeds on the next move accordingly.

1. TT=AWAY, TR= AWAY
   RMGC= if the container with the highest priority in the inbound side of the block is not on top of its stack, reallocate the container on top of its stack according to the heuristic. If the container with the highest priority is on top of its stack implement the same procedure on the container with the next highest priority and so on.
2. TT=LOADED, TR=EMPTY
   RMGC= as the minimization of the ship berth time and the TT waiting time is much more important to the terminal than the minimization of truck turnaround time, priority is given to the TT and the RMGC unloads the TT and loads the container onto the block according to the heuristic.

3. TT=AWAY,TR=EMPTY
   RMGC= If the container with the highest priority in the inbound side of the block is on top of its stack load the container to the truck. If the container with the highest priority in the outbound side of the block is not on top of its stack reallocate the container on top of its stack according to the heuristic.

4. TT=LOADED,AGV=AWAY
   RMGC= unload the TT and load the container onto the block according to the heuristic.

EUROPEAN

OUTBOUND RMGCs (Quayside):

In the European or perpendicular layout the Quayside RMGCs interfere only with TTs and not with highway trucks

The RMGCs handling outbound containers, that is export and transshipment containers, are faced with the tasks below:

1. Load an outbound container from the block to a TT
2. Unload an outbound or inbound container from a TT to the block
3. Rehandle
4. Reallocate

Rehandle:

Since the quayside RMGCs transact only with the TTs and the gateside RMGCs transact only with trucks in the European layout, a problem emerges with containers ending up in the wrong block side instead of the side they are supposed to be. TTs deliver import containers to the outbound side and trucks deliver export containers to the inbound area of the block. Hence, YCs must also handle the task of delivering containers to the side they belong. In order to do this, cranes will often cross to the other side of the block something that leads to crane interference problems. When a YC needs to handle a task in a given bay and its passage to the bay is blocked by the other YC, it becomes idle until the way is cleared and valuable operational time is lost in the process. To deal with this issue, a decision making plan is proposed for YCs operating in perpendicular layouts which is presented below.

Each time the RMG has to attain a task, the TT can be in three different states with regard to the RMGC:

TT: AWAY-LOADED-EMPTY

From the above is concluded that every time the RMGC has to handle a task it is faced with a 1X3 matrix of possible situations. These situations are presented below and the decision making that comes along with them is presented below. The RMG reassesses the situation and the state of the matrix after every single move it does and proceeds on the next move accordingly.

1. TT=LOADED
   RMGC= unload the TT and load the container onto the block according to the heuristic. Depending on the type of the container delivered by the TT (import or

transshipment) and factoring in crane interference, the search space for the optimal stack by the heuristic is established as follows.

If the container delivered is a transshipment container it must be stacked in the outbound side of the block. So the search space is defined beginning from the first bay and extending to the last bay of the outbound side. If however the inbound YC is currently operating within the outbound side the search space is now defined beginning from the first bay in the outbound side and extending to furthest bay with uninterrupted access available. Access is considered available if the path to a bay for one of the two cranes is not interrupted by the other. If the container delivered is an import container it should optimally be stacked in the inbound side of the block. So if there is uninterrupted access available for the outbound crane to inbound bays the crane proceeds to stack the container there. If there is no such access to inbound bays the search space is defined as in the transshipment container case and it will be rehandled to the inbound side later on during crane idle time. We have to note here as well, that containers that need to be rehandled are stacked by the heuristic in the same stacks as much as possible in order to avoid getting buried by non-rehandle containers. By implementing the above rules for defining search space any possible crane collision scenario is avoided and crane interference and idle time is reduced as much as possible.

Example: We have a block with 20 bays and two cranes operating. The outbound side extends from bay No.1 to bay No.10 and the inbound side extends from bay No.11 to bay No.20. The quayside RMGC picks up an import container from a TT and is about to unload it onto the block. At the same time the gateside RMGC is performing a task at bay No.15. Hence the search space becomes *SS=(1,14)*. But, since the container optimally should be unloaded to the inbound side to avoid extra future rehandles and there are inbound bays with uninterrupted access available, the search space becomes *SS=(11,14).*

2. TT=EMPTY
   RMGC= If the container with the highest priority in the outbound side of the block is on top of its stack, load the container to the TT. If the container with the highest priority in the outbound side of the block is not on top of its stack reallocate the container on top of its stack according to the heuristic.

3. TT=AWAY
   RMGC= if there is a container waiting to be rehandled to the inbound side the RMGC gives priority to this task as long as there is uninterrupted access available to any bay in the inbound side. Priority is given to rehandle tasks because we want to avoid containers dwelling in the wrong side of the block. Eventually they

will be buried under other containers and the RMGCs will be forced to perform extra reallocation tasks to in order to deliver them in the right side. If there are no rehandle tasks waiting, or if such a task is not available to be performed at the time, the YC proceeds to perform a reallocation task according to the heuristic.

INBOUND RMGCs:

RMGCs handling inbound containers are faced with the tasks below:

1. Load an inbound container from the block to a truck
2. Unload an outbound container from a truck to the block
3. Rehandle
4. Reallocate

Each time the RMGC has to attain a task, the truck can be in three different states with regard to the RMGC:

TR: AWAY-EMPTY-LOADED

From the above is concluded that every time the RMGC has to handle a task it is faced with a 1X3 matrix of possible situations. These situations are presented below and the decision making that comes along with them is presented below. The RMG reassesses the situation and the state of the matrix after every single move it does and proceeds on the next move accordingly.

1. TR= EMPTY
   RMGC= If the container with the highest priority in the inbound side of the block is on top of its stack, load the container to the truck. If the container with the highest priority in the outbound side of the block is not on top of its stack reallocate the container on top of its stack according to the heuristic.

2. TR=LOADED
   RMGC= unload the truck and load the container onto the block according to the heuristic and the available search space as established in the outbound RMGC section.

3. TR=AWAY
   RMGC= if there is a container waiting to be rehandled to the outbound side the RMGC gives priority to this task as long as there is uninterrupted access available to any bay in the outbound side. If there are no rehandle tasks waiting, or if such a task is not available to be performed at the time, the YC proceeds to perform a reallocation task according to the heuristic.

5.5 ENERGY CONSUMPTION

5.5.1 YARD CRANES ENERGY CONSUMPTION

According to He, Huang & Yan (2015) yard crane energy consumption can be estimated as:

YCkwh= 2kwh/move +0.0206 kwh/m

The first part of the above equation can be accounted to the energy consumed by the hoist and trailer and is a fixed value of 2kwh per container movement while the second one refers to the energy consumed during gantry movement and is proportionate to the distance travelled by the gantry.

Since block sizes are variables in the simulation model, YC sizes vary as well since their size is a function of the number of stacks in a block St and the maximum stack height M. Since YC sizes vary, the power needed to move them varies as well. Since the power required to perform a hoist and trailer movement is affected only by the weight of the container moved the first part of the equation remains the same as it is not affected by YC size. The second part of the equation however is altered by YC size as it refers to gantry movements. A change in YC size and weight impacts the power demand for gantry movement directly. Assuming all YCs, regardless of size, maintain the same gantry service speed and acceleration, we proceed to estimate the energy consumption of YCs with regard to their size.

The torque required to move the crane gantry can be formulated as:

$$T = F \times R$$

Where $F = F_i + F_r + F_d$ and R is the radius of the crane's wheels.

F_i is the force required to accelerate and decelerate the gantry and is described by Newton's law as

$F_i = m \times a$,

where m is the mass of the crane and a the acceleration of the crane.

F_r is the force of friction described as

$F_r = C_r \times m \times g$,

where C_r is the friction coefficient and g the force of gravity.

F_d is the force of drag described as

$$F_d = \frac{1}{2} \times \rho \times C_d \times S \times V^2 ,$$

where ρ is the density of air, C_d is the drag coefficient, S the projected surface of the YC to the wind, and V is the speed of the gantry.

Assuming a YC can be modeled as a structure of 3 steel beams of equal thickness, 2 vertical and 1 horizontal, then its mass can formulated as

$m = X \times (St \times w_r + 2 \times M \times l_h)$, where X in t/m

Accordingly its projected surface can be formulated as

$S = Y \times (St \times w_r + 2 \times M \times l_h)$, where Y in m

Assuming the energy consumption formula YCkwh shown above represents an average size YC of

$St=10$, $M= 5$ and $S=S_1$, $m=m_1$, $F_i=F_{i1}$, $F_r=F_{r1}$, $F_d=F_{d1}$

then the ratio of mass of a different size YC to the average one can be formulated as

$$\frac{m}{m_1} = \frac{(St \times w_r + 2 \times M \times l_h)}{(10 \times w_r + 2 \times 5 \times l_h)}$$

and the ratio of projected surface as

$$\frac{S}{S_1} = \frac{(St * w_r + 2 * M * l_h)}{(10 * w_r + 2 * 5 * l_h)}$$

and the ratio of F_i, F_r *and* F_d

$$\frac{F_i}{F_{i1}} = \frac{m}{m_1}$$

$\frac{F_r}{F_{r1}} = \frac{m}{m_1}$, C_r is considered fixed

$\frac{F_d}{F_{d1}} = \frac{S}{S_1}$, C_d is considered fixed

Finally, out of the above the ratio of torque and consequently of gantry energy consumption is formulated as

$\frac{E}{E_1} = \frac{(St \times w_r + 2 \times M \times l_h)}{(10 \times w_r + 2 \times 5 \times l_h)}$ where $E_1= 0.0206$ so

$$E = 0.0206 \times \frac{(St \times w_r + 2 \times M \times l_h)}{(10 \times w_r + 2 \times 5 \times l_h)}$$

Now we will proceed to convey the energy consumption estimated for YCs in the simulation to the annual energy consumption. The flows of containers to YCs for Asian and European layouts are showcased in the matrix below.

ASIAN			EUROPEAN		
	IN	OUT		IN	OUT
Outbound YCs	*Tr+Ex*	*Tr+EX*	Outbound Ycs	*Im+Tr*	*Tr+EX*
Inbound YCs	*Im*	*Im*	Inbound Ycs	*Ex*	*Im*

Table 12. Flows of containers to YCs for Asian and European layouts

Hence the annual kwh consumptions can be estimated as:

ASIAN		EUROPEAN	
Outbound Ycs	$Annualkwh = Simkwh \times 2 \times \frac{(Tr+Ex)}{\left(Load_{sim} + Dis_{sim} \times \left(\frac{Tr}{Tr+Im}\right) + Del_{sim}\right)}$	Outbound YCs	$Annualkwh = Simkwh \times \frac{(Im + 2 \times Tr + Ex)}{Ship_{sim}}$
Inbound YCs	$Annualkwh = Simkwh \times 2 \times \frac{Im}{Dis_{sim} \times \left(\frac{Im}{Tr+Im}\right) + Rec_{sim}}$	Inbound YCs	$Annualkwh = Simkwh \times \frac{(Im + Ex)}{Truck_{sim}}$

Table 13. YCs annual kwh consumption estimation

5.5.2 STS CRANES ENERGY CONSUMPTION

According to Geerlings & Van Duin (2011), STSC energy consumption can be formulated as:

STSkwh=6kwh/move

The flows of containers to STSCs are showcased in the matrix below.

	IN	OUT
STSCs	*Tr+Ex*	*Tr+Im*

Table 14. Flows of containers to STSCs

Hence the annual STSC energy consumption is formulated as:

$$STSkwh = 6 \times (Im + 2 \times Tr + Ex)$$

5.5.3 AGVs ENERGY CONSUMPTION

According to Saanen (2016), AGV energy consumption can be formulated as:

AGVkwh=17kwh/hour

Hence the annual STSC energy consumption is formulated as:

$AGVkwh = 17/60 \times TT\ operational\ time$, where *TT operational time* in minutes

5.5.4 Trucks ENERGY CONSUMPTION

According to Zamboni (2013), highway truck diesel oil consumption inside the terminal can be formulated as:

TRl= 1.2kg/km(Euro 5) or TRl= 1.7kg/km(Euro 3)

The simulation assumes all trucks entering the terminal comply with Euro 5 technology standards.

The annual truck Diesel oil consumption is formulated as:

$TRl = 1.2/1000 \times D_{trE} \times (Im + Ex)$ for European layouts

$TRl = 1.2/1000 \times D_{trA} \times (Im + Ex)$ for Asian layouts, where *DtrA and DtrE* in meters

5.5.5 Ships ENERGY CONSUMPTION

According to Winnes & Parsmo (2016), ship MDO consumption for containerships during quay operations in a port can be formulated as:

$SHl = 0.7 \times 2.9kg \times \left(\frac{GT}{1000}\right) / hour$, where *GT* is the ship's gross tonnage

Annual ship MDO consumption can be formulated as:

$SHl = 0.7 \times 2.9kg \times \left(\frac{GT}{1000}\right) \times SOT \times n_{SH}$, where *SOT* is the average Ship Operational Time and n_{SH} is the number of vessels berthed per year.

n_{SH} can be formulated as:

$$n_{SH} = \frac{(Im + 2 \times Tr + Ex)}{(n_{QC} \times QC_{sim})}$$

6. VALIDATION

After establishing the simulation model we proceed to validate it using 'Optimizing the yard layout in container terminals' (Lee & Kim 2012). In this paper the authors use an analytical approach, instead of a simulation one that the current section established, to determine the best container terminal layouts both for Asian and European terminals given a set of restrictions.

Main Differences

The most important differences between Lee & Kim and the current section are:

1. Lee & Kim propose an analytical optimization method to establish the best layout while the current section follows a simulation based approach to solving the problem.

2. Different optimization objectives. Lee & Kim aim to minimize the total investment and operational cost of the terminal given a set of restrictions, while the current section's goal is to optimize the layout so as to minimize the energy consumption and emissions output of terminals under a set of restrictions. In the current section the total cost is used as a restriction parameter for minimizing emissions. All the other restrictions implemented are the same ones used in Lee and Kim.

Current Section	Lee & Kim (2012)
MIN(Emissions)	*MIN(Total Cost)*
Subject to:	Subject to:
Max allowed	*Max allowed*
1. Available quay space	1. Available quay space
2. Average TTs turnaround time	2. Average TTs turnaround time
3. Average trucks turnaround time	3. Average trucks turnaround time
4. Total cost	
Min allowed	*Min allowed*
1. Storage space	1. Storage space

Table 15. Current section & Lee & Kim (2012) problem formulations

3. Lee & Kim use a single cycle policy in the TT operations while the current section's simulation model is built around a double cycle operation policy.

4. Lee & Kim assume a remarshalling method is being used when loading outbound containers to TTs. This means they assume that all containers bound to be loaded onto the same ship are already stacked in the same bays and occupy them fully. As a result of that YCs handling delivery operations pick up containers one by one in the order they are stacked and there are no reallocation movements required by cranes. On the other hand, when it comes to truck delivery operations no remarshalling is assumed and YCs have to reallocate in order to deliver import containers to trucks. The current section assumes that no remarshalling operations occur in the yard and thus treats TT delivery tasks exactly like truck delivery, meaning YCs have to perform reallocation tasks for delivering outbound containers as well.

Validation Results

Validation is done on four different cases. The first case showcases data of a real container terminal using an Asian layout. The second case showcases data of a real container terminal using a European layout. All data are provided by Lee & Kim (2012). The other two cases consist of results coming from the analytical model proposed by Lee & Kim and present better alternative layouts, according to the authors, to the ones implemented by the real terminals showcased. In the following segment we will compare the results on performance indicators derived from our simulation to the ones produced by the analytical model of Lee & Kim (2012).

Expected Results

The performance indicators compared are YC cycle times. Tables 18, 20 showcase the results. Highlighted in green color are the indicators that where expected to be approximately the same. These are *CR* & *CU*. The indicators highlighted in red color were expected to differ. *CL* value was expected to be higher in the current simulation model because, as noted before, there are no remarshalling operations involved in the model, in contrast to the analytical model, and thus reallocation tasks affect the *CL* cycle time. *CD* value was expected to be lower in the current simulation model because the *CD* cycle time is affected by reallocation operations in the analytical model and due to the heuristic proposed in the current section reallocations are reduced in comparison to the average reallocations per container formula (Kim 1997) used in the analytical model.

	CONSTANTS	SOURCE
l_v	300	Lee & Kim 2012
l_b	6.458	Lee & Kim 2012
l_h	2.591	Lee & Kim 2012
w_r	2.838	Lee & Kim 2012
w_h	26	Lee & Kim 2012
w_v	16	Lee & Kim 2012
h_T	518400	Lee & Kim 2012
c_{QC}	2.4	Lee & Kim 2012
n_{QC}	3	Lee & Kim 2012
u	0.6	Lee & Kim 2012
v_l	200	Lee & Kim 2012
v_e	300	Lee & Kim 2012
v_b	180	Lee & Kim 2010
v_s	150	Lee & Kim 2010
v_{hl}	50	Lee & Kim 2010
v_{he}	83	Lee & Kim 2010
T_p	5	Lee & Kim 2010
u_{QC}	0.8	Lee & Kim 2012
δ	0.3	Lee & Kim 2012
QC_{sim}	200	

Table 16. Simulation constants values

6.1 ASIAN

	VARIABLES		
Ex	360700	D_{Ex}	10080
Tr	757800	D_{Tr}	2880
Im	412900	D_{Im}	7200
n_{YC}	5	l_q	1500

Table 17. Simulation variable values

	Real	Current Section	Lee & Kim	Current Section
(R, C, St)	(9, 8, 6)	(9, 8, 6)	(5, 7, 11)	(5, 7, 11)
(B, M, H)	(27, 4, 2.40)	(27, 4, 2.40)	(28, 7, 4.20)	(28, 7, 4.20)
CR (min)	1.4	1.1	1.83	1.69
CD	1.69	1.33	2.71	1.99
CL	0.98	1.23	1.44	2.45
CU	0.95	1.03	1.4	1.42

Table 18. Simulation results

6.2 EUROPEAN

	VARIABLES		
Ex	230000	D_{Ex}	10080
Tr	550000	D_{Tr}	4608
Im	220000	D_{Im}	10080
n_{YC}	2	l_q	1200

Table 19. Simulation variable values

	Real	Current Section	Lee & Kim	Current Section
(C, St)	(28, 9)	(28, 9)	(13, 26)	(13, 26)
(B, M, H)	(40, 5 , 3)	(40, 5 , 3)	(22, 8, 4.8)	(22, 8, 4.8)
CR (min)	2.89	2.81	2.65	2.69
CD	3.47	2.95	4.2	3.72
CL	2.89	3.02	2.65	3.93
CU	2.89	2.81	2.65	2.69

Table 20. Simulation results

6.3 <u>Comments on validation results</u>

1. *CR* and *CU* values proved to be approximately even in most cases as expected, although in the Asian layouts *CR* values present a higher than anticipated divergence.

2. *CL* values in the simulation model were higher than the analytical one as expected.

3. *CD* values in the simulation model were lower than the analytical one as expected.

7. NUMERICAL TESTS

After validating the simulation model we proceed to conduct several numerical tests to estimate the best layout solutions emission wise in conjunction to terminal annual throughput rates. At first we examine the two real world terminals used in the validation process earlier. Later we will examine the case of Piraeus Container Terminal (PCT), in Piraeus Greece.

Due to the stochastic nature of certain aspects of the simulation model (container priority numbers distribution, truck arrival rates, transporter waiting times) the optimal layout solution can vary. After conducting several simulation runs the layout solution that dominates the most runs is established as the best one. Also an average standard deviation (ASD) value is estimated for the main output variables in order to define the amount of fluctuation in these variables. For each run, a maximum cost/container constrain *(Tcost)* and a maximum allowed average turnaround time *(TCST)*, where *CST=max(CR+CL+WO,CD+WI,CU+WI)),* is established. The simulation then proceeds to find the lowest CO2 emission layout under the given constrain set. The simulation results are presented in the matrixes below.

	CONSTANTS	SOURCE		**CONSTANTS**	SOURCE
l_v	300	Lee & Kim 2012	v_b	180	Lee & Kim 2010
l_b	6.458	Lee & Kim 2012	v_s	150	Lee & Kim 2010
l_h	2.591	Lee & Kim 2012	v_{hl}	50	Lee & Kim 2010
w_r	2.838	Lee & Kim 2012	v_{he}	83	Lee & Kim 2010
w_h	26	Lee & Kim 2012	T_p	5	Lee & Kim 2010
w_v	16	Lee & Kim 2012	*GT*	40000	
h_T	518400	Lee & Kim 2012	*kwhCO2f*	0.79	
c_{QC}	2.4	Lee & Kim 2012	*DieselCO2f*	2.65	
n_{QC}	3	Lee & Kim 2012	*MDOCO2f*	3.17	
u	0.6	Lee & Kim 2012	u_{QC}	0.8	Lee & Kim 2012
v_l	200	Lee & Kim 2012	δ	0.3	Lee & Kim 2012
v_e	300	Lee & Kim 2012	QC_{sim}	200	

Table 21. Simulation constants values

7.1 ASIAN

7.1.1 1 million containers throughput

	VARIABLES		
Ex	230000	D_{Ex}	10080
Tr	550000	D_{Tr}	4608
Im	220000	D_{Im}	10080
n_{YC}	5	l_q	1200

Table 22. Simulation variable values

TH= 1 MILLION CONTAINERS						
TCST=4						ASD (Average Standard Deviation)
Tcost/container(€)	14.5	16	19	22	25	
R	3	4	6	7	7	
C	4	5	5	5	4	
B	40	30	26	20	22	
St	16	16	13	14	16	
M	5	4	4	4	4	
CO2con(kg)	22.42	21.1	20.71	20.38	20.37	0.1
KWHcon(kwh)	20.38	18.73	18.21	17.88	17.89	
LITcon(lit)	2.26	2.25	2.26	2.23	2.22	
CR%	61.75	61.46	61.18	61.49	61.35	
TT%	10.03	8.68	8.26	7.85	8.04	
SH%	21.35	22.69	23.12	23.5	23.5	
TR%	6.86	7.17	7.44	7.17	7.11	
CR	1.43	1.28	1.2	1.18	1.17	0.07
CD	1.59	1.34	1.26	1.23	1.23	0.05
CL	1.75	1.26	1.17	1.15	1.14	0.02
CU	1.25	1.2	1.13	1.15	1.14	0.03
WI	1.03	0.76	0.45	0.38	0.38	0.02
WO	0.8	0.51	0.3	0.26	0.26	0.02
CST	3.98	3.05	2.67	2.59	2.57	
cost/container (€)	14.15	15.65	18.99	21.67	22.94	0.04

Table 23. Simulation results

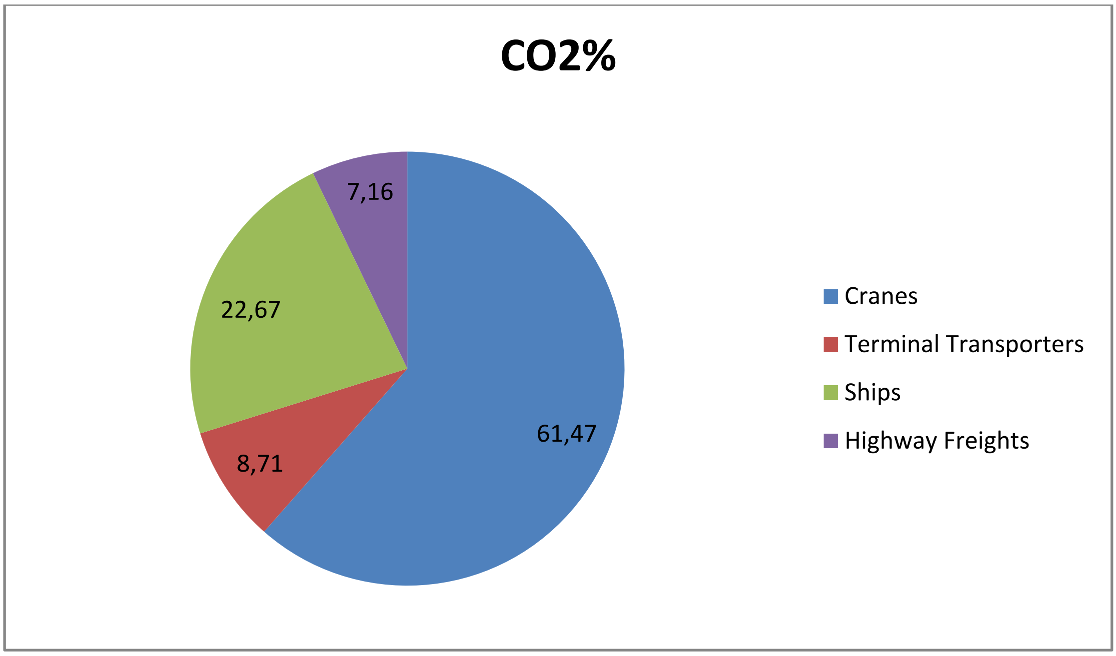

Figure 26. CO2% percentage distribution among terminal operation elements

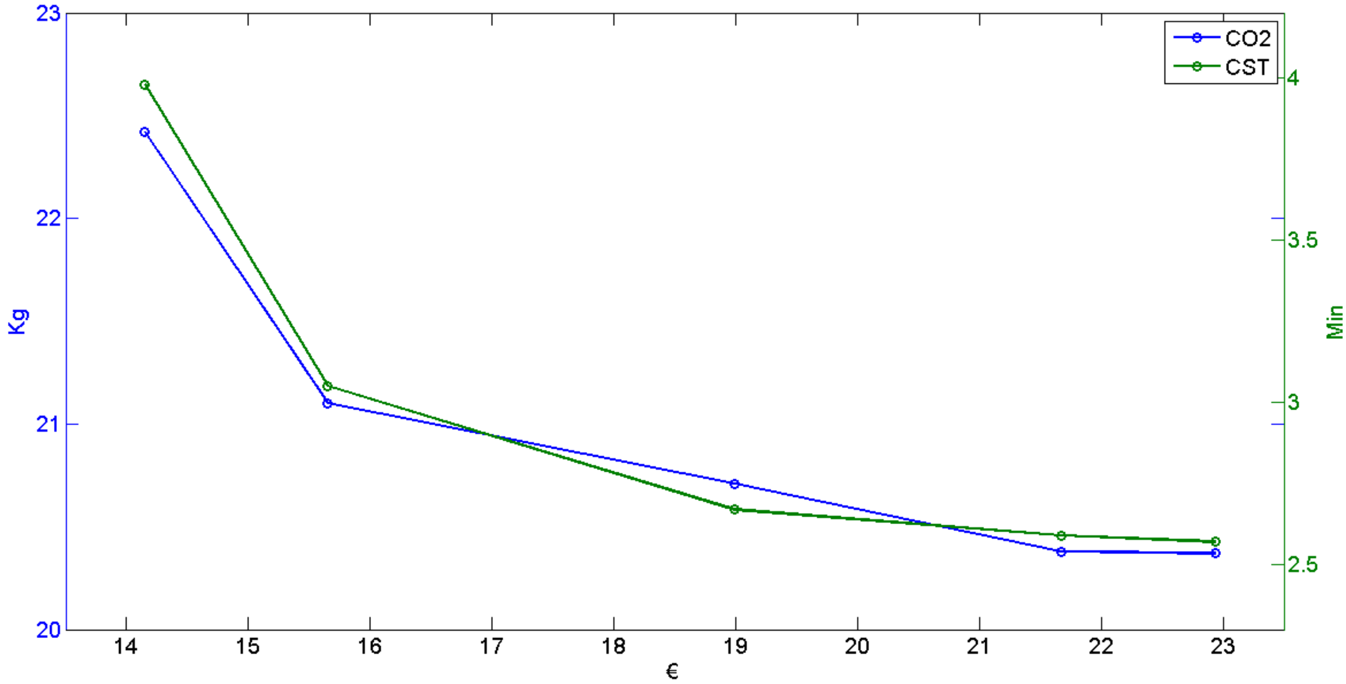

Figure 27. CO2 per container and CST (max average turnaround time) with regard to the total cost per container.

7.1.2 1.5 million containers throughput

	VARIABLES		
Ex	360700	D_{Ex}	10080
Tr	757800	D_{Tr}	2880
Im	412900	D_{Im}	7200
n_{YC}	5	l_q	1500

Table 24. Simulation variable values

TH= 1.5 MILLION CONTAINERS						
	TCST=4					ASD
Tcost/container(€)	13	16	19	22	25	
R	4	6	7	8	9	
C	5	6	5	5	5	
B	38	26	22	20	20	
St	13	13	16	15	15	
M	5	4	4	4	4	
CO2con(kg)	22.37	20.82	20.42	20.21	20.41	0.1
KWHcon(kwh)	19.96	18.17	17.76	17.48	17.6	
LITcon(lit)	2.36	2.32	2.29	2.29	2.33	
CR%	61.25	60.48	60.37	60.18	59.82	
TT%	9.27	8.47	8.32	8.15	8.3	
SH%	20.65	22.18	22.61	22.85	22.62	
TR%	8.84	8.87	8.7	8.81	9.26	
CR	1.38	1.27	1.24	1.24	1.23	0.08
CD	1.59	1.33	1.26	1.25	1.24	0.06
CL	1.68	1.21	1.19	1.16	1.17	0.02
CU	1.19	1.12	1.18	1.17	1.11	0.03
WI	1.09	0.64	0.60	0.49	0.39	0.03
WO	0.91	0.47	0.38	0.35	0.30	0.03
CST	3.97	2.95	2.80	2.75	2.70	
Total cost/container (€)	12.72	15.77	18.83	20.27	22.33	0.04

Table 25. Simulation results

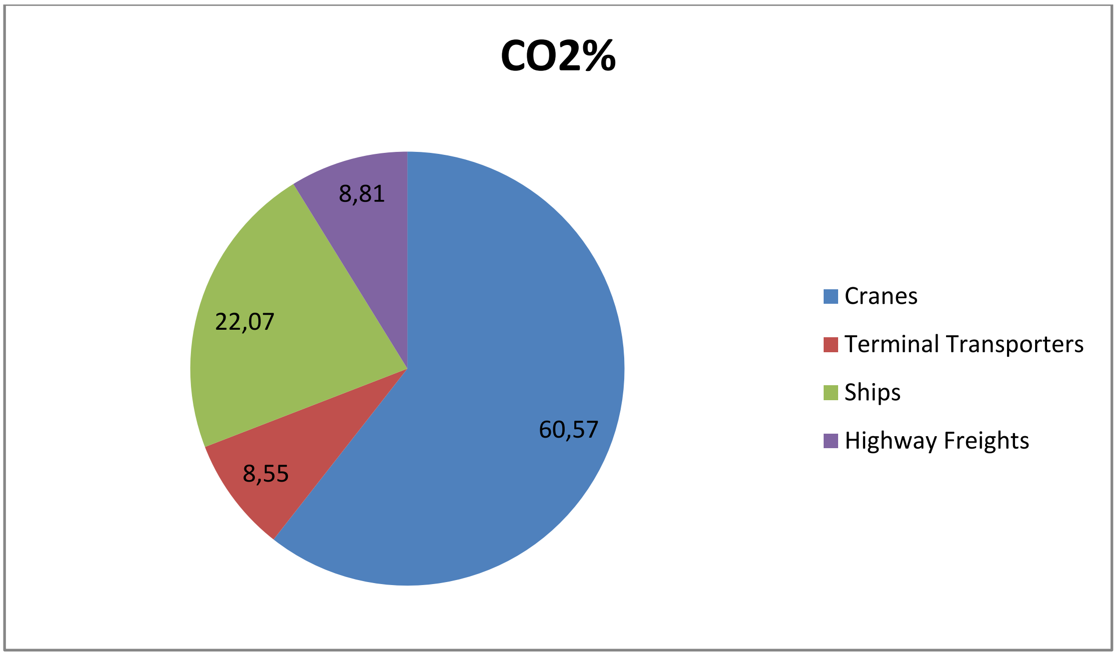

Figure 28. CO2% percentage distribution among terminal operation elements

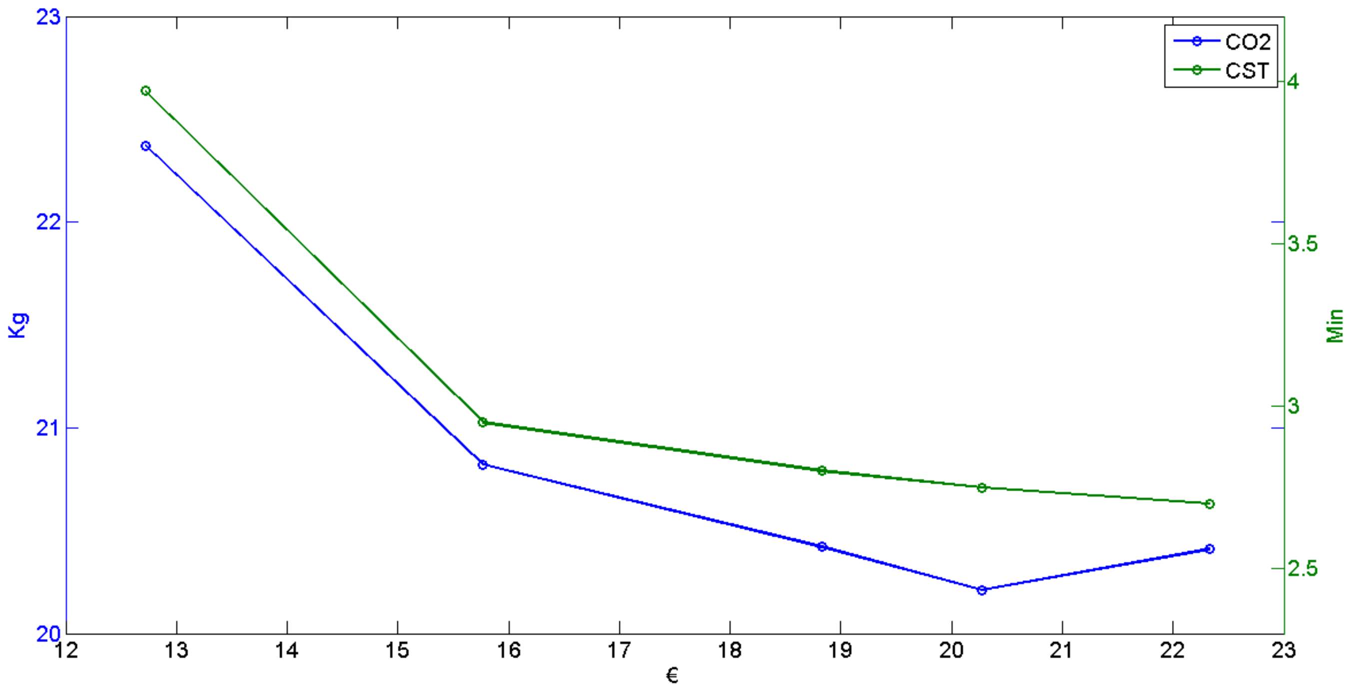

Figure 29. CO2 per container and CST (max TT average turnaround time) with regard to the total cost per container.

7.2 EUROPEAN

7.2.1 1 million containers throughput

	VARIABLES		
Ex	230000	D_{Ex}	10080
Tr	550000	D_{Tr}	4608
Im	220000	D_{Im}	10080
n_{YC}	5	l_q	1200

Table 26. Simulation variable values

TH= 1 MILLION CONTAINERS					
TCST=6					ASD
Tcost/container(€)	15.4	17.8	20.2	22.6	
C	19	21	28	33	
B	22	34	38	42	
St	16	14	9	7	
M	6	4	4	4	
CO2con(kg)	25.75	24.7	24.05	24.25	0.13
KWHcon(kwh)	25.28	23.86	23.09	23.2	
LITcon(lit)	2.05	2.08	2.13	2.17	
CR%	72.29	70.05	70.04	70.24	
TT%	5.98	6.51	6.63	6.58	
SH%	19.31	19.68	19.53	19.71	
TR%	2.42	3.77	3.8	3.47	
CR	2.26	2.25	2.37	2.43	0.05
CD	2.40	2.44	2.50	2.65	0.08
CL	2.45	2.48	2.53	2.69	0.06
CU	2.26	2.25	2.37	2.43	0.05
WI	0.60	0.50	0.37	0.29	0.03
WO	1.01	0.84	0.62	0.49	0.03
CST	5.72	5.57	5.52	5.61	
Total cost/container (€)	15.36	17.61	19.94	21.79	0.09

Table 27. Simulation results

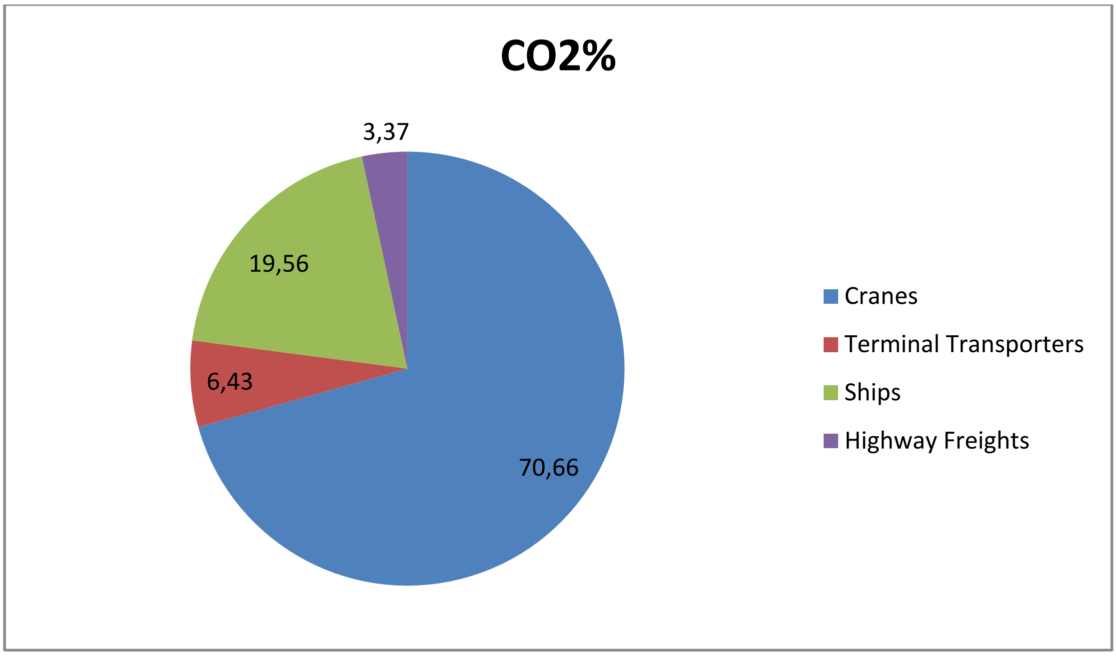

Figure 30. CO2% percentage distribution among terminal operation elements

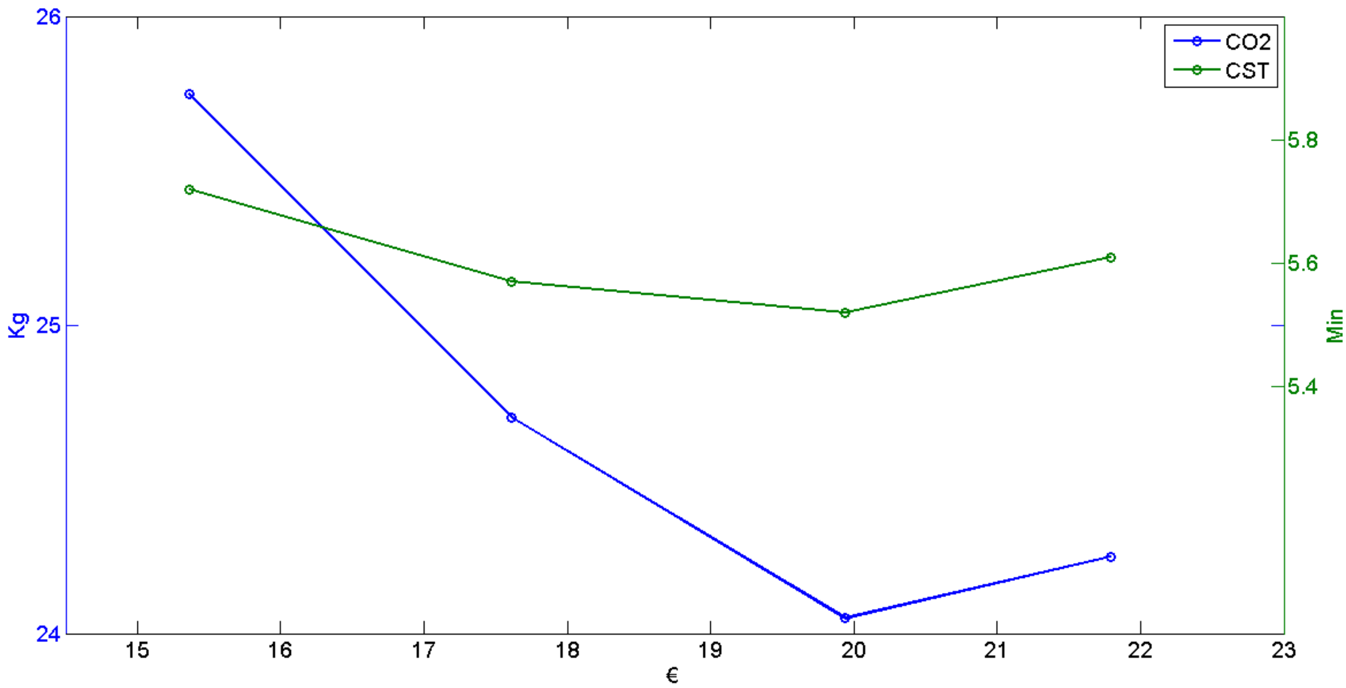

Figure 31. CO2 per container and CST (max TT average turnaround time) with regard to the total cost per container.

7.2.2 1.5 million containers throughput

	VARIABLES		
Ex	360700	D_{Ex}	10080
Tr	757800	D_{Tr}	2880
Im	412900	D_{Im}	7200
n_{YC}	5	l_q	1500

Table 28. Simulation variable values

TH= 1.5 MILLION CONTAINERS					
TCST=6					ASD
Tcost/container(€)	14	15.5	17	18.5	
C	26	31	33	38	
B	22	28	36	40	
St	14	11	10	8	
M	6	5	4	4	
CO2con(kg)	25.26	24.42	24.04	24.21	0.13
KWHcon(kwh)	24.51	23.44	22.78	22.83	
LITcon(lit)	2.1	2.1	2.15	2.2	
CR%	72.64	71.72	70.03	68.88	
TT%	5.98	6.37	6.67	7.03	
SH%	18.52	18.31	18.75	19.17	
TR%	2.85	3.61	4.55	4.92	
CR	2.27	2.30	2.29	2.38	0.05
CD	2.37	2.33	2.49	2.61	0.09
CL	2.41	2.37	2.53	2.65	0.06
CU	2.27	2.30	2.29	2.38	0.05
WI	0.70	0.59	0.41	0.28	0.03
WO	0.91	0.76	0.54	0.46	0.03
CST	5.59	5.43	5.36	5.49	
Total cost/container (€)	13.95	15.35	16.75	18.22	0.09

Table 29. Simulation results

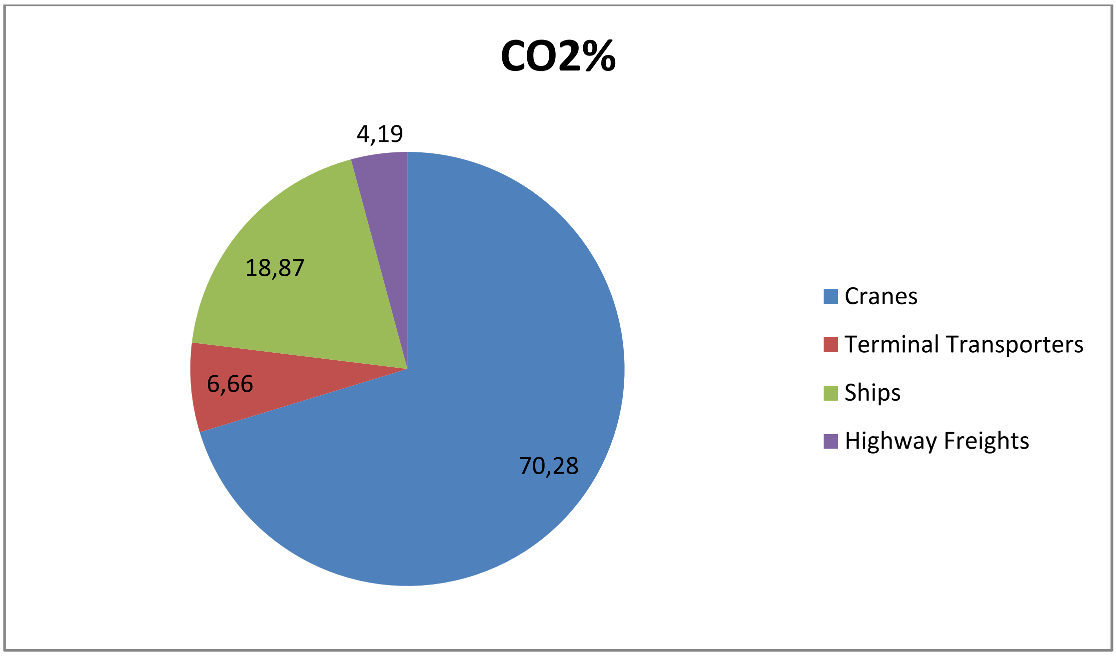

Figure 32. CO2% percentage distribution among terminal operation elements

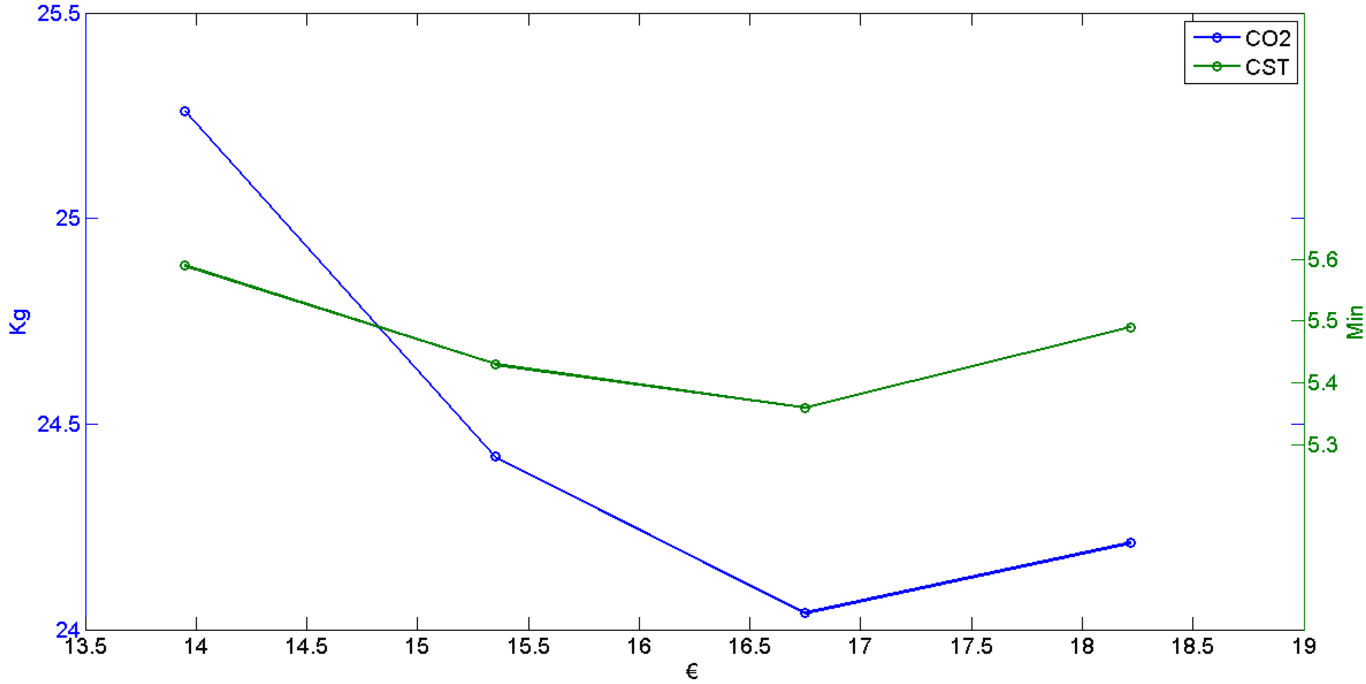

Figure 33. CO2 per container and CST (max average turnaround time) with regard to the total cost per container.

7.3 Asian vs European Comparison

7.3.1 1 million containers throughput

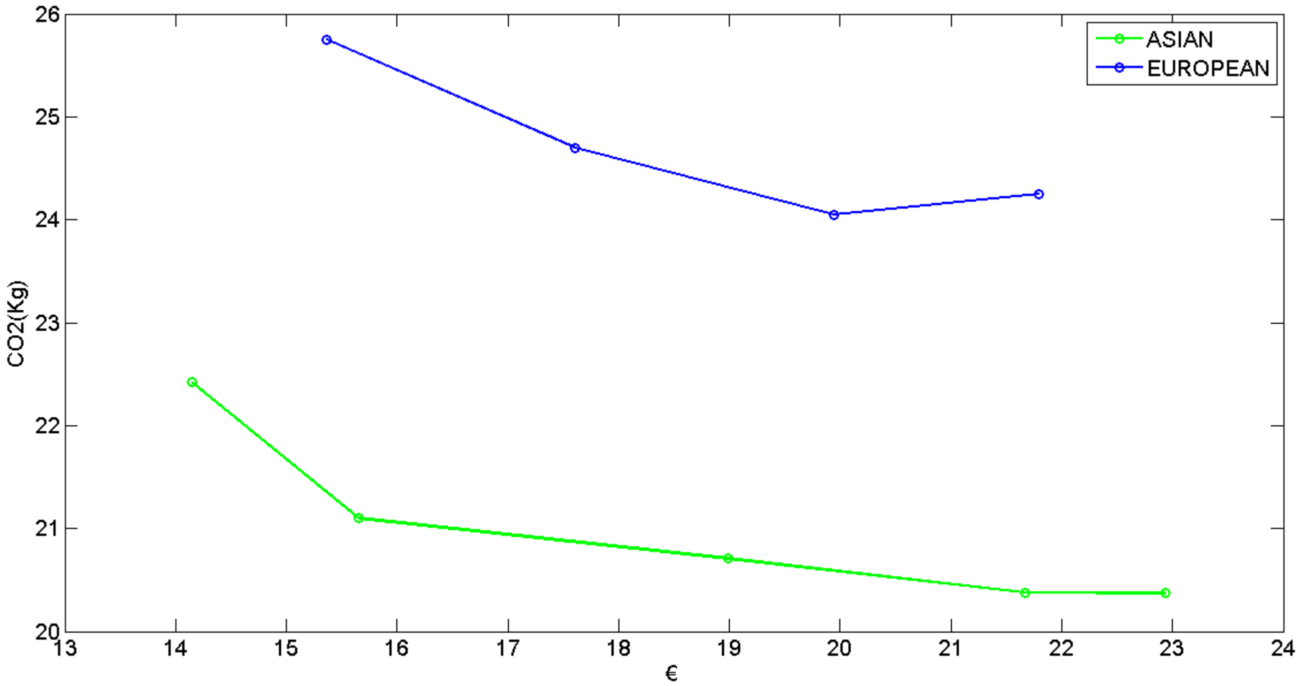

Figure 34. CO2 per container comparison between Asian and European layouts with regard to the total cost per container at 1 million throughput.

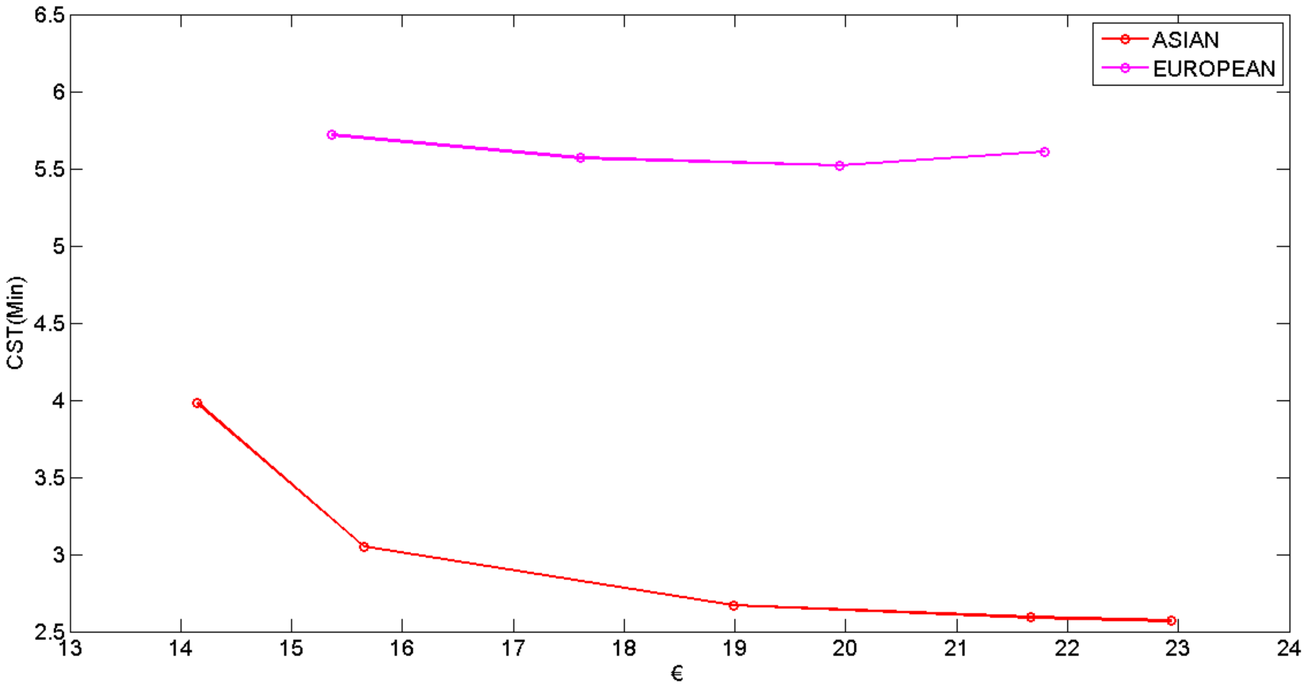

Figure 35. CST comparison between Asian and European layouts with regard to the total cost per container at 1 million throughput.

7.3.2 1.5 million containers throughput

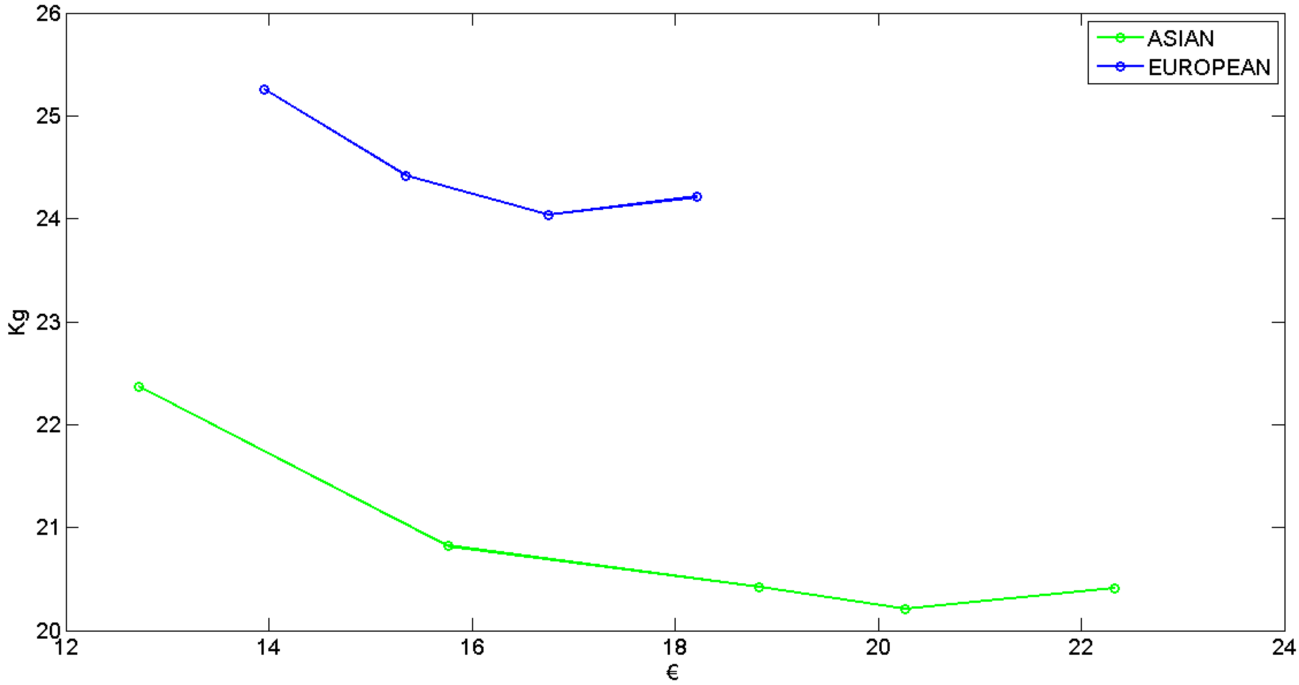

Figure 36. CO2 per container comparison between Asian and European layouts with regard to the total cost per container at 1.5 million throughput.

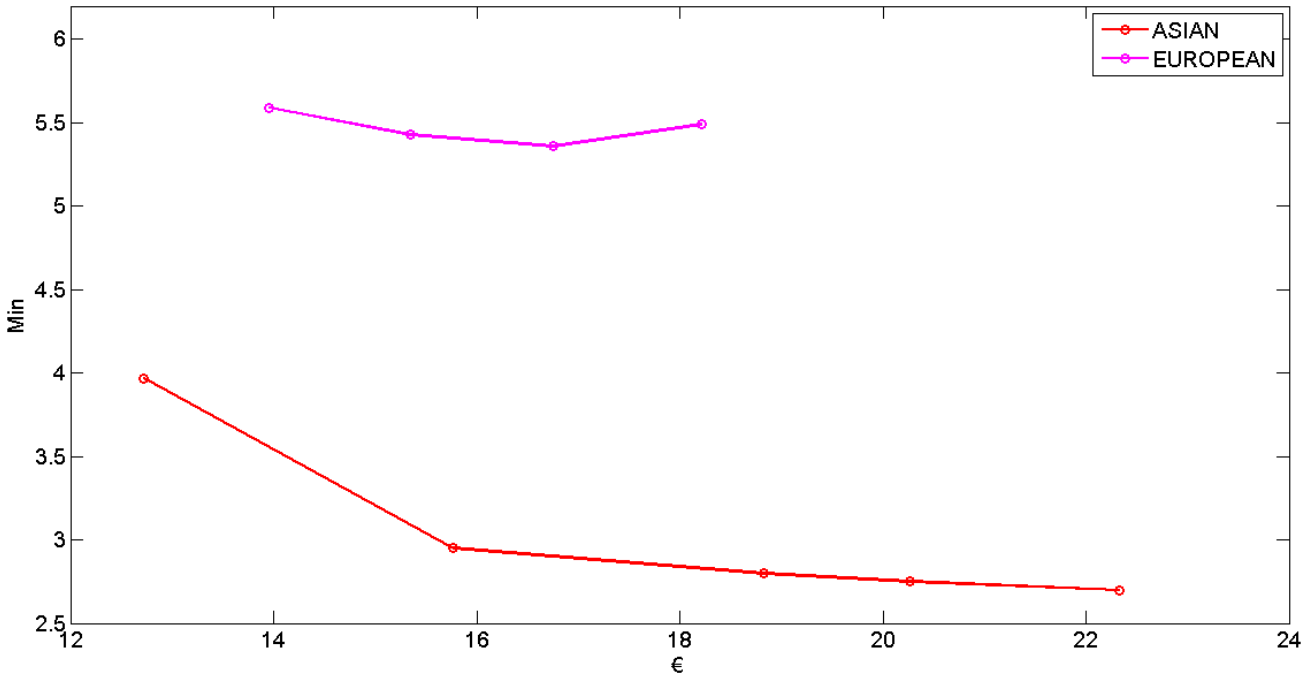

Figure 37. CST comparison between Asian and European layouts with regard to the total cost per container at 1.5 million throughput.

7.4 Conclusions

1. Asian container terminal layouts proved to be more efficient than European ones in all cases examined (Figures 34,35,36,37). For the same amounts of investment and operational cost per container, Asian layouts outperformed their European counterparts both in energy consumption and emission efficiency and in terminal transporter and truck turnaround times. Although in European terminals TT and truck routes are severely shorter than in Asian ones, the amount of YC energy consumption is so much higher in European terminals that it ultimately leads to greater amounts of emissions released. The fact that causes this disparity between YC operational efficiency between the two layouts is the much greater number of parallel gantry movements European layout YCs are forced to conduct due to the nature of the layout design. This is also the reason why YC cycle times are increased, affecting directly TT and truck waiting times as well, leading to higher overall average turnaround times.

2. When it comes CO2% distribution between the two layouts it becomes clear that the most important difference lies in cranes. European layouts average approximately 10% more crane CO2% distribution than Asian layouts due to the extended parallel YC gantry movements as explained earlier. Terminal transporter and highway freight percentage distribution is about 3% less in European layouts and finally, ship percentage distribution is approximately even for both layouts (Figures 26, 28, 30, 32).

3. For both layouts, Figures 27, 29, 31, 33 show that there is a critical point after which further increase in investement does not lead to increased efficiency. On the contrary emissions and turnaround times increase after that point. This is thus, the optimal cost/container point for each layout under the given input variables at which energy consumption is minimized and operational efficiency is maximized.

   The main reason for this curve behavior is the following. Operational and emission efficiency increases as the number of YCs increases in the yard. Raising the number of YCs leads to lower cycle and waiting times as there is more equipment to service the container traffic rates outputted through the terminal quay and gate. Especially considering that the current study assumes a fixed number of STSCs and TTs per quay length, the number of YCs is a focal point to achieving optimal efficiency. The problem is that after a certain number of YCs, the benefits from the increase in operational efficiency become less than the additional costs deriving from extra YCs and ground space investments.

4. Minimizing the maximum stack height is important for both layouts and leads to increased efficiency. Asian layouts performed better with low number of bays and high number of stacks. European layouts performed better with high number of bays and low number of stacks. Increasing the number of stacks can affect layout emissions in two contradicting ways. On the one hand increasing the number of stacks leads to decreasing the number of reallocations (Kim 1997), but on the other hand it leads to increased YC sizes. Bigger YCs have a severe negative impact on emissions when they perform high amounts of gantry movements, like in the case of European layouts. In low gantry movement layouts (Asian) the decrease in reallocations plays a more important part. Thus, Asian layouts perform better with high number of stacks and European layouts with low number of stacks.

5. For each terminal examined in both Asian and European layouts the CO_2/container difference, between the best and worse layout examined by the simulation, was about 12-15kg CO_2/container. The size of the variance observed indicates the critical importance of implementing a good layout design in container terminals.

8. PIRAEUS CONTAINER TERMINAL (PCT)

Figure 38. Piraeus Container Terminal (PCT)

PCT (Figure 38) is one of the fastest growing container terminals in the Mediterranean with an annual throughput of *5.5 million containers*. It is divided into 2 Piers, each of which is divided in an east and west side. In the current segment we examine the Pier 2 East Side terminal.

The terminal has an Asian layout design. The quay length of the terminal is l_q*=780m*. Due to the shape of the terminal, the storage yard area extends a bit further than the quay length and is not of rectangular shape. Thus, the storage yard length limits vary from *780m to 820m* and also the number of bays is not even among blocks, varying from *52 to 60 bays* per block. So in order to examine the terminal through the simulation model we assume that is of rectangular shape with a storage yard limit of *800m* and a fixed number of *56 pays per block*. The storage yard width limit was set to *230m*. The number of stacks per bay *St* and the maximum height per stack *M* is even among blocks, with *St=9 and M=6*. The number of YCs per row is *4*. Also the lengths of the horizontal and vertical isles are inversed to what was set by Lee & Kim 2012, with w_v*=26m and* w_h*=16m*. The annual throughput of the entire Pier 2 is 3.2 million containers. The annual throughput of Pier 2 East Side was estimated to be proportional to the ratio of Pier 2 East Side quay length to the total Pier 2 quay length. The quay length of Pier 2 East Side extends to *780m* while the total extends to *1480m* and thus, the annual throughput was set to *Th= 1,686,486* containers. The numbers of export, import and transshipment containers were set to *562162 containers*. The average dwell times for each container type were set to *2880 minutes*.

	CONSTANTS	SOURCE		**CONSTANTS**	SOURCE
l_v	300	Lee & Kim 2012	v_b	180	Lee & Kim 2010
l_b	6.458	Lee & Kim 2012	v_s	150	Lee & Kim 2010
l_h	2.591	Lee & Kim 2012	v_{hl}	50	Lee & Kim 2010
w_r	2.838	Lee & Kim 2012	v_{he}	83	Lee & Kim 2010
w_h	16	Lee & Kim 2012	T_p	5	Lee & Kim 2010
w_v	26	Lee & Kim 2012	*GT*	40000	
h_T	518400	Lee & Kim 2012	*kwhCO2f*	0.79	
c_{QC}	2.4	Lee & Kim 2012	*DieselCO2f*	2.65	
n_{QC}	3	Lee & Kim 2012	*MDOCO2f*	3.17	
u	0.6	Lee & Kim 2012	u_{QC}	0.8	Lee & Kim 2012
v_l	200	Lee & Kim 2012	δ	0.3	Lee & Kim 2012
v_e	300	Lee & Kim 2012	QC_{sim}	200	

Table 30. Simulation constants values

8.1 Optimal solution under cost constriction

Firstly, the real terminal layout was simulated through the model. After that, the simulation was set to find a better solution emission wise, under the constriction of the cost of the real layout obtained by the simulation. The simulation results are showcased below.

	VARIABLES		
Ex	562162	D_{Ex}	2880
Tr	562162	D_{Tr}	2880
Im	562162	D_{Im}	2880
n_{YC}	4	l_q	780

Table 31. Simulation variable values

PIRAEUS CONTAINER TERMINAL		
PIER 2 EAST SIDE		
TH= 1,686,486 MILLION CONTAINERS		
	REAL	OPTIMAL
R	4	3
C	2	3
B	56	30
St	9	15
M	6	6
CO2con(kg)	20.82	20.45
KWHcon(kwh)	18.5	18.52
LITcon(lit)	2.23	2.08
CR%	62.62	64.13
TT%	7.58	7.43
SH%	19.78	20.14
TR%	10.02	8.3
CR	1.4	1.3
CD	1.83	2.03
CL	1.57	1.99
CU	1.2	1.29
WI	1.55	1.87
WO	1.00	1.21
CST	3.97	4.50
Total cost/container (€)	7.70	7.00

Table 32. Simulation results

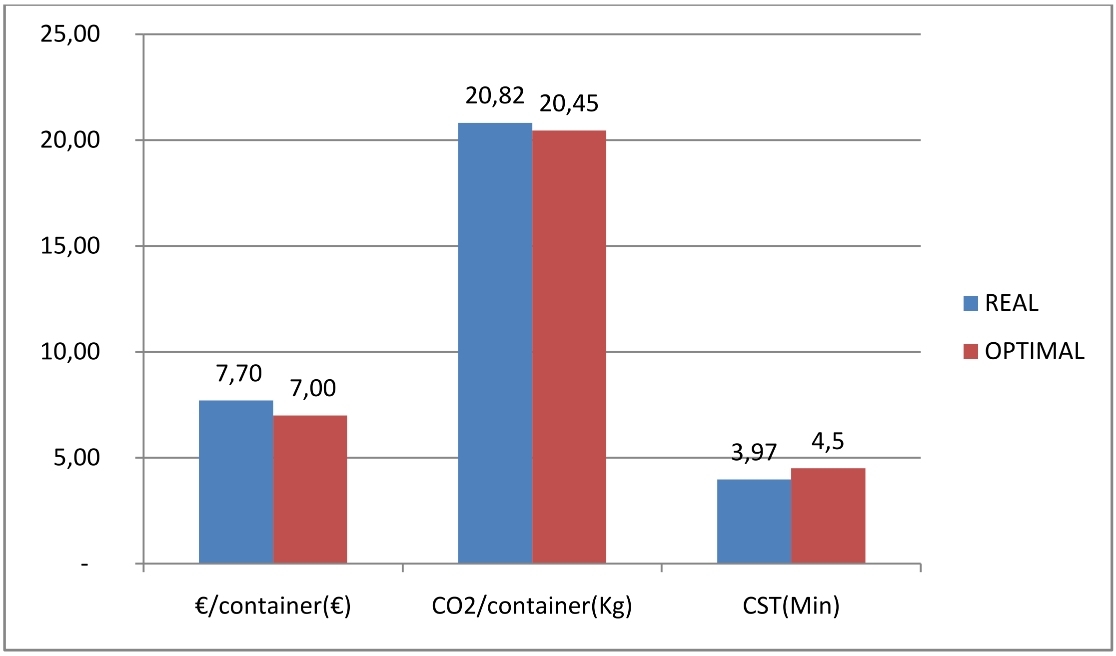

Figure 39. Cost, CO2 and CST value comparison between the real terminal and the optimal terminal layout, both obtained from the simulation model.

The optimal layout has less *R, B* values, greater *C, St* values, and even *M* values with the real one. The comparison between the two layouts showed that the optimal one produced slightly less CO2 emissions at a slightly cheaper cost too than the real one. On the other hand, the real terminal achieved slightly faster turnaround times than the optimal one (Figure 39).

The small variance range between the two layouts in all major indicators shows that the Pier 2 East Side terminal is an exceptionally well designed one. The simulation conducted shows why PCT is one of the fastest growing terminals in Southern Europe. And most importantly indicates that it achieves high growing rates while maintaining an environmentally friendly ‘green’ port approach.

8.2 Optimal solution without cost constriction

The process of finding the optimal terminal layout is repeated with the constriction of the real layout cost this time. Hence, the best emission wise solution without implementing cost restrictions is searched for. The results are presented below.

	VARIABLES		
Ex	562162	D_{Ex}	2880
Tr	562162	D_{Tr}	2880
Im	562162	D_{Im}	2880
n_{YC}	4	l_q	780

Table 33. Simulation variable values

PIRAEUS CONTAINER TERMINAL		
PIER 2 EAST SIDE		
TH= 1,686,486 MILLION CONTAINERS		
	REAL	OPTIMAL
R	4	4
C	2	4
B	56	26
St	9	13
M	6	5
CO2con(kg)	20.82	19.80
KWHcon(kwh)	18.50	17.63
LITcon(lit)	2.23	2.11
CR%	62.62	62.45
TT%	7.58	7.88
SH%	19.78	20.80
TR%	10.02	8.87
CR	1.40	1.29
CD	1.83	1.65
CL	1.57	1.35
CU	1.20	1.21
WI	1.55	1.40
WO	1.00	0.97
CST	3.97	3.61
Total cost/container (€)	7.70	8.06

Table 34. Simulation results

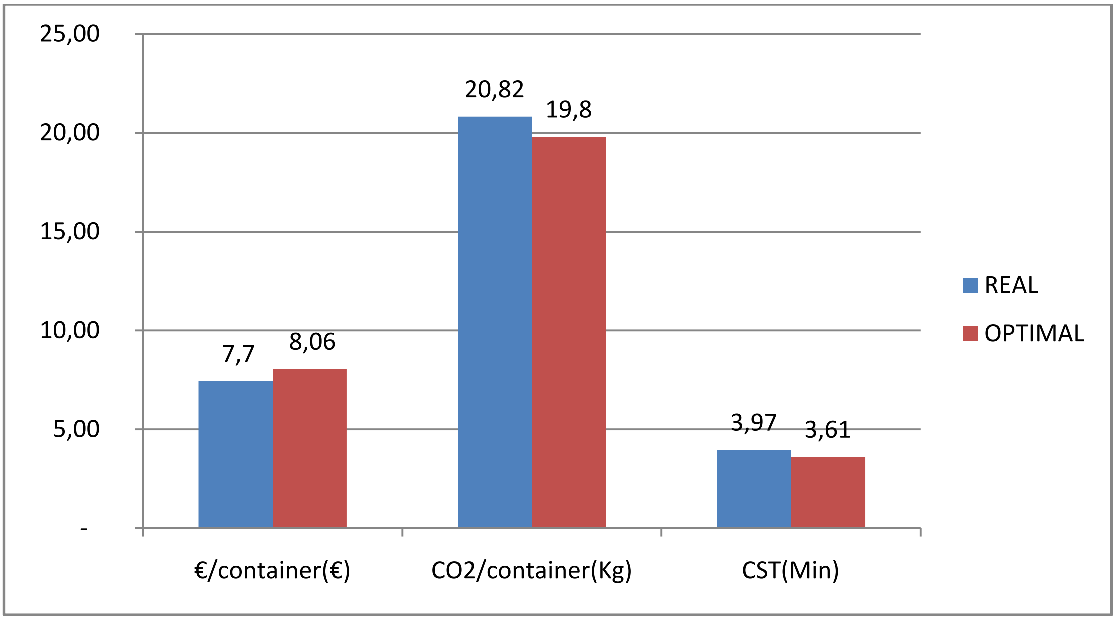

Figure 40. Cost, CO2 and CST value comparison between the real terminal and the optimal terminal layout, both obtained from the simulation model.

The optimal layout has less *M, B* values, greater *C, St* values, and even *R* values with the real one. The comparison between the two layouts showed that the optimal one produced less CO2 emissions per container at the expense of a slight extra cost per container. (Figure 40)

8.3 Terminal expansion optimal solution

In the current segment the simulation was set to find the optimal solution assuming a terminal expansion is planned. The expansion scenario assumes an increase to *Th= 2 million containers* under the same quay length and container yard area. The results are showcased below.

	VARIABLES		
Ex	666667	D_{Ex}	2880
Tr	666666	D_{Tr}	2880
Im	666667	D_{Im}	2880
n_{YC}	4	l_q	780

Table 35. Simulation variable values

PIRAEUS CONTAINER TERMINAL	
PIER 2 EAST SIDE	
TH= 2 MILLION CONTAINERS	
	OPTIMAL
R	4
C	5
B	20
St	12
M	6
CO2con(kg)	20.35
KWHcon(kwh)	18.42
LITcon(lit)	2.08
CR%	63.95
TT%	7.55
SH%	20.24
TR%	8.27
CR	1.55
CD	2.15
CL	1.48
CU	1.48
WI	1.95
WO	1.21
CST	4.24
Total cost/container (€)	7.28

Table 36. Simulation results

The simulation showed that an expansion up to 2 million containers in the Pier 2 East Side terminal is feasible without any further investments to increase quay length and storage yard space. This increase in throughput can be achieved while maintaining approximately the same levels of *Cost/container, CO2/container and CST* values. Hence, there is potential for further growth and improvement in PCT.

9. CONCLUSIONS

This study proposed a method to address the container reallocation and retrieval problem. A heuristic was developed to minimize unproductive yard crane moves. The heuristic proposed in the current study averaged only 3% more moves than the lower bound. Also, a simulation model of a container terminal was created in order to establish the optimal container yard layout, depending on the expected annual throughput and the available quay length, with aim to minimize CO_2 emissions. Two popular types of yard layout in practice were examined, the Asian and the European layout. For each layout, the optimal block length, width and height was examined, as well as the optimal number of rows and columns of blocks. Asian container terminal layouts proved to be more efficient than European ones in all cases examined. It was found that the majority of CO_2 emissions is attributed to terminal cranes (YCs & STSCs), although this find is highly sensitive to the kwh to CO_2 conversion factor and could vary notably in terminals receiving energy from alternative energy sources. It was found that every layout presented a critical point beyond which investing more money does not lead to increased performance and energy efficiency. In both layouts it was found that decreasing the height of blocks was beneficial to terminal performance. Asian layouts performed better with low number of bays and high number of stacks, while European ones performed better with high number of bays and low number of stacks. Piraeus Container Terminal performed better with more columns of blocks with less bays and more stacks than the current layout. For future analysis, numerous sensitivity analysis tests should be made to evaluate various variables that were established as constants in the current simulation model. Such variables are the number of STSCs per ship, the number of YCs per row of blocks, the gantry, trolley and hoist speed of yard cranes, kwh to CO_2 conversion factor and more.

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