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Yard Crane Pools and Optimum Layouts for Storage Yards of Container Terminals

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ABSTRACT

As more and more container terminals open up all over the world, competition for business is becoming very intense for container terminal operators. They are finding out that even to keep their existing Sea Line customers, they have to make them happy by offering higher quality service. The quality of service they can provide depends on their operating policies and the design of the terminal layout. Existing layouts based on designs prepared a long time ago pose inherent limitations. We summarize some of these problems, and report on newer operating policies and designs which can help improve performance.

Keywords: Container terminals, EXSY (export storage yards), YC (yard cranes), Crane clashing, Crane overloading, Cross-gantrying, Congestion, QC (quay crane) rate, Storage space allocation policy, YC scheduling, Investment in cranes, Storage blocks and their optimum size, YC pools.

1. INTRODUCTION

Container terminals are service centers in ports that serve sea-faring container vessels to unload import containers and load export containers, or transfer containers from one vessel to another. When a container vessel arrives at the port, the terminal provides a berth for it to dock. Then the **QC**s (quay cranes, or shore cranes) at the berth begin servicing it, each QC handling a section along the length of the vessel known as a hatch. There may be several hatches in the vessel, typically 3 to 4 QCs work on a vessel at a time.

A QC unloads import containers from the hatch and puts each on a **YT** (yard truck, also called internal tractor, or prime mover etc.) waiting under it on the ground. The YT then takes that container to the **SY** (storage yard) for temporary storage until its owner picks it up from the terminal using his/her own truck called **XT** (external truck), or it is retrieved from storage to be transferred to another vessel when that vessel arrives at the terminal.

For sending goods to another port customers pack them in containers, and deliver the packed containers on their XTs to the container terminal. At the terminal these containers are unloaded from XTs, and put into temporary storage in the SY. When the vessel into which they are to be loaded docks in the terminal, these containers are retrieved from storage and carried by YTs to the berth; these YTs park under the appropriate QC which lifts the containers and loads them into the vessel.

In the layouts in common use today, the SY is divided into rectangular regions called **blocks**. Each block is typically 65' (feet) wide and 860' long. A 20' container, called **teu**, is 8' wide and 20' long, now-a-days there are 40' containers with the same width, but teu remains the standard unit for measuring container shipping volume. Each block is divided into **stacks** for container storage. The width of the block is divided into 7 rows, 6 for stacks and the 7th for truck passing. The storage area of a block is six stacks wide and forty 20' stacks long (stacks for storing 40' containers occupy two 20' stacks with a common width line). In each stack containers are stored one on top of the other, 4 to 6 containers high depending on the height of the **YC** (yard crane) serving the block.

YCs (now-a-days usually rubber tired gantry cranes or **RTGC**s) transfer containers between trucks (YT or XT) and the stacks in the block, they straddle the entire width of the block beneath them and move along the length of the block. YC movement transferring a container from a YT or XT to a stack is called an **uplift**, its move of a stored container from its stack onto a YT is called a **downlift**. A **zone** in the SY is a sequence of blocks all aligned lengthwise, i.e., consecutive blocks in a zone share a common width line. YCs can move easily from block to block in a zone, such movement of a YC is called its **linear gantrying**. But to move from one zone to another, it has to make vertical turns called **cross gantrying** which is very time consuming. A cross gantrying YC blocks the road to other vehicles, thus disrupting traffic.

A QCs top speed is 40 **lift**s (container moves between vessel and shore) per hour if it does not have to wait for trucks under it to take away the import containers it is unloading, or to bring export containers for it to load while it is loading. But at most terminals they average only 25 or so lifts/hour. The average number of lifts achieved at a terminal per QC working hour, known as the **QCR** (QC rate) is an important performance measure of the terminal.

Another important measure by which terminals are judged is the **average vessel turnaround time**, this is highly correlated (with negative correlation) to the QCR.

So, we will use the QCR as the measure of performance to maximize. To attain a top QCR value, the flow of containers back and forth between the shore and the SY has to proceed smoothly like clockwork, so that QCs don't have to incur idle time waiting for YTs.

The maximum handling capacity of a YC is 25 lifts/hour, much slower than that of a QC at 40. Since YCs have to store import containers being unloaded by a QC, and send back to the QC the YTs bringing them; and also retrieve stored export containers to feed a QC while it is loading export containers into the vessel; about two YCs have to work smoothly to keep a QC working at top speed. To attain the highest QCR, it is important to coordinate the activities of the YCs, YTs serving QCs properly.

For ease of unloading, vessels normally dedicate each hatch of a vessel to containers going to a single destination port. When a QC is loading containers in a hatch, the YCs serving it should retrieve all export containers to be loaded into this hatch in quick succession and dispatch them to the QC smoothly, for the QC to attain a high QCR. This points out the great importance a suitable layout for the SY, and of storing export containers in such a way that YCs can retrieve them quickly when needed. For this reason the layout design of the SY, and the storage space allocation policy used by the terminal are very critical to keep QCR high. A great deal of research has been reported in the literature for determining optimum storage space allocation policies. This is one of the foci of this paper too.

Export containers are classified into groups called **consignments** or **container groups**. Containers in a consignment have the same length, destination port; and are to be loaded into ships belonging to the same liner service, and belong to the same weight class. Because of this, they can be loaded into the same hatch of the vessel in any order, and can also be stored in the SY in a single stack in any order. Also since they all go into the same hatch of the same vessel, they will be retrieved from the stack one after the other in succession, from the top of the stack to the bottom without any reshuffling. The number of containers in a group may vary from 2 to 20 or more in practice.

Here we described the equipment used, and the operations inside the terminal only briefly to help the reader understand our strategy described later. For a complete description of terminal operations and the environment there for decision making (see Silberholz et al., 1991; Kozan, 1997; Nevins et al., 1998; Meersmans and Dekker, 2001; Zhang et al., 2002; Lee et al., 2003; Linn et al., 2003; Linn and Zhang, 2003; Steenken and Stahlbock, 2004; Murty et al., 2005a; Murty et al., 2005b; Dekker et al., 2006; Petering and Murty, 2006; Petering et al., 2006; and Petering, 2007).

2. IMPORTANCE OF MAXIMIZING THE QCR IN CONTAINER TERMINALS

For the container terminal two powerful incentives for maximizing its QCR are: 1) economic incentive of higher business turnover using the same equipment and labor force, 2) satisfaction in the eyes of customer sea-lines, and the prestige and reputation for the terminal that comes with it. But there is a much more powerful incentive that is of great importance which we describe below.
The sea and the shoreline surrounding it are the most wondrous treasures of planet earth. Before humans ventured into the sea, perhaps 20,000 years ago, the sea water used to be completely inhabited by the world of coral of unimaginable beauty. The early seafaring humans only thought of the coral as a bothersome obstruction for fulfilling their desire to travel to far off lands, and destroyed everything in their way to clear passage for sea boats. That destruction continues even today, as a result only a small fraction of the original coral world survives, and even that small amount is expected to die off in the next 30 to 40 years due to human caused pollution of various kinds.

In South Korea there is a beach area advertised as the *Coral Beach*, a great attraction for tourists from around the world. The entire beach area there is lined to some depth with pulverized white coral, and all the tourists walk on it with looks of great admiration. When we visited that place, we felt sad that we humans seem to be the only creatures who revel admiringly on the destruction caused by us.

The shoreline of the sea is also facing a similar fate. Container terminals convert a long stretch of the shore into a business operated as a service center for vessels, completely destroying all the natural beauty of that portion of the shore. Countries around the world are building more container terminals to accommodate the ever increasing volume of business, gobbling up more of the shoreline. If existing terminals can operate at higher efficiencies, we may be able to avoid the need for building new terminals. This points out another powerful motivation to improve the operational efficiency of existing terminals.

3. THE MULTIOBJECTIVE NATURE AND THE SCOPE OF THE PROBLEM

In this problem, maximizing the QCR is clearly the single well defined objective. However, the QCR is greatly influenced directly or indirectly by many factors in daily operations at the terminal, but the contribution of each factor is stochastic, and it is very hard to get an expression for QCR as a function of these factor levels. So, it seems that the only practical way to optimize decision making in daily operations at the terminal is to treat it as a multi-objective problem optimizing the various factors influencing the QCR. We will now discuss the most important of these factors.

1. Cross gantrying frequency: The cross gantry movement of YCs between zones is very slow, and obstructs the movement of YTs on the road; thus hampering the ability of these equipments from serving their QCs promptly. So, an important objective in container terminal decision making is to keep cross gantrying frequency as low as possible.

2. Congestion on the road system inside the yard: This slows down the movement of YTs between the shore and the SY, hampering their ability to serve QCs promptly. This is a very difficult objective function to quantify, but clearly it should be minimized. The study reported in Murty et al., 2005a and 2005b has shown that congestion can be minimized by distributing the YT traffic evenly on all the road segments in the yard, which can be achieved by appropriate storage space allocation and YT dispatching policies.

3. **YC overloading frequency**: Since a QC's working rate is about twice that of a YC, about two YCs or more have to serve a QC to keep it fully occupied. If a small number of YCs are forced to serve some QCs, they may find themselves **overloaded** to keep the QCs busy, and the chance of QCs having to remain idle for some time increases. The frequency of these occurrences should be minimized.

4. Crane clashing frequency: In many busy terminals they usually station 2 or more YCs in a block during periods of heavy activity in that block. In such a block, if two YCs are required to retrieve simultaneously two containers stored in separate stacks that are close to each other, one of them has to remain idle until the other finishes retrieving its container. This is because working YCs should be separated by a minimum distance (typically 170 feet or eight 20' stacks long) to avoid running into each other and causing serious accidents. This type of incident is called **crane clashing** (Petering and Murty, 2006; Petering, 2007). It wastes YCs time, and if it is a frequent occurance it slows their work and their ability to serve QCs promptly. So the occurrence of crane clashing incidents should be minimized to keep QCR level high.

For achieving high QCR values, these are the most important objectives to control. We will discuss strategies for optimizing these four objectives.

Many terminals which have a reasonable area of land available for their operations divide their SY into three separate areas labeled the **ISY** (import SY), **EXSY** (export SY), and the **EMSY** (empty container SY).

All containers which arrive on a vessel and are bound to inland destinations are called **import containers**, these are stored in the ISY. These import containers will be picked up by XTs or trains and taken by land to their inland destinations.

All containers which are to be loaded into vessels (containers that arrive from inland exporters on their XTs, or **transfer containers** that arrived by another vessel earlier) are called **export containers**, these are stored in the EXSY. They will be retrieved from storage and loaded into their respective destination vessels when they arrive.

Empty containers are stored in the EMSY. They may be transported subsequently to another port on vessels, or picked up on XTs by inland exporters to load their export goods. Because they are light, stacking or retrieving empty containers from stacks needs simpler equipment than the YCs discussed above.

In this paper we consider only decision problems relating to storage and retrieval of export containers in the EXSY.

At most container terminals around the world, the export yards follow a **homogeneous stacking policy**, i.e., in each stack containers from only one consignment are stored. This implies that containers stored in a stack can be retrieved in any order, and hence in the EXSY of such terminals there is no need for any unproductive reshuffling of containers by the YCs.

4. CONTROLLABLE ITEMS IN DECISION MAKING THAT AFFECT THE OBJECTIVE FUNCTIONS

Many decisions to be made in the course of daily operations of the terminal affect the objectives directly or indirectly. But due to the uncertainties in terminal operations, the effects are also uncertain and indirect. For example, consider two consignments of containers to be loaded into two different hatches of a single vessel. Since export containers may arrive at the terminal up to 7 days before the arrival of their vessel, the decision on whether to store these consignments in the same block, and if so in stacks close to each other, may have to be made several days before their vessel arrival. Since schedules for QCs working on this vessel are drawn up only a few hours before vessel arrival, at the time of making the storage location decision, we will not know whether the two QCs that work on the hatches into which these consignments are to be loaded may be working simultaneously or not.

If these consignments are stored in stacks near to each other in the same block, and if it so happens that the QCs that will be loading these consignments work at the same time; retrieving them from those nearby stacks will result in a crane clashing incident for two YCs working in their block, or a YC overloading incident for a single YC to retrieve them; with the net result that one of those two QCs has to incur some idle time.

The very large number of decisions to be made in daily operations at container terminals, indirect interactions between them, and the different time frames in which they are made; make it impossible to determine the objective functions to be optimized as deterministic mathematical functions of the decisions. These coupled with the uncertainty in vessel arrival times and the volume of work load that they bring with them, and random variations in the travel times of YTs within the yard make it impossible to obtain optimum decisions using a deterministic mathematical model. The only possible way of getting good decisions is to develop several policies for making decisions, compare their performance in comprehensive simulation runs, and then select the one giving best results in them to implement.

5. PLANNING POLICIES BASED ON TREATING ALL YC's OPERATING IN A ZONE AS A POOL OF YC's SERVING THAT ZONE COLLECTIVELY

Many terminals try to manage the scheduling of YCs to blocks individually, without taking too much advantage of the fact that linear gantrying of a YC within a zone is quite fast compared to its cross gantrying between zones, with the result that several cross gantrying moves do occur in practice.

Most terminals want the YC/QC ratio of around 2.5 to 3.5 or even higher. Higher values for this ratio require higher investment in YCs which is not very attractive. One strategy which avoids cross gantrying altogether, and also does not need high YC/QC ratios to get good performance is to treat all the YCs allocated to a zone as a **pool of YCs** sharing the work in that zone as a pool. It is attractive because linear gantrying of YCs is quite fast. In this section, we discuss operational details for implementing this YC pool concept in practice; i.e., the rules for storage space allocation, detailed YC work scheduling, and YT dispatching under it; that are likely to minimize crane overloading, congestion on the roads inside the terminal, and QC idle time waiting for YTs.

Rules for Storage space allocation

We have already discussed that there must be at least two YCs serving each working QC, so each consignment must be split between at least two YC working regions. In fact studies reported in Murty et al., 2005a and 2005b; Petering and Murty, 2006; and Petering, 2007 have shown that even more dispersion with each consignment having one or a small number of stacks in each block is beneficial. The storage space allocation policy discussed below takes advantage of these findings.

The data needed for storage space allocation is the expected retrieval times of various stacks having one or more containers stored in them in various blocks. This data indicates the date of retrieval fairly accurately, but the time of retrieval on that day is usually not reliable. However, this is the only information we have available to base our planning, and we use it.

The problem of allocating a stack in a block to a consignment can be looked at as a bin packing problem with blocks as bins, and stacks for consignments as goods to be packed in bins. To minimize crane overloading, we should make sure that the expected retrieval times of the various stacks in each block are as far away from each other as possible, this can be achieved by maximizing

θ = (the sum of absolute deviations between expected retrieval times of various pairs of stacks in the territory).

The rule that we will use to determine the block in which the next export container arriving in the SY should be stored, is an adaptation to this problem, of the best fit on-line heuristic for bin packing. This on-line heuristic has been shown to produce high quality near optimum solutions in a variety of bin packing applications.

Another thing that we need to optimize is congestion on the road system. In Murty et al., 2005a and 2005b it has been shown that this can be achieved by YT dispatching strategy that disperses YT traffic throughout the SY as much as possible. We use the strategy developed there. We will now describe the policy for storage space allocation to a new container arriving for storage.

1: Storage space allocation for the 1st container in a group to arrive: If this is the first container of its group to arrive, and if there are blocks which are completely empty at that time, select one of those and store this container in an arbitrary empty stack in that block.

1.1: If fill ratios of all blocks are positive at that time, for each block with an empty stack (suppose this set of blocks is E_1), compute the: sum over all occupied stacks in the block of:

(|(estimated retrieval time of the new container) – (estimated retrieval time of that stack)|).

Find the set S_1 of all blocks which have near maximum value for this sum among the. set E_1. Open an empty stack for storing this new container in a block that has the smallest number of trucks waiting for service among those in the set S_1.

2: Storage space allocation for subsequent arrivals from a group when a stack storing this group has space to store it: If this is not the first container in its group to arrive, find the set S_2 of all blocks in which there is a stack allocated for this group earlier, and that stack has space to store this new container. Among all the blocks in the set S_2, find the one with the smallest number of waiting trucks in it at that time, store this new container in the top position of the stack allocated for this group earlier in that block.

3: Storage space allocation for subsequent arrivals from a group when all earlier stacks storing this group are full: Suppose this is not the first container in its group to arrive, and all the stacks allocated for this group earlier are already full.

3.1: At that time if there is a block which is completely empty, select one of those and store this container in an arbitrary empty stack in that block.

3.2: At that time if there is no block which is completely empty, for each block with an empty stack (suppose this set of blocks is E_3), compute the sum over all occupied stacks in the block of:

| (estimated retrieval time of the new container) – (estimated retrieval time of that stack) |.

Find the set S_3 of all blocks which have near maximum value for this sum among the set E_3. Open an empty stack for storing this new container in a block that has the smallest number of trucks waiting for service among those in the set S_3.

Policy for YC Scheduling

We divide the day into **planning periods** of some convenient length, $\bar{t}$ say, for preparing detailed work schedules for each YC. $\bar{t}$ is a period of relatively small duration like 15 to 30 minutes, so that during the previous period the control room has reasonably accurate knowledge of which QC will be loading what containers in the planning period, together with an estimate of the time at which each of those containers will be loaded.

4: Generating the downlift workload in each zone during the planning period: Consider a QC, say QC1 which will be loading during the planning period. If it is expected to load ℓ (= 12 say as an example) containers from a consignment during the planning period. This workload of ℓ = 12 containers to be retrieved from storage and dispatched to QC1 is distributed among the zones which have stacks of containers of this consignment in storage, in proportion to the number of YCs stationed in them during the planning period. Then repeat the same with all the QCs which are expected to be loading during the planning period.

In the planning period, the YCs in each zone carry out the downlift jobs in the schedule for that zone in the order of its estimated time. YCs can linear gantry from one block to another quite easily, so we treat all YCs in a zone as a pool to handle the workload in that zone generated above.

5: Generating YC work schedule for downlifts: Let m be the number of YCs in the pool serving a zone in the planning period. Divide the zone into work areas in the planning period for the YCs in its pool, the work area for each YC is called its **segment** for the planning period. This division is carried out by examining the zone from one end to the other, say left to right. The leftmost segment for the leftmost YC in the zone consists of the subset of leftmost stacks in the zone such that: (the sum of downlifts in them in the planning period) is as close to ((the total number of downlifts in the zone)/m) as possible. Then the set of downlifts in this segment are made into a list sorted in the order of expected time. Other segments are formed the same way with the remaining portion of the zone. Each YC carries out the downlifts in its segment in order of expected time.

6: Allocation of uplifts to YCs: The total number of downlifts in a YCs segment is a measure of the down-lift workload in the planning period allotted to that YC at this stage. Additional workload to this YC in the form of uplifts will come during the planning period itself as the storage space allocation policy allots arriving containers to store to one of the blocks in its segment.
Let *increasing order* for segments in a zone at any point of time in the planning period refer to the sequence of them in increasing order of the sum:

(number of downlifts in that segment in the planning period) + (number of uplifts allotted to territories in that segment by the storage space allocation policy so far).

The total workload for a YC in a period is the sum of the downlifts, and uplifts that it carries out. We can equalize the total workload for the YCs in a zone in the planning period, by modifying the storage space allocation policy discussed above, to disapatch the export containers arriving for storage in the planning period in the zone, to segments in their increasing order in such a way that the total workload in all of them balances out.

Policy for YT Dispatching

We will use the concept discussed in Murty et al., 2005a and 2005b in which all YTs are considered as a pool serving the group of working QCs. We also adopt the YT dispatching policy developed there that helps minimize congestion.

7: YT dispatching policy

7.1: **Dispatching empty YTs from SY to shore**: For each YT returning empty from the SY to the shore, dispatch it to the QC that has the smallest number of YTs in the queue under it, among all the QCs engaged in unloading at that time.

7.2: **Dispatching YTs from shore to SY**: These YTs are carrying containers unloaded by a QC, to the SY for storage. The storage space allocation policy discussed above provides rules to be used for selecting a block to dispatch this truck to. Among the various blocks considered for this choice by those rules, they select one that has the smallest number of trucks waiting for service from the YC.

7.3: **Dispatching XTs bringing export containers from outside**: This decision is conveyed to the driver of the XT as he is entering the terminal gate. The storage space allocation policy discussed above provides rules to be used for selecting a block to dispatch this truck to. Among the various blocks considered for this choice by those rules, they select one that has the smallest number of trucks waiting for service from the YC.

7.4: **Dispatching YTs carrying export containers to shore**: For each YT going to the shore from the SY with an export container, dispatch it to the QC loading that consignment at that time. If there are 2 or more such QCs, dispatch it to the one that has the smallest queue of such trucks under it.
These operating policies are formulated using principles that have been shown to lead to good performance in earlier research publications, in particular Murty et al., 2005a and 2005b; Petering and Murty, 2006; and Petering, 2007. However the performance of these policies has yet to be evaluated using a comprehensive simulation package of container terminal operations.

6. ALTERNATE LAYOUTS FOR EXSY

When the operating policies discussed in Section 5 are implemented, crane clashing incidents may occur. The present division of the SY into blocks 40 stacks long implies that during busy activity periods some blocks may have 2 or more YCs working in them, this provides opportunities for crane clashing incidents.

In practice, crane operators of adjacent cranes can communicate with each other. Crane operators can make slight alterations in their work sequences by communicating with each other whenever they seem to be headed for a clashing incident, and avoid any disruption of their work schedules. So, if crane clashing is infrequent, it can be ignored in our search for optimal operating policies.

Of course crane clashing can be totally eliminated by dividing the SY into blocks of smaller size (i.e., consisting of less than 40 stacks) which we call territories in which at most one YC will work at any time. The operating policies discussed in Section 5 can be implemented to satisfy the additional constraint that the working segment of any YC in a zone in any planning period consists of an integer number of such territories. This guarantees that crane clashing cannot occur. Since reducing block size decreases land utilization (because it leads to more land allocated to roads between consecutive blocks), this alternative merits consideration only if crane clashings are a frequent occurrence affecting performance.

Let a denote the size of a block in terms of the number of stacks. The above discussion suggests that the operational efficiency of the terminal may depend on the value of block size a in the layout design of the terminal.

The optimum value of a, and the effectiveness of the operating policies discussed in Section 5 with it, can only be evaluated using a comprehensive simulation package of terminal operations. Several simulations packages for container terminal operations have been developed already and these are used to analyze various operating policies (see the papers by Borovits and Ein-Dor, 1975; Shabayek and Yeung, 2002; and Hartmann, 2004. Petering, 2007 has developed a comprehensive simulation package recently. We will carry out an evaluation using it, and discuss the results in a subsequent publication. Also, extensions to import yards, and to container terminals which store both import, export containers together in the same yard are being studied.

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