OPTIMIZING CONTAINER TERMINAL OPERATIONS

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A Collaboration Between
Optimizing Container Terminal Operations

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The Logistics Institute – Asia Pacific (TLI – Asia Pacific) is a collaboration between the National University of Singapore and the Georgia Institute of Technology. Modelled after The Logistics Institute (TLI) at Georgia Tech, the Institute’s vision is to be the premier institute in Asia Pacific nurturing logistics excellence through research and education. TLI - Asia Pacific was awarded the prestigious Asian Freight & Supply Chain Award (AFSCA) for Best Educational Course Provider for four consecutive years, from 2003 to 2006.

The Institute provides postgraduate education in logistics and SCM at the MSc and PhD level, notably the Dual Masters Degree in Logistics and SCM. It also undertakes leading-edge research and development in supply chain engineering, technology and management in collaboration with industry; and hosts a regular series of Think Tables that brings thought leaders in research and industry to discuss contemporary issues, challenges and solutions in supply chain management in a dynamic environment.

The key research themes for Phase 2 include:

**Supply Chain Intelligence:** This area seeks to focus on providing an overarching analysis of the logistics market, the trade flows, and economic barometers of the various countries in Asia as far as it pertains to effective supply chain management for various industries. Interest in this area is heavily driven by data, empirics and company cases. The Institute conducts annual on-going surveys to test the pulse of the respective markets and industries such as cold chain, 3PL, etc.

**Supply Chain Optimisation:** This, being the traditional and existing strength of the Institute, seeks to deepen expertise in supply chain global network design and optimisation, involving the respective modes of transportation. Intensive supply network simulation on a regional/international basis e.g. port and maritime logistics, consolidation of logistics hubs, flexibility of regional distribution centres are a primary feature of this group. Other areas of interest include system productivity at the port, the integration of manufacturing and services within the value network, dynamic pricing and revenue management for high end perishables, and the study of mergers and acquisition and its impact on the respective industries.

**Supply Chain Technology:** This is an emerging area for the Institute, which intends to look at the test bedding of RFID and data capture related technologies, within the context of an independent environment. Work done in this area involves both investigative led research and joint development of supply chain technology based innovation with other agencies and companies. Policy and implementation issues pertaining to new supply chain technology and the end-to-end supply chain network are undertaken on a contract research basis.
Executive Summary

Container terminal yards are basically places for temporary storage of incoming and outgoing containers to facilitate the container flow. Different types of equipment are utilized in container terminals, such as quay cranes (QCs), yard cranes (YCs) and yard trucks (YTs). All kinds of equipment need to be carefully controlled and coordinated to generate higher throughput for terminal operators. At the same time, as the sizes of container ships are getting larger and larger and the requirement from customers is more demanding, operational efficiency in container terminals needs to be improved and optimized accordingly to meet customer satisfaction level.

This white paper describes a project carried out by TLI – Asia Pacific for PSA Singapore. In the project, TLI – Asia Pacific proposed a yard control system to automatically provide routing and dispatching instructions to YCs and YTs, so as to maximize the gross crane rate (GCR) for QCs. The system handles the following three problems in real time:

1. Allocation of YCs to yard zones (inter-zone YC deployment);
2. YC routing and scheduling within each yard zone;
3. YT dispatching.

Three solutions for Problem (1), twelve solutions for Problem (2) and four solutions for Problem (3) were proposed.

To validate the performance of the proposed system and algorithms, a simulation model was constructed to test the performance of various combinations of algorithms. In all, 788 scenarios were considered. Results indicate that solutions for Problem (2) gave rise to notably different GCRs. YC routing policies which prioritize retrieval jobs normally perform 3% better on average. It is also found that a random container storage policy performed better than a storage policy based on the idea of big yard clusters by about 6%.

Overall, this research shows how PSA Singapore can potentially increase its operational efficiency without any additional capital investment when: 1) The YC routing policy is chosen based on the YC/QC ratio and YT/QC ratio; 2) Yard retrieval operations is prioritized; and 3) Random container storage policy is used.

The research conducted in this project is also applicable to other industries; although the setting might not be exactly the same, the principles are virtually identical.
Background

The Port of Singapore is the world’s largest transshipment port. It is strategically located at the crossroads of the world’s busiest maritime trade routes. The container terminals operated by PSA Corporation provide temporary storage for containers in transit from one port to another. The success or failure of such terminals depends on how effectively they act as a buffer between various trade lanes. If the buffer is effective, vessels from different trade routes will remain on schedule with substantial economic benefit for the entire global economy. The physical entity lying at the heart of this buffer is the container storage yard itself, and the fleets of YCs and YTls that are responsible for handling cargo in the yard. The YCs, YTls, and the storage yard can be viewed as a single yard system that serves the QCs which are directly responsible for loading and unloading container vessels.

The GCR of QCs, which is the most important performance measure of a transshipment container terminal, is the long-run average number of containers transferred between vessel and shore per hour per QC. A high GCR, while desirable, can only be achieved if the yard system can process the jobs (of storing and retrieving containers) as quickly as they are generated by the QCs.

Figure 1 shows typical container flows within a transshipment container terminal. The QCs connect the container flows between the vessels and the yard. The YCs handle the containers entering in and transferring out of the yard system. During the unloading of vessels, the containers are unloaded by QCs, transported via YTls to yard blocks and handled by YCs. Similarly for vessel loading, albeit with the flow reversed.

Terminal Operational Challenges

Containers produced a huge reduction in port handling costs, contributing significantly to lower freight charges and, in turn, boosting trade flows. Containerization is an important element of the innovations in logistics that revolutionized freight handling in the 20th century.
The first vessel built to carry containers began operation in Denmark in 1951 and the growth of modern container shipping industry dates back to 1956. Nowadays, container ships are built with capacities to carry thousands of containers. Figure 2 shows the number of container ships classified in terms of TEU capacity. Observe the fact that although the number of container ships with capacity between 500 and 1,000 is the biggest one, their contribution in terms of TEU capacity is relatively small. In fact, the number of ships with a capacity more than 5,000 TEUs increases rapidly in the new millennium. For example, accordingly to AXS-Alphaliner, the number of ships with a capacity more than 7,500 TEUs at the beginning of 2006 was only 86, but the number rockets to 141 at the beginning of November 2006, an increase of 64% during 10 months.

Not surprisingly, as the number of big vessels increases, the average capacity of ships is also expanding quickly. Table 1 provides the top 10 liners in the world with their declared capacity in terms of TEU and number of ships. Notice that the average capacity for those top market players is more or less 3,000 TEUs per ship.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Operator</th>
<th>TEU</th>
<th>Ships</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>APM-Maersk</td>
<td>1,768,010</td>
<td>565</td>
<td>3129</td>
</tr>
<tr>
<td>2</td>
<td>Mediterranean Shg Co</td>
<td>994,815</td>
<td>315</td>
<td>3158</td>
</tr>
<tr>
<td>3</td>
<td>CMA CGM Group</td>
<td>665,627</td>
<td>283</td>
<td>2317</td>
</tr>
<tr>
<td>4</td>
<td>Evergreen Group</td>
<td>536,490</td>
<td>161</td>
<td>3332</td>
</tr>
<tr>
<td>5</td>
<td>Hapag-Lloyd</td>
<td>451,878</td>
<td>136</td>
<td>3323</td>
</tr>
<tr>
<td>6</td>
<td>COSCO Container L.</td>
<td>390,558</td>
<td>130</td>
<td>3004</td>
</tr>
<tr>
<td>7</td>
<td>CSCL</td>
<td>387,768</td>
<td>131</td>
<td>2960</td>
</tr>
<tr>
<td>8</td>
<td>Hanjin / Senator</td>
<td>348,873</td>
<td>88</td>
<td>3964</td>
</tr>
<tr>
<td>9</td>
<td>APL</td>
<td>339,863</td>
<td>108</td>
<td>3147</td>
</tr>
<tr>
<td>10</td>
<td>NYK</td>
<td>320,224</td>
<td>121</td>
<td>2646</td>
</tr>
</tbody>
</table>

Source: AXS-Alphaliner
With such an average capacity for each container ship, loading and unloading them quickly becomes a critical issue for container terminal operators. Industries of maritime transportation and container terminal operation are both capital-intensive ones. Operational efficiency not only increases the throughput of terminals and ships, but also has a great financial impact.

For a specific container terminal, there are operational constraints when different kinds of equipment are working together. Figure 3 displays a sketchy layout of a container terminal; where yard zones, yard blocks, vessels, QCs, and YCs are labeled for easy identification. Each yard zone (i.e. yard section) consists of a group of adjacent blocks that are aligned lengthwise and that together form a single lane for YC movement. Each block can be further divided into rows, slots, 40' stacks, and ground slots as indicated in Figure 3. The small black rectangles represent YTs. The YCs are allowed to gantry linearly along the section, as indicated by the blue arrows shown around YC 24. The YCs are also permitted to cross gantry to another section depending on the workload in the current and destination sections as shown by the green arrow. However, cross gantry operations are more time-consuming and therefore should be executed carefully. Even within a section, the linear gantries of YCs are slow since YCs are bulky. Once a YC enters a section, the order of the YCs is fixed since YCs cannot physically cross each other within the section. Another major constraint on the movement of YCs is that any two YCs should be kept apart for a safety distance (usually in terms of slots, e.g., 8 slots apart) at any time in a block. Therefore, when a YC is stationary at a particular slot, certain slots on the left side and right side of that slot are not accessible by other YCs.

In this project, TLI – Asia Pacific proposed a yard control system to efficiently control the movement of YCs and YTs at PSA Singapore so as to maximize the GCR for a fixed number of YCs and YTs. This system works in real-time on a live data feed in a container terminal environment.
Literature Review

Excellent surveys of recent research on container terminal operations are found in Meersmans and Dekker (2001), Steenken et al. (2004), and Vis and de Koster (2003). Good overviews of container terminal operations and equipment are given by Kozan (2000) and Murty et al. (2005).

On YC control, many papers consider the scheduling of a single rubber-tired gantry crane (RTGC, i.e. YC) where the containers are grouped and the YC must retrieve containers from specified groups according to a fixed sequence, without due dates or release times, while minimizing travel distance. Since containers belonging to a specific group may be stored in multiple locations, both the YC route and number of containers picked up at each slot are decisions to be made (Kim and Kim, 2003, 1999, 1997; Narasimhan and Palekar, 2002). Ng and Mak (2005) focus on a single YC scheduling problem where every job has a fixed location and ready time, and the goal is to minimize job waiting time.

For the scheduling of multiple YCs, Cheung et al. (2002), Linn et al. (2003), and Zhang et al. (2002) develop methods for allocating YCs among yard blocks in an entire terminal and for scheduling cross-gantry moves, but do not consider individual container handling operations or linear gantry moves. Kim and Bae (1998) construct detailed RTGC schedules for the remarging operation within a single yard block. Kim et al. (2004) construct detailed RTGC schedules for small scenarios involving the loading of a single vessel in isolation. Kim and Park (2004) use a greedy randomized adaptive search procedure to construct detailed schedules for QCs to process a vessel considering QC interference constraints. Ng (2005) is the only paper that proposes a method for constructing detailed schedules for all RTGCs at a container terminal on a continuous time basis. However, Ng (2005) does not require the YCs to be separated by a minimum distance. Overall, none of the above studies proposes a comprehensive, real-time YC routing system that is designed for deployment in the field.

Nishimura et al. (2005) is the only study that focuses on YT control. However, that paper only considers YT routing and assumes a relatively static environment where each YT continues along a cyclical path with limited opportunities for re-routing. There are many papers on automated guided vehicle (AGV) dispatching that are relevant to the current project. van der Meer (2000) provides a comprehensive introduction to AGV dispatching methods. For multi-load AGV systems in container terminals, Chan (2001) uses simulation to compare two alternative dispatching strategies for the case where there are $n$ single-level, multi-load AGVs and $m$ containers waiting to be moved. However, the assumption that all $m$ jobs are ready at time 0 does not reflect the true nature of container terminal operations. Grunow et al. (2004) and Guenther et al. (2004) study the dispatching of single-level, dual load AGVs in an automated container terminal. The AGVs can accommodate one 40’/45’ container or up to two 20’ containers. In these studies, the details of AGV routing and traffic control are ignored and only dispatching is studied.

While the literature contains many articles on container terminal operations, only a few studies focus on yard operations, and almost no studies propose systems for routing and dispatching YCs and YTs in real time.
Solution Methodology

To gauge the merit of the proposed yard control system and various algorithms for equipment dispatching, TLI – Asia Pacific developed a discrete event simulation model that tracks the detailed movement of each container passing through a container terminal over a period. The modular structure of this model allows different algorithms for YC scheduling, YC routing, and YT dispatching to be tested and compared. The main output from the simulation model is the average, long-run QC rate (i.e. GCR) that a given combination of YC scheduling, YC routing, and YT dispatching algorithms can sustain.

Model Framework

The simulation model has several noteworthy features. The model accommodates two container sizes (20’ and 40’). YT’s are allowed to haul up to two 20-foot containers at the same time. YCs can make inter-zone cross-gantry moves. Also, the number of active YT’s varies depending on the number of busy berths. Each QC handles containers according to a sequence that has some flexibility for some reshuffling of the order in which the lifts are performed. All containers enter the terminal by ship and all containers leave by ship; there are no gates. YC-YC interference is realistically modeled. In particular, all YCs are separated by a certain minimum distance (e.g. 8 slots = 170 feet) at any time. In the model, the traveling and handling times for all machines follow probability distributions. In order for one machine to pass a container to another machine, the status of both machines must meet a “handshake” protocol. Containers may be stored randomly or according to a yard template which pre-allocates certain storage locations for keeping cargo that is destined for only a small subset of vessels. Yard templates, if they are used, are constructed intelligently by a simulated annealing routine.
The yard control system has six different decision making modules: (A) a YC cross gantry decision module; (B) a multiple YC scheduling module; (C) an individual YC routing algorithm; (D) an individual YC routing on-the-fly algorithm; (E) a workcenter YT assignment algorithm; and (F) an individual YT dispatching algorithm. The general framework of the yard control system is shown in Figure 4 where the six decision modules are shown in light green rectangles. Arrows indicate how algorithms are triggered as events unfold inside the terminal. Module A is designed to handle YC cross gantry. Modules B, C, and D address YC dispatching within one yard zone. Modules E and F address YT routing.

**Major Components**

**Table 2: Major components in the simulation model**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td>The event-scheduling is used to make sure the time advances properly in the simulation model. There are two kinds of events: primary and secondary.</td>
</tr>
<tr>
<td>Job</td>
<td><em>Job</em> is central to the simulation model. A job is defined as the movement of a single container from yard to quay or vice versa. All active jobs are maintained in the simulation program.</td>
</tr>
<tr>
<td>Terminal status</td>
<td>Terminal status reflects the state of the container terminal at every instant of time. Every kind of asset and equipment also has its status.</td>
</tr>
<tr>
<td>Container group</td>
<td>A <em>container group</em> is the set of containers with the same length, weight class, destination port, and are loaded onto ships from the same liner service. This concept is used to control the loading and unloading sequence of containers.</td>
</tr>
<tr>
<td>Location</td>
<td>Locations refer to any stack/ground slot, any QC, or any YC cross gantry staging areas in the yard. Equipment is instructed to locations to pick up a job.</td>
</tr>
<tr>
<td>YT instruction</td>
<td>YT’s are instructed to go to a specific location, such as “QC 3, group 26 or group 778, Unload” and “ground slot 773, group 190, Retrieval.”</td>
</tr>
<tr>
<td>YC instruction</td>
<td>YCs are instructed to a specific ground slot followed by an action. Such as “ground slot 251, cross gantry to ground slot 2519”, “ground slot 2937, group 232, Retrieval” and “ground slot 1177, idle”.</td>
</tr>
<tr>
<td>QC instruction</td>
<td>QC’s are instructed to perform a certain type of operations (either unloading or loading) and the group the job belongs to. Such as “Loading, group 319” and “Unloading, group 9119”.</td>
</tr>
<tr>
<td>Handshake protocol</td>
<td>Handshake protocols are used for equipment interaction, and therefore enables containers to be passed from one kind of equipment to the other.</td>
</tr>
</tbody>
</table>

Table 2 presents the major components in the simulation model. It is written in C++ and uses events to drive the simulation program. The events are sorted by increasing time; thus, the first event in the program is the next event that occurs. There are two kinds of events: primary and secondary. A primary event generally (A) causes an immediate change in the state of the container terminal, (B) causes other events, some primary and some secondary, to occur immediately along with the primary event, and (C) causes other primary events to occur at some future time. The second major component is the job. The concept of a *job* is central to the running of the simulation program. A job is
defined as the movement of a single container (either 20’ or 40’) from yard to quay or vice versa. Throughout each simulation run, the program carefully maintains a list of all jobs that are currently active or are expected to be active in the near future. Terminal status reflects the overall condition of the terminal; it depends on (1) the operational status of every entity at the terminal, (2) the positions of all containers in the storage yard, (3) the schedules for each piece of equipment, and (4) the current status of the job list. Container group is a very important concept in the simulation program to control the order of container loading and unloading sequences. Containers in the same group should have the same length, weight class, destination port, and are loaded onto ships from the same liner service. Containers belonging to the same group can be considered indistinguishable for vessel loading purposes. Locations are used to mark places where a container can travel. There are three types of locations in the simulation program which denote (1) specific 20’ stacks (i.e. ground slots) in the yard, (2) specific QCs, or (3) specific YC cross-gantry staging areas in the yard. The remaining components in Table 2 are used to give instructions to different kinds of equipment and the way they can interact with each other. Normally, a machine is instructed to a location, with an assignment of loading or unloading, and a specific container group. When two machines interacts with each other, the instruction given to them need to match so that the hand over can be carried out seamlessly.

**Experimentation**

**Table 3: Container terminal specifications**

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berths</td>
<td>9</td>
</tr>
<tr>
<td>Vessel calls per week</td>
<td>90</td>
</tr>
<tr>
<td>Expected QC lifts per week</td>
<td>172,800</td>
</tr>
<tr>
<td>Yard blocks</td>
<td>90</td>
</tr>
<tr>
<td>Yard sections</td>
<td>10</td>
</tr>
<tr>
<td>Slots per block</td>
<td>42</td>
</tr>
<tr>
<td>Rows per block</td>
<td>6</td>
</tr>
<tr>
<td>Maximum stack height</td>
<td>6</td>
</tr>
<tr>
<td>QCs</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 3 gives the major specifications of the container terminal we considered in the experiments. All vessels calling at the terminal are the same size and unload almost the same number of containers. Vessels are not allowed to leave the terminal unless all of their boxes have been unloaded and loaded.

**Table 4: Number of policies considered**

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of YC cross gantry policies</td>
<td>3</td>
</tr>
<tr>
<td>Number of YC routing policies</td>
<td>12</td>
</tr>
<tr>
<td>Number of YT dispatching policies</td>
<td>4</td>
</tr>
<tr>
<td>Number of container storage policies</td>
<td>3</td>
</tr>
<tr>
<td>YT/QC ratios</td>
<td>3</td>
</tr>
<tr>
<td>YC/QC ratios</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4 shows the number of policies considered in the simulation program. Three YC cross gantry policies, 12 YC routing policies, 4 YT dispatching policies and 3 container storage policies are considered. In addition, different equipment ratios are also investigated: 3 YT/QC ratios and 4 YC/QC ratios are examined. Overall, 788 scenarios are considered in the experimentation.

Discussion

Among all scenarios inspected in the experimentation, the most influential policies are the YC routing policies and the container storage policies.

YC routing policies determine the instructions given to each YC. Based on job types, job locations and YC locations, all together 12 policies are devised for YC routing. Figure 5 depicts the performance of three different YC routing algorithms under different YC/QC ratios. The “1, 2, 3” on X axis represent three different YC/QC ratios; “” stands for the algorithm where all jobs are treated homogeneously; “” indicates the algorithm differentiates the job types and “” uses a more sophisticated schedule for YC dispatching. It can be observed that under different equipment ratios, as more pieces of equipment are employed, the performance for the three algorithms increases respectively. However, the marginal improvement diminishes as more machines are used. This is due to the increased YC-YC interference and physical limitations of a container terminal yard. On the other hand, different YC routing algorithms give notably different results when using identical resources. As shown in Figure 5, the performance increases when switch from treating all jobs homogenously to differentiating job types, and carefully schedule YC dispatching gives the best performance.

The container storage policy decides how containers are organized within the yard. Among the three storage policies proposed in this research, random storage policy performs best. Figure 6 presents the improvement (in red) after the storage policy is switched from clustered storage policy to random storage policy. The difference between the two policies is more significant when the YC/QC ratio is high. This indicates storing containers randomly reduces the impact of YC-YC interference and consequently, leads to a higher GCR.
Figure 7 shows the effects of changing the YC routing policy, storage policy and their combined effects under a particular combination of YC/QC ratio and YT/QC ratio. It can be observed that by solely changing the YC routing policy and storage policy, the improvement will be 3.66% and 5.49%, respectively. The combined effect of changing the two policies together will lead to an increase of 8.06% on GCR.
Under another combination of YC/QC and YT/QC ratios, the improvement of GCR is even larger. Figure 8 shows the results. In this combination of parameters, changing the YC routing policy gives 6.48% performance increase, and changing the storage policy incurs 8.87% improvement. Combined impacts lead to a quite impressive performance increase of 18.09% on GCR.

**Recommendations**

Based on the research carried out in this project, container terminal operational efficiency can be improved when:

1. The YC routing policy is chosen based on the YC/QC ratio and YT/QC ratio;
2. Yard retrieval operations are prioritized;
3. Random container storage policy is used.

**Conclusion**

In this project, TLI – Asia Pacific proposed a yard control system to automatically give routing and dispatching instructions to YCs and YTs at PSA Singapore, so as to maximize the GCR given a fixed number of YCs and YTs. This system handles the following three problems in real time:

1. Allocation of YCs to yard zones (inter-zone YC deployment);
2. YC routing and scheduling within each yard zone;
3. YT dispatching.

A discrete event computer simulation model was developed to track the detailed movement of every container passing through a container terminal during a certain period. The modular structure of the simulation model allows various algorithms for the above three problems to be tested independently.
and compared against each other. The main output from the model is the average quay crane (QC) rate (i.e. GCR) that a given combination of algorithms can sustain. In the experiments, TLI – Asia Pacific considered a massive container terminal with 9 berths, 90 yard blocks, 36 QCs, and 90 vessel calls per week. Three different container storage policies, three possible YT/QC ratios and four possible YC/QC ratios were considered. Different combinations of algorithms for Problems (1), (2) and (3) above were considered, with each combination giving rise to a different yard control system. Altogether, 788 scenarios were considered. The research results provide important insights of operational efficiency improvement for PSA Singapore.

The research conducted in this project is also applicable to other industries; although the setting might not be exactly the same, the principles are virtually identical.
References


