A Simulation Approach for Performance Evaluation of Proposed Automated Container Terminals

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Abstract—Boom in the world trade, scarcity of land for yard expansion in many ports, and deployment of new massive megaships have magnified the need for finding better ways of performing container terminal operations. High-density Automated Container Terminals (ACTs), with high operation efficiency and requiring less land, can thus become potential candidates for meeting future demand for higher capacity. In this paper, several high-density ACT systems are proposed and designed to meet the future projection made by several ports. A microscopic simulation model is developed and used to simulate the different ACT systems for the same operational scenario. The performance results and characteristics of the ACT systems are used as inputs to a cost model in order to compare their cost for meeting the demand for high capacity. The simulation results show that the proposed ACT systems can meet the future capacity demand of ports by requiring less land and at lower cost depending on various factors, such as the cost of land, labor etc. that are described and analyzed. The implementation of the proposed automated concepts will require additional studies where labor issues and concerns about job losses due to automation need to be addressed.

I. INTRODUCTION

Worldwide container trade is growing at a 9.5% annual rate and every major port is expected to have double or triple its cargo by 2020. To handle this amount of freight and reduce the cost per "twenty-foot Equivalent Unit" (TEU) slot, shipping companies are forced to order bigger ships. New massive container ships on one hand, and scarcity of the yard land on the other hand put an enormous pressure on port authorities to find and deploy effective container handling systems in order to increase the throughput of the current container terminals. One way to improve performance and efficiency and meet future capacity demands at ports without the use of additional land is to improve existing facilities by using advanced technologies. The application of information technologies and improvement of management are considered solutions that don’t require too much investment and changes of physical facilities [1]. Akio et al [2] developed an algorithm that deals with the berth allocation problem that minimizes the ship time at the port. Konings [3] addressed a concept of integrated centers for the transshipment, storage, collection and distribution of goods. In our previous work [4], [5], we investigated the use of automated guided vehicles and automated shuttles driven by linear motors for the movement of containers within the terminal and showed considerable improvements in capacity. In this paper, we address the design, modeling, simulation and evaluation of several ACTs that include AGV-ACT, LMCS-ACT, GR-ACT and AS/RS-ACT. A model is developed and used to simulate all the operations of the ACT down to the finest detail of the characteristics of each piece of equipment. The model is exercised for each ACT system based on the same operational scenario, i.e. based on the same incoming and outgoing traffic of containers at the interfaces. The operational scenario was developed based on expected future demand. Performance criteria that include throughput, ship turn-around time, etc. are used to evaluate each system and make comparisons. The paper is organized as follows: Section 2 presents the general layout of the proposed ACT, the operational scenario based on the projected demand and the performance criteria and cost model used to evaluate different ACT systems. Sections 3 present the design of the proposed AGV-ACT, LMCS-ACT, GR-ACT and AS/RS-ACT. In section 4 we compare and evaluate the proposed ACT systems and final section is a conclusion.

II. AUTOMATED TERMINALS

The general layout of the automated container terminals considered in this paper is shown in Figure 1.

![Diagram of Automated Container Terminals](image)

Figure 1: General Layout of Automated Container Terminals

Figure 1 shows the interfaces of the gate, the train and quay crane buffers with the storage yard. In the case of the AGV-ACT the storage yard is a collection of stacks separated by roads where the containers are stacked and served by yard cranes. AGVs are used to transfer containers within the terminal and the storage yard. In the case of the LMCS-ACT the storage yard is the same as in the case of the AGV-ACT system. The only difference is that shuttles driven on a linear motor conveyance system are used for the transport of containers. For the GR-ACT and AS/RS-ACT, the container storage yard in Figure 1 is replaced with a number of GR units and AS/RS modules. AGVs in these cases are used to transfer the containers between the GR (AS/RS) buffers and the gate, train and quay crane buffers.
The gate buffer is designed to interface between the manual operations (inland side) and the automated ones (internal terminal side). It provides a physical separation between the manual and automated operations for safety reasons and also for efficiency. It helps reduce the turnaround time for trucks by providing a temporary storage area for the export containers and the import containers waiting to be picked by trucks. The train buffer is the area next to the train where loading and unloading between the AGVs and the train takes place.

The design of the ACT and its characteristics such as storage capacity, number of gate lanes, number of berths, number of quay cranes etc are based on the future projection [6]. In another word, it depend on the expected volume of containers the ACT has to process, the ship/truck/train arrival rates and the volume of containers they carry etc. These considerations together with the type of available equipment could be used to specify and design the components of the ACT system in general and specifically for each concept.

The operational scenario is based on the projected demand of ports [6] and will be used to evaluate different ACT systems. It is summarized as follows:

**Ship Arrival Rate:** One ship every 24 hours to be unloaded and loaded with 6,800 TEUs in less than 24 hours (desired ship turnaround time 16 hours).

**Container Arrival/Departure Rate by Trucks:** Poisson distribution with a mean of 85 containers/hour.

**Container Arrival/Departure Rate by Trains:** 57 containers/hour.

- **Number of export containers, bound for one ship, arrived by trucks and trains**

<table>
<thead>
<tr>
<th>Container Arrival Times</th>
<th>2nd day before ship arrival</th>
<th>1st day before ship arrival</th>
<th>to be loaded on the ship directly</th>
</tr>
</thead>
<tbody>
<tr>
<td>by trucks</td>
<td>816 TEUs</td>
<td>2,940 TEUs</td>
<td>1,234 TEUs</td>
</tr>
<tr>
<td>by trains</td>
<td>544 TEUs</td>
<td>1,268 TEUs</td>
<td>816 TEUs</td>
</tr>
</tbody>
</table>

- **The cumulative numbers of export containers, arriving by trucks and trains every day**

  **by trucks:** 4,080 TEUs: 30% delivered to the ship directly without storing in the yard; 50% arrive one day and 20% arrive two days in advance of the bound ship.

  **by trains:** 2,720 TEUs: 30% delivered to the ship directly without storing in the yard; 50% arrive one day and 20% arrive two days in advance of the bound ship.

- **Number of import containers, unloaded from one ship and retrieved by trucks and trains**

<table>
<thead>
<tr>
<th>Same day while the ship is at berth</th>
<th>1st day after ship left the berth</th>
<th>2nd day after ship departed</th>
</tr>
</thead>
<tbody>
<tr>
<td>by trucks</td>
<td>1,224 TEUs</td>
<td>816 TEUs</td>
</tr>
<tr>
<td>by trains</td>
<td>816 TEUs</td>
<td>544 TEUs</td>
</tr>
</tbody>
</table>

- **The cumulative numbers of import containers that are retrieved by trucks and trains**

  **by trucks:** 4,080 TEUs: 30% retrieved directly from the ship without intermediate storage; 20% retrieved same day but after the ship departed; 30% retrieved from the storage yard (came one day ago); 20% retrieved from the storage yard (came two days ago).

  **by trains:** 2,720 TEUs: 30% retrieved directly from the ship without intermediate storage; 20% retrieved same day but after the ship departed; 30% retrieved from the storage yard (came one day ago); 20% retrieved from the storage yard (came two days ago).

The performance criteria that are used in this study to evaluate and compare different ACT systems are summarized as follows.

**Throughput:** The number of moves per hour per quay crane

**Throughput per acre:** The throughput per acre

**Ship turnaround time:** The time it takes for the ship to get loaded/unloaded in hours

**Truck turnaround time:** The average time it takes for the truck to enter the gate, get served, and exit the gate minus the actual processing time at the gate

**Gate utilization:** Percent of time the gate is serving the incoming and outgoing container traffic

**Container dwell time:** Average time a container spends in the container terminal before taken away from the terminal

**Idle rate of equipment:** Percent of time the equipment is idle

Costs associated with container handling and storage operations within a terminal can be classified into the following three categories:

- **Cost of Locations:** that is the cost of locations where activities (operations) take place, e.g. storage area, berth, etc.
- **Cost of equipment,** the cost of yard equipment e.g. yard cranes, quay cranes, AGVs, etc.
- **Labor costs**

A cost model based on the cost categories above for average cost per container (ACC) has been developed in our work [6] and it is used to evaluate the proposed concepts.

III. PROPOSED CONCEPTS

A. **AGVS-ACT**

Figure 2, shows the basic configuration of the proposed AGV-ACT system. In order to meet the desired storage capacity of about 22,000 TEUs [6] the size and layout of the storage is chosen according as follows: The storage yard consists of 36 stacks of containers and is divided into two sections. The import storage area where the import containers are stored and the export storage for export containers. Each stack has 288 containers when containers are stacked 4-high. It leads to the maximum capacity of the storage yard be 10,368 containers, i.e. 20,736 TEUs. In addition to the storage yard, containers can also be stored at the gate buffer whose maximum storage capacity is 1,728 TEUs giving a total storage capacity for the terminal of 22,464 TEUs, which is close to the desired capacity, and the terminal dimensions are calculated to be 1,633*1,875 ft² (70.29 acres). The terminal has strong similarities with existing terminals. In particular it has similarities with the Sea-Land terminal at the Port of Long Beach. Two types of
roads are used in the proposed container terminal: transit roads, and working roads. The transit roads are denoted by dashed lines and the working roads by solid lines. No loading or unloading takes place along the transit roads as these roads are used by AGVs to get to different points in the terminal. Loading and unloading take place along the working roads. The vertical four-lane transit roads allow direct access between the gate buffer and the berth in order to deliver containers between them without intermediate storage in the yard. A similar access is provided in the rail side. The terminal operates as follows: A truck arrives at the gate, it checks in and moves along the gate buffer where it gets unloaded by a yard crane. The truck is either empty or it gets loaded again at the buffer before exiting gates. The yard crane at the gate buffer loads the container directly to an AGV or if an AGV is not available it stores the container at the buffer temporarily. An export container loaded to an AGV at the gate buffer is either transferred directly to a quay crane to be loaded on the ship, or it is transferred to a particular stack to be unloaded by a yard crane and stored in the yard. Similarly, an AGV loaded with an import container by a quay crane transfers the container to the yard for storage or to the gate or the train buffer.

B. LMCS-ACT

The LMCS yard layout is identical to that of the AGV-ACT system of Figure 2 except that the paths are pre-built guide ways. For instance, a two-lane road in the AGV-ACT system becomes a two-guide way tracks that allow shuttles to travel in opposite directions. The shuttles can be considered as AGVs moving on a fixed path.

![Figure 2: AGV-ACT layout](image)

C. GR-ACT

The concept of loading and unloading containers in the yard using overhead rail and shuttles allows utilizing yard space more efficiently. It uses linear induction motors, located on overhead shuttles that move along a monorail above the terminal. The containers are stacked beneath the monorail and can be accessed and brought to the ship as needed. The concept of the overhead grid rail (GR) system was used to design, simulate and evaluate a GR-ACT system. The results developed in [7] are used here in order to compare the GR-ACT system with other automated systems. The GR-ACT system shown in Figure 3 is similar to that of AGV-ACT system with storage yard replaced with 8 GR units. The use of several GR units instead of a large one is done for robustness and reliability purposes as well as for simplifying the operations [7]. The number of units is chosen so that the storage capacity of the GR-ACT system is the same as that of the AGV-ACT and LMCS-ACT systems. Due to the high density of the GR units, however, less land is needed to obtain the same storage capacity. As a result the total size of the terminal is 1,472*1,875 ft² (63.36 acres) for the same storage capacity of about 22,000 TEUs.

The 8 GR units communicate with the other parts of the yard through the GR Gate/Train (G/T) buffers: 1a, 2a, ..., 8a and the GR quay buffers: 1b, 2b, ..., 8b. There are vertical transit roads between each two units. These transit roads are used for transferring containers—using AGVs—to/from the gate buffer directly to the berth area. The containers that have to stay in the yard are stored in the GR units. The units number 1, 2 and 7, 8 are used for storing import containers to be taken away by trucks and trains. The units 3, 4 and 5, 6 are used to store export containers brought in by trucks and trains. Note that in each unit only one operation can take place at each time. For example the shuttles within GR unit 1 can serve either the buffer 1a or 1b but not both at the same time.

![Figure 3: The GR Automated Container Terminal](image)

The interaction of the GR unit buffers with AGVs is as follows: One AGV in one cycle goes from gate or train buffer with an export container, unloads the container at the G/T buffer (either 3a or 4a) and travels empty to the G/T buffer (either 1a or 2a) where it is loaded by an import container and travels back loaded to the gate or train buffer. The AGVs at the rest four units are operating as follows: When the ship is present, an AGV in one cycle goes from the quay buffer (either 5b or 6b) with an export container, unloaded the container at the quay crane, loads an export container from the quay crane and travels to the GR quay buffer (either 7b or 8b) where it unloads the container to the quay buffer and travels empty back to the GR buffers 5b or 6b. When the ship is not present then the units 5, 6, 7, and 8 operate similar to the units 1, 2, 3, 4.
D. AS/RS-ACT

AS/RS with high-density storage capabilities could play an important role in the future container terminal activities. It can be built on a small piece of land and add capacity by increasing the number of floors. The promise in the high productivity of the AS/RS lies in its capability to have access to any container within the storage structure randomly, without having to reschedule containers.

An AS/RS module has four major components: Storage and Retrieval Machine (SRM), rack structure, horizontal material handling system, and planning and controls. The SRM simultaneously moves horizontally and vertically to reach a certain location in the rack structure. The original design of the AS/RS module consisted of only two racks served by an SRM [8]. It was found that one SRM for two racks was more than needed to achieve a certain input/output throughput. In an effort to meet demand and at the same time keep the cost low we modified the original design so that one SRM can serve 6 racks. Therefore, in each AS/RS module served by a single SRM we have 6 rack structures that are built to store containers. The SRM is designed to move from one set of two racks to another within the module. Each module has two buffers, one on each side. Each buffer has two slots, one for outgoing containers to be picked up by AGVs and one for incoming containers brought in by AGVs. These buffers are referred to as Pick-up and Delivery (P/D) buffers.

In this concept, we replace the import and export container storage area in the AGV-ACT system by AS/RS modules. As shown in Figure 4, the number of AS/RS modules is chosen so that the storage capacity is close to 22,000 TEUs. Assuming that each rack can store 120 (12*10 cells) containers and each AS/RS module consists of 6 racks, the storage capacity requirement of 10,368 TEUs can be achieved with 15 AS/RS modules. The total storage capacity of the AS/RS-ACT system is equal to 15 * 6 * 120 * 2 = 21,600 TEUs which together with the 1,728 TEUs that could be stored at the gate buffer it gives a total possible storage capacity of 23,328 TEUs and the dimension of AS/RS-ACT system 1,265*1,875 ft² (54.45 acres).

The lanes adjacent to the gate buffer and P/D buffers and the roads adjacent to the train/AGV interface are considered to be working roads, while all the other roads are transit roads. The two transit roads located on both sides of the AS/RS structure allow the direct transfer of containers that are not required to be stored in the yard. The containers that need to be stored (retrieved) in (from) the AS/RS structure are transferred by AGVs from (to) quay crane, gate and train buffers. One AGV in one cycle carries an export container from the gate buffer to an AS/RS module P/D buffer where it unloads the container and gets loaded with an import container that it transfers back to the gate buffer. Similarly, one AGV in one cycle goes from the berth area to a specific P/D buffer (on the ship side) with an import container, delivers it to the P/D buffer, gets loaded with an export container, which it transfers back to the berth area.

![Figure 4: Automated terminal yard layout using AS/RS](image)

IV. SIMULATION

The transfer of containers between different transportation modes and storage area to be carried out by the AGVs in each ACT system can be divided into three tasks.

**Task 1:** Under this task the following sub tasks are to be performed: 1) Transfer of containers between the quay crane and gate buffers. 2) Transfer of containers between the quay crane buffers and the storage area. 3) Transfer of containers between the quay crane and train buffers.

**Task 2:** Under this task containers are transferred between the gate buffer and the storage area.

**Task 3:** Under this task the containers are transferred between the train buffer and the storage area.

The terminal could be viewed as a network of intersections with nodes where loading and unloading takes place. In our design the AGVs are allowed to travel on the right lane of a two-lane road in their moving direction. Therefore, once the pick-up and drop-off points are assigned to a particular AGV, the path is uniquely determined by using the intermediate nodes and any possible conflict between AGVs needs to be resolved [6]. The number of quay cranes required to serve the ship with 3,400 40-foot containers (6,800 TEUs) is given by the relationship

\[ ST = \frac{3.400}{42} \frac{1}{NC} \]

where \( ST \) denotes the ship turnaround time, \( NC \) denotes the number of quay cranes and 42 is the speed of quay crane. We assumed a desired ship turnaround time of about 16 hours, which means that 5 quay cranes are required to meet the expected loading/unloading demand. The trucks are served according to a FIFO (first-in-first-out) service discipline and the arrivals are modeled as a Poisson process, with a constant arrival rate \( \lambda \). The mean service time of a truck at the inbound gates is assumed to be 3 min and at the outbound gates 2 min. Service times are assumed continuous random variables exponentially distributed with service rate \( \mu \) equal to 1/(mean service time). The minimum number of lanes \( n \) can be determined from the following inequality:

\[ \lambda/\mu < n \]
By assuming a 24-hour operation we find that the truck (inbound) arrival rate is equal to \( \lambda = 2,856/24h = 119/h = 1.98/\text{min} \). Then for \( \mu = 1/3 \) (assuming a 3 min service rate) we have \( \lambda/\mu = 1.98/0.33 < 6 \) which implies that a minimum of 6 lanes is required in the inbound-gate in order to meet the demand. The mean service time at the outbound-gates is assumed to be 2 minutes which gives \( \mu = 1/2 \) per min. The arrival rate at the outbound gate is equal to \( \lambda = 2,856/24h = 119/h = 1.98/\text{min} \) which is the same as the arrival rate at the inbound gates. Since, \( \lambda/\mu = 1.98/0.5 < 4 \) the minimum number of lanes in the outbound-gate required to meet the demand is equal to 4. The number of 6, 4, 2, and 1 lanes for the inbound and outbound gate respectively are the minimum possible. As the above inequalities are tight, the use of 6, 4 lanes at the gate will lead to a high utilization of the gate during the assumed scenario. Small deviations from the assumed arrival and departure rates may cause saturation at the gates that lead to congestion on both sides of the gates. In order to avoid such situations we increase the number lanes for the inbound-gate to 9 and for the outbound-gate to 6. The same characteristics of equipment used in each ACT system are summarized as follows:

- No. of Berths: 1
- No. of quay cranes: 5
- Capacity of quay cranes: 42 moves per hour (combined loading and unloading)
- No. of gate lanes: 9 inbound, 6 outbound
- Gates service time: 3 min inbound-gate, 2 min outbound-gate
- Capacity of yard cranes at buffer: Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 65 seconds to unload/load an AGV.
- No. of yard cranes at gate buffer: 6
- No. of yard cranes at Train buffer: 2
- No. of yard cranes at Import and Export storage yard: 36
- Speed of AGVs: 10 mph for empty, 5 mph for loaded AGVs

The additional equipment specific to each ACT system is:

- **AGV-ACT and LMCS-ACT:**
  - Yard cranes for import, export storage yard: We assume that one yard crane is used for each stack that is a total of 36 yard cranes are used in the yard.
  - Number of AGVs: The minimum number of AGVs that are required to meet the demand of the AGV-Act (LMCS-Act) system is determined by exercising the simulation model of the terminal for different combinations of AGVs. The objective is to have a sufficient number of AGVs to feed the quay cranes fast enough so that the cranes operate close to their maximum capacity. This in turn will guarantee that the ship turnaround time is minimized. We assume that the system is loaded, i.e., there are always containers ready to be processed by the AGVs at each buffer. While this scenario may not be true all the time, the system should have sufficient number of AGVs to deal with such possible extreme situation. The results of the simulations are presented in Figure 5. In Figure 5, the number of AGVs for tasks 1, 2 and 3 satisfy the ratio 6:3:1. For example, the simulation run that has 24 AGVs serving the quay crane buffer is the same simulation run for 12 AGVs serving the gate buffer and 4 AGVs serving the train buffer. As shown in Figure 5(a), 48 AGVs are sufficient to meet the maximum expected capacity of the quay cranes, which is 42 moves/hour/crane. Figure 5(b) and (c) show the throughputs of the cranes at the gate and train buffers.

![Figure 5](image)

**Figure 5:** (a) throughput of quay crane, (b) throughput of buffer crane and (c) throughput of train crane versus the number of AGVs used

The number of AGVs for each task is calculated by choosing the combination with the minimum total number of AGVs that meet the expected maximum demand for Tasks 1, 2 and 3. Considering that the maximum expected average throughput of the cranes at the gate and train buffers is 34 and 28.3 moves/hour/crane, it follows from Figure 5 that the combination (48,26,6), i.e. 48 AGVs for Task 1, 26 for Task 2, and 6 for Task 3, a total of 80 AGVs will meet the demand for the AGV-ACT system.

- **GR-ACT**
  - Speed of loading and Unloading the GR buffers: It is assumed that it takes 30 seconds with a 10% variance to load or unload a container to/from an AGV.
  - Number of shuttles: The number of overhead shuttles in each GR unit is 15.
  - Number of AGVs: Simulations were used to calculate the minimum number of AGVs that are needed in order to meet the demand. In Figure 6 the number of AGVs for tasks 1, 2 and 3 satisfy the ratio 6:3:1. The Figure shows that the combination (42,21,6) - i.e. 42 AGVs for Task 1, 21 for Task 2 and 6 for Task 3, a total of 69 AGVs - can meet the required demand for the GR-ACT system.

![Figure 6](image)

**Figure 6:** (a) throughput of quay crane vs. no. of AGVs, (b) throughput of crane at gate buffer vs. no. of AGVs and (c) throughput of train crane vs. no. of AGVs.

- **AS/RS-ACT**
  - Speed of loading unloading at the P/D buffers: In [8] the operations within the AS/RS module were optimized so that at the P/D buffers an AGV can be served (load it and unload it) within 45 seconds with 10% variance.
  - Number of AGVs: The AS/RS-ACT system was simulated with different combinations of AGVs performing tasks 1 to 3 in order to calculate the minimum number of AGVs that is necessary to keep the quay cranes operating close to maximum capacity. Figure 7 shows that the combination
(36, 14, 5) - i.e. 36 AGVs for Task 1, 14 for Task 2 and 5 for Task 3, a total of 55 AGVs - can meet the required demand for the AS/RS-ACT system.

![Figure 7: (a) throughput of quay crane vs. no. of AGVs, (b) throughput of buffer crane vs. no. of AGVs and (c) throughput of train crane vs. no. of AGVs](image)

### A. Performance Analysis

The equipment characteristics of each ACT system together with the container movements as mentioned in operational scenario are used as inputs to the simulation model. We assume that the patterns of container arrivals and departures to/from the terminal by ship, trucks and train are repeated every 24 hours so that a 24-hour simulation was sufficient to make projections about annual productivity. The results of a one-day (24-hour) simulation are shown in Table 4.1.

<table>
<thead>
<tr>
<th></th>
<th>AGV-ACT</th>
<th>LMCS-ACT</th>
<th>GR-ACT</th>
<th>AS/RS-ACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship turnaround time (hours)</td>
<td>16.81</td>
<td>16.83</td>
<td>16.47</td>
<td>16.24</td>
</tr>
<tr>
<td>Throughput of terminal, while the ship is at berth</td>
<td>40.45</td>
<td>40.40</td>
<td>41.68</td>
<td>41.7</td>
</tr>
<tr>
<td>Throughput of the terminal per acre</td>
<td>0.579</td>
<td>0.575</td>
<td>0.652</td>
<td>0.767</td>
</tr>
<tr>
<td>Gate utilization (%)</td>
<td>65.7</td>
<td>66.03</td>
<td>65.7</td>
<td>66.4</td>
</tr>
<tr>
<td>Truck turnaround time (sec)</td>
<td>127</td>
<td>127</td>
<td>120</td>
<td>110.7</td>
</tr>
<tr>
<td>Throughput (train crane)</td>
<td>29.4</td>
<td>29.4</td>
<td>28.6</td>
<td>30.6</td>
</tr>
<tr>
<td>Throughput (buffer crane)</td>
<td>33.7</td>
<td>33.7</td>
<td>35.7</td>
<td>38.32</td>
</tr>
<tr>
<td>Idle rate of AGVs</td>
<td>36.3%</td>
<td>36.3%</td>
<td>31.8%</td>
<td>39.9%</td>
</tr>
<tr>
<td>Idle rate of gate buffer cranes</td>
<td>12.7%</td>
<td>12.7%</td>
<td>10.8%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Idle rate of train cranes</td>
<td>23.0%</td>
<td>23.0%</td>
<td>31.9%</td>
<td>27.9%</td>
</tr>
<tr>
<td>Idle rate of quay cranes</td>
<td>31.7%</td>
<td>31.8%</td>
<td>31.8%</td>
<td>32.3%</td>
</tr>
<tr>
<td>Container dwell time (hours)</td>
<td>19.1</td>
<td>19.1</td>
<td>19</td>
<td>18.9</td>
</tr>
<tr>
<td>ACC (US$)</td>
<td>77.3</td>
<td>147.4</td>
<td>90.1</td>
<td>102.2</td>
</tr>
</tbody>
</table>

Since the number of equipment and vehicles in each ACT system is chosen so that the ACT system can meet the same demand it is not surprising that the performance for each system is almost identical for all measures with the exception of the throughput per acre. The highest throughput per acre was obtained for the AS/RS-ACT system since it requires less land to be implemented for the same storage capacity. Next comes the GR-ACT system that also requires less land for the same storage capacity.

The significant difference between the various systems is the average cost per Container (ACC). The LMCS-ACT was found to be the most expensive due to the high infrastructure cost associated with the LMCS. The second most expensive system is the AS/RS-ACT, due to the infrastructure cost of the AS/RS structure. The AGV-ACT system was found to be the most cost effective followed by the GR-ACT.

The ship turnaround time obtained from the simulations for each ACT is about 16 hours, which is close to desired one of 16 hours. It should be noted that the idle rate of the cranes is calculated over a period of 24 hours. Since the ship was at the berth for only about 16 hours, it means that the quay cranes were idled for 24-16=8 hours, which is 33.0% of the time. From simulations indicating that while the ship was at the berth the quay cranes were operating very close to maximum capacity. Similarly, after the ship is serviced the AGVs responsible for the task of serving the ship will be idle until the next ship arrives about 8 hours later. This accounts for most of the idle time for the AGVs.

### V. CONCLUSION

Four fully automated container terminal concepts are proposed, analyzed and evaluated. The results indicate that the capacity of existing terminals can be dramatically improved by using automation. Each concept is designed to meet the same demand. As a result the concepts share the same performance characteristics. The difference between the four concepts is in the land use and average cost for a moving a container through the terminal. The implementation of these concepts will require additional studies where labor issues and concerns about job losses due to automation need to be addressed.

### VI. REFERENCES