Comparing Different Technologies for Containers Movement in Marine Container Terminals

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Abstract—The explosive growth of freight volumes has greatly increased the work of seaports and urged the port authorities to adopt advanced technologies to cope with the booming container ships. Automated operations providing high efficiency have been considered as one of the ways to deal with this problem. Linear Motors Conveyor Systems (LMCS) and Automated Guided Vehicle Systems (AGVS) are the two candidate automation systems that can be used to improve the performance of yard operations. In this paper, simulation models of LMCS and AGVS employed in marine container terminals are developed to investigate the effect of automation and different cargo handling technologies. Yard performance measures are evaluated by Multi Attribute Decision Making (MADM) method to determine the optimal number of vehicles needed to be deployed. The simulation results show how the performance of the terminal increases when LMCS/AGVS are deployed. The differences between the two technologies, LMCS and AGVS, are also investigated using the developed simulation models.

Index Terms—Automation, Automated guided vehicles, Linear motors, Multi Attribute Decision Making, Marine terminals.

I. INTRODUCTION

The large increase in trade pushes the growth of container volumes transported by ships through seaports. For instance, the Port of Long Beach, USA has experienced 14% of container growth from 3.5 million TEUs (Twenty-foot Equivalent Unit) in 1997 to 4 million TEUs in 1998 and an increase of 7.6% over 1998 to 4.4 million TEUs in 1999. A continuing growth is expected in the near future. Furthermore, introduction of the post-Panamax container ships carrying increased number of containers puts the pressure on terminal operations to achieve higher level of efficiency.

It is well known that automation of tasks, i.e., yard operations, can increase the efficiency and reduce the operating cost [1]. LMCS and AGVS thus emerged as the candidates to be implemented in automated container terminals.

LMCS are currently used widely for smaller scale manufacturing applications, such as conveyance systems for sorting systems or assembly plants. However, the technology is scalable to larger tasks, such as maritime container terminal operations. The feasibility of employing this technology in maritime container terminals has been proved at Euroware Container Terminal in Hamburg, Germany, where a pilot of fully automated container yard was constructed in 1997.

With the improvement of computing power and vehicle sensor capabilities, the AGVS are implemented intensively in the manufacturing systems that conduct material handling and transporting items from one location to another. The automated guided vehicles (AGVs) are currently successfully used as yard vehicles that carry containers in the Port of Rotterdam, The Netherlands and the Thamesport, England.

The objective of this research is to investigate the advantages of automated yard operations over manual yard operations, and to compare the automated yard operations when two different technologies, AGVS and LMCS, are deployed at marine container terminals. MADM method is used to determine the optimal number of vehicles (that are called shuttles in LMCS and AGVS in AGVS) needed to be deployed in the proposed container yard. For the same system, several possible operation policies are simulated, and a performance decision criterion is applied to determine the optimal policy. In this research, the simulation models of two proposed systems are developed. In each system, the various numbers of deployed vehicles are simulated. The resulting performances of the two technologies are compared and analyzed.

This paper consists of six sections. Section 2 describes the operation of a manually operated container yard. In section 3, the operation of an automated container yard deploying two different technologies are discussed. Section 4, illustrates the criteria for performance evaluation. In Section 5, three examples used for the simulation of yard operations are presented and results are analyzed. The final section is the conclusion.

II. MANUALLY OPERATED CONTAINER YARD

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Norfolk International Terminal (NIT), USA, is used as a base scenario for manual operations. It is equipped with three quay cranes (QCs) with the capacities of 45 moves per hour. The terminal yard is divided into two main parts: the wheeled storage area and the gantry crane storage area. The wheeled storage area is used for short-term container storage and the containers in this area are mounted on chassis. The gantry crane storage area, which is closer to the dock than the wheeled area, is equipped with rubber tired gantry cranes which load and unload the terminal tractors (hostlers).

A simulation study [2] is performed to compare different scenarios of manually operated yard equipment at NIT. 7 rubber tired gantry cranes are used at the gantry crane storage area, 18 hostlers for serving the QCs and 7 hostlers for serving the wheeled storage area. The simulation study showed that the average productivity achieved under this scenario is 28 moves per hour per QC.

According to the analysis presented in [3], despite the fact that the average operating speed of manually operated hostlers is about 17 mph, a hostler moves approximately 6 containers/hour. That is the average time for a move, which thereafter is called Average Move Time, is about 10 minutes. A move is defined as the movement of a container from the initial pick-up point to a destination point (including the time the hostler waits to get loaded or unloaded). By using the fact that the average distance traveled by a hostler is 0.284 mile, it can be concluded that the Average Actual Speed (AAS) in mph of the hostler can be approximated as follows:

\[
AAS = \frac{\text{AverageDistance}}{\text{AverageMoveTime} - \text{LoadingTime} - \text{UnloadingTime}} = \frac{0.284}{0.167 - T_l - T_u} \tag{1}
\]

where \(T_l\) is the loading time, and \(T_u\) is the unloading time (in hours). These times are needed for the hostler to be loaded by the yard crane (YC) and unloaded by the QC.

III. AUTOMATED CONTAINER YARD

A. Linear Motor Technology

A linear induction motor operates on the same basic principles as a conventional rotary induction motor, except that instead of the coils being wound around a shaft, the entire assembly is "unwound" into a linear configuration. Running current through the unrolled, flattened stator moves a metal flat blank, which is placed above the stator, as though it is a rotor [4]. By controlling an array of linear motors that are placed underneath a platform, one can accurately move the platform (given that it is on a sliding or rolling surface).

Linear motor systems have several attractive characteristics: The motors are very reliable, and last a long time. Platforms, which are conveyed via linear motor technology, are unmanned, and have very few moving parts. The wheel assembly on the platform is the only moving part. Also, no power is required onboard the platform.

![Diagram](image)

**Fig. 1:** The layout of the container yard for LMCS.

1) Yard Configuration

The layout of proposed automated yard is designed similar to the current terminal yards (Fig.1). The dimension of the yard is about 700 feet (213.36 m) width and 1400 feet (426.72 m) length. The yard consists of two major parts: storage and dock area. Storage area consists of three blocks, and each block has six storage stacks. In each stack there are 20 columns and 6 rows which results in 2,160 cells in the yard. It is assumed that each cell can be stacked up to three containers. Therefore, the capacity of the yard is 6,480 TEUs.

Each pair of dotted lines in Fig.1, represents a road in the yard. In order to have smooth traffic for transferring containers within the yard, the roads are divided into two types: working road (WR) and transit road (TR). All transit and working roads for the left block are marked by T.R. and W.R. as shown in Fig. 1. To prevent heavy congestion and blocking, WRs are reserved for drop off and pick up activities, while TRs are used only to reach a specific WR or to reach the dock area. Shuttles are not allowed to enter any WR unless they need to perform the pick up or drop off task in that road. All roads in the yard are considered to be unidirectional and are installed with a one-way guidrail. The dispatch of shuttles is called static. That is, the path will not change once it is assigned to a shuttle.

In the storage area, a yard crane (YC) is assigned to each stack. As shown in Fig. 1, there are two roads (parallel to the ship) adjacent to each storage stack. The one further from the ship is referred as the corresponding adjacent WR. To make our proposed container yard comparable to the NIT, three QCs are deployed in the dock area. YCs are responsible for loading/unloading containers between storage stacks and shuttles in the corresponding adjacent WR, whereas the QCs are responsible for loading/unloading container shuttles to/from the ships. It is assumed that YCs and QCs serve shuttles based on the first come first served rule (FCFS).
Fig. 2a demonstrates the path to/from a typical cell (say X) in the proposed yard. Based on the description of the yard, the route from the dock area to cell X and from cell X to the dock area is uniquely determined. To reach cell X there are two possible directions to travel along: clockwise and counter-clockwise. The question is how to determine the direction of the movement on the route so that the traveling time on the selected path becomes shorter.

Assuming that there is no congestion on the route, let's model the path of Fig. 2a by a graph consisting of nodes connected by sets of arcs, as shown in Fig. 2b. The nodes represent the intersections and loading points on the path. Node 1 is the entrance/exit point to the block. Node 4, is the pick up node representing the location of the YC. Other nodes represent the intersection points.

![Diagram of the path](image)

Fig. 2: (a) The path to cell X in the container yard, (b) the associated graph.

An arc connecting two nodes represents a guide rail that a shuttle can move from one node to the other. There is a distance associated with each arc. The problem here is to assign the moving direction of each arc such that the total time that a particular shuttle needs to travel from node 1 to node 4 and goes back from node 4 to node 1 is the minimum. Let's define $d_{ij}$ as the distance between the two adjacent nodes $i$ and $j$. This distance is fixed and independent of the moving direction, i.e. $d_{ij}=d_{ji}$. Assume that the speed of the loaded shuttle, $v_l$, is smaller than that of the unloaded one, $v_u$, i.e. $v_u>v_l$. The problem of finding the shorter time direction can be formulated as follows:

$$
\min \left\{ t_{\text{unload}} + t_{\text{load}} \right\}_{\text{clockwise}} + t_{\text{unload}} + t_{\text{load}} \right\}_{\text{counter-clockwise}}
$$

(2)

where $t_{\text{unload}}$ and $t_{\text{load}}$ represent travel times of unloaded and loaded shuttles. Let's define $d_{124}=d_{23}+d_{34}$ and $d_{45}=d_{45}$. Knowing that $d_{ij}=d_{ji}$, Eq. 2 can be written as follows:

$$
\min \left\{ \frac{d_{124}}{v_u} + \frac{d_{45}}{v_l} \right\} + \left\{ \frac{d_{45}}{v_u} + \frac{d_{124}}{v_l} \right\}
$$

(3)

For any typical pick up point such as X in Fig. 2a, $d_{23}=d_{45}$ and $d_{23}>d_{45}$ which results in $d_{124}>d_{45}>0$. Knowing that $v_u>v_l>0$, we get the following inequality:

$$
(d_{124} \times \frac{1}{v_u} + d_{45} \times \frac{1}{v_u}) > (d_{124} \times \frac{1}{v_u} + d_{45} \times \frac{1}{v_l})
$$

(4)

Equation 4 indicates that for being able to travel on the shorter time direction in the loading operation, the unloaded shuttle should travel from node 1 to node 4 via nodes 2 and 3. After being loaded, the shuttle should continue its travel from node 4 to node 1 via node 5.

2) Control Logic for Container Shuttles

The purpose of the control logic for the container shuttle is to establish and maintain a desired sequence of events. When a shuttle is available, a container in the yard is assigned to the shuttle to be picked up. Meanwhile, the container number is added to the corresponding YC's queue. If there is no other container in the queue, the corresponding YC starts the process of loading operation.

The control logic of the LMCS needs to resolve possible conflicts and deadlocks in the movement. A conflict occurs when two or more vehicles require a common resource (road) at the same time. To resolve the conflict, a safety zone around each shuttle is applied such that no other shuttles are allowed to enter the zone. The priority is given to the shuttles that are traveling in the transit roads.

A deadlock occurs when a resource is shared by two machines and leads to a situation that none of the machines can continue its job. When two or more containers in one stack have been assigned to shuttles, it is possible that the shuttles arrive at the WR not according to the order of the containers in the YC's queue. To prevent this type of deadlock, the containers are reassigned to the shuttles as soon as the first shuttle arrives at the corresponding WR.

A shuttle arrives at the dock area, it selects a QC based on one of the following policies: (a) the minimum number of shuttles in its queue, (b) the minimum traveling distance between the shuttle and the QC. When a shuttle arrives at the dock area, it applies policy (a) to find the appropriate QC. If all QCs' queues are occupied with the same number of shuttles, then policy (b) is utilized.

B. Automated Guided Vehicle System Technology

AGVS is a hierarchical supervisory system and physically consists of vehicles, sensor devices, onboard computing devices, communication kits and host computers. The higher level control system located in the host computer coordinating and managing the movements of material handling devices such as YCs and AGVs is the key that make the whole system work. In contrast, the lower level control systems belonging to individual vehicles conduct the control of the navigation system and the driving system (e.g., motors, transmission, brake, etc.)

The conventional devices applied in navigation systems for the movement guidance of AGVs are inductive guide wire or optical visible line, painted or made with tapes on the floor. Recently, more advanced devices are available for
different applications, such as microwave transponders, camera vision system and differential GPS, etc.

1) Yard Configuration

The yard shown in Fig. 3 has three blocks and is almost the same as the yard used in LMCS technology, except that the roads have two lanes. In contrast to LMCS, no pre-built rail is required in this system. The roads used for transferring and loading/unloading containers are also called TR and WR and functions of TR and WR are exactly the same in both applications. In every block, the two-lane roads between container stacks are WRs. The roads that surround the blocks are TRs except the upper border roads, which are WRs.

Each container stack is divided into two parts, and each part contains three container rows. Adjacent to each part is a working lane, and this working lane is the only lane that can be used to load/unload containers to/from that part. The lanes in both working and transit roads are considered to be unidirectional lanes and the four-lane roads are actually two two-lane roads such that no AGV is allowed to cross the median between the two roads.

The lanes in the working roads can only be occupied by one AGV at a time to resolve the possibility of blocking. This means once a working lane is assigned for an AGV, no other AGVs will be assigned to that lane until the lane is declared empty. The dispatch of AGVs is also static.

It is assumed that each stack is equipped with one YC, and it is responsible for loading/unloading containers to/from the adjacent lanes to the stack. Therefore, if two AGVs occupy two lanes adjacent to a stack at the same time, the AGVs would be served by the YC based on FCFS rule. There are three QCs on the dock area, and the service rule of the QC is FCFS.

In LMCS, the shuttles are dispatched based on the shortest time paths between containers and QCs obtained from the Eqn.(2), while in AGVS, due to the constraint of unidirectional lanes, the paths between containers and QCs are unique and have the shortest distances.

2) Control Logic for AGVs

The control logic of AGVS is similar to that of LMCS. In AGVS, the traffic system is more complex as compared to LMCS and leads to more complex conflict resolution rules. There are three possibilities of conflicts. They are resolved by the developed algorithm as follows.

1. AGVs moving in opposite directions on the same path. A road has two lanes for opposite traffic, and each lane is unidirectional and AGVs are only allowed traveling on the right hand lane in their moving directions. This conflict is resolved.
2. Different speed of AGVs traveling along the same path. For simplifying the control logic, Low Speed Zones are designed to resolve this conflict. The speeds of all the AGVs in these zones have to be the same and equal to the lowest possible speed to avoid collision.

3. AGVs arriving at an intersection from different paths at the same time. A 'modified first come first pass' (MFCFP) concept, which is similar to the 'stop sign' rule in urban traffic is introduced. The difference to the 'stop sign rule' is that the AGV does not need to stop before an intersection if no other AGVs are in the intersection.

An AGV arrives at the dock area, and it selects a QC based on the minimum number of AGVs in the QC's queue. If all the QCs' queues have the same number of AGVs, then the QC with shortest distance is assigned to the AGV.

Fig. 3: The layout of the container yard for AGVS.

IV. EVALUATION OF YARD OPERATIONS USING MADM

In order to analyze simulation results, and to provide the required data for evaluating the yard performance some key concepts are defined as follows.

- **Definition 1:** Busy Period of a Vehicle. A vehicle is called to be in its busy period if it is in one of the following situations:
  1. Being served by either a QC or a YC.
  2. Traveling in the yard to load/unload an assigned container.

- **Definition 2:** Busy Period of a QC. A QC is said to be in its busy period if it is occupied with loading/unloading task.

- **Definition 3:** Busy Period of a YC. A YC is said to be in its busy period if it is occupied with loading/unloading task.

- **Definition 4:** Idle Period of a Vehicle, a QC, or a YC. A vehicle, a QC, or a YC is said to be in its idle period when it is not in its busy period.

- **Definition 5:** Idle Rate (IR). The idle rate ($IR_i$) of an equipment $i$ is defined as following.

\[
IR_i = \frac{\text{Idle Period (i)}}{\text{Busy Period (i)} + \text{Idle Period (i)}} \times 100\%
\]
Definition 6: Average Idle Rate (AIR). The average idle rate of $N$ pieces of equipment is defined as:

$$ AIR = \frac{\sum \text{IR}}{N} $$

Definition 7: Throughput. The average number of containers being loaded/unloaded per hour per QC is referred to as the throughput of the terminal.

The choice of the performance index would very much depend on the specific priorities of the terminal operation. In general, the performance index should be thorough and be a function of many weighted variables. The choice of these weights would depend on the specific terminal objectives. The MADM deals with problems that involve multiple criteria and it is suitable to be applied to evaluate the complex port operation systems.

MADM is a technique that tries to measure goal accomplishments by establishing reasonable “attributes”. Based on the chosen attributes, “Alternatives” are then constructed. Usually, all attributes are not of equal importance to a decision-maker so that every attribute is assigned with different appropriate weights [5].

Assume that the set of all attributes is $S = \{X_1, X_2, ..., X_I\}$, and the set of all alternatives is $\Psi = \{A_1, A_2, ..., A_I\}$. Also assume that the outcome of alternative $A_i$ with respect to attribute $X_j$ is $x_{ij}$, and $w_j$ is the weight for outcome $x_{ij}$. Then, $V(A_i)$, the value of alternative $A_i$ is defined as:

$$ V(A_i) = U_i(x_{i1}, x_{i2}, ..., x_{ij}, ..., x_{iI}, w_{i1}, w_{i2}, ..., w_{ij}) , \quad i = 1, 2, ..., I $$

(5)

The function $U_i: \mathbb{R}^I \times \mathbb{R}^I \rightarrow \mathbb{R}$ is the value generator for alternative $A_i$. The decision-maker then chooses the best alternative $A^*$, usually the minimum or maximum, from all alternatives as follows:

$$ A^* = \{A_i \mid \max_i V(A_i) \text{ (or } \min_i V(A_i)) \} , \quad i = 1, 2, ..., I $$

(6)

In this paper, we use one of the most widely used and best known MADM methods, Simple Additive Weighting Method (SAWM). In this method the relative importance weight is given to each attribute $X_j$ rather than to each outcome $x_{ij}$. Then, the SAWM can be written as follows:

$$ V(A_i) = \sum_{j=1}^{I} w_j x_{ij} , \quad i = 1, 2, ..., I $$

$$ A^* = \{A_i \mid \max_i V(A_i) \text{ (or } \min_i V(A_i)) \} , \quad i = 1, 2, ..., I $$

and

$$ \sum_{j=1}^{I} w_j = 1 . $$

(7)

The data are collected by simulating different number of vehicles deployed in the yard and the MADM is used to find the best performance index and determine the optimal number of vehicles. It is assumed that the overall terminal layouts are given (Fig.1&3), and the number of YCs and QCs is fixed. Then, it is obvious that the alternatives of SAWM should be the number of vehicles deployed in the yard, and the AIRs of the equipment in the yard are chosen as attributes. Therefore, in Eq. (7), the attributes are: ($x_{ij}$) the AIR of the QC, ($x_{ij}$) the AIR of the YC and ($x_{ii}$) the AIR of the yard vehicles.

V. SIMULATION

Due to the difficulty of implementing AGVS and LMCS, computer models as tools to simulate the AGVS and LMCS and/or the port related operations are widely used. Therefore, in order to evaluate performance and examine feasibility, development of simulation models is the first step towards implementation.

The manual operation of the container yard is simulated using the data provided in [2,3]. To simulate the automated yard operation, two technologies, LMCS and AGVS, are studied and compared. The following are assumed as characteristics of the equipment in the yard:

- Performance of the YCs:
  - Travel speed is 5 mph when move for loading/unloading container. It needs 15 sec. For lining up with the stack, and the average time of loading a container is 50 seconds.
  - Speed of the QCs: 75 moves/hour
  - Speed of loaded shuttles: 5 mph (2.24 m/s).
  - Speed of unloaded shuttles: 10 mph (4.48 m/s).
  - Time for shuttles to turn at corners: 5 seconds.

Simulation 1: (Manual Operations). 18 vehicles are deployed for loading operation. The AAS of hostlers is given in Eq. (1), and the speed of QCs and YCs are as described above. The throughput achieved in our simulation for this scenario is about 27 container per QC per hour which is comparable with the actual statistical data obtained at the NIT [1]. Our simulation results are compatible to that of the NIT due to the following factors:

(1) Despite the fact that the capacities of the QCs at the NIT are 45 moves per hour, the current average speed of QCs is about 30 moves per hour. Thus, the number of yard vehicles used cannot feed QCs at their capacity, and the time needed to load a hostler in the yard and to unload it by the QC is negligible compared to the time needed for the hostler to travel in the yard. Since the hostlers are traveling with average speed equal to AAS in Eq. (1) and the number of hostlers is the same as the ones considered in [2], the productivity of the two yards should be approximately

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*The speed of the QCs is based on current and expected performance of advanced cranes, which are either in use or in conceptual designs. The speed of the shuttle is chosen to be similar to that of the AGVs used at Rotterdam.*
the same despite the fact that the layouts of the two yards are slightly different.

**Simulation 2:** (LMCS technology) The yard configuration and control logic are as described in the last section. Different number of shuttles are deployed: 6, 9, . . . , 21 and 24. As shown in Fig. 4a, increasing the number of shuttles in the yard results in an increase in the yard throughput. However, the maximum throughput is about 72 containers per hour per QC, which is very close to the capacity of a QC. The difference is due to computational errors in the simulation.

**Simulation 3:** (AGVS technology) The yard configuration and control logic are as described in the last section. The different numbers of deployed AGVs are simulated. As shown in Fig. 4a, the maximum capacity of QC can be reached when 24 AGVs are deployed.

![Fig. 4: Simulation results of AGVS and LMCS.](image)

Although the throughputs of the two systems are almost the same as shown in Fig. 4(a), the AIRS of Vehicles, as shown in Fig. 4(d), vary significantly. This is due to the fact that shuttles need to spend longer time traveling between QCs and containers than AGVs, as the result of spending 5 more seconds in each turn. Although the AGVs spend shorter time traveling, the random arrival of AGVs under the QCs’s creates longer queuing times for AGVs that diminish the effect of shorter traveling time. The bigger AIR gives AGVS more room for improvement than LMCS. Comparing the throughputs of manual (simulation 1) and automated yard (simulations 2 and 3) operations, a double increase of the automated yard’s throughput is observed when 18 vehicles are deployed. This result shows that automated technologies can be used to improve the efficiency of yard operations.

To find the optimum number of vehicles for simulation 2 and 3, the SAWM is employed. The weighted penalties are presented in the form, $W = (w_1, w_2, w_3)$. Fig. 5(a) and (b) illustrate the values of alternatives, $V(A_i)$, for $A_i \in \Psi$, $\Psi = \{6, 9, . . . , 24\}$, with respect to different weight penalties. In graphs 1, 2, and 3 of Fig. 5(a) and (b) the optimum number of vehicles is found based on single criterion decision making. That is, using AIR of either QCs, $W = (1, 0, 0)$, or YCs $(0, 1, 0)$, or vehicles $(0, 0, 1)$ as weights, leads to choosing either the maximum or the minimum number of vehicles in $\Psi$. In graphs 4, 5, and 6 in Fig. 5(a) and (b), all three attributes are taken into account and for both systems the number of vehicles which minimizes the performance index is around 21.

![Fig. 5: Yard performance of (a)LMCS (b)AGVS with respect to different weight penalties.](image)

**VI. CONCLUSION**

When big container ships are loaded/unloaded in the fast growing marine container terminals, employing LMCS or AGVS technologies can increase terminal throughputs.

In this paper, the simulation models of LMCS and AGVS employed in the proposed yard layout are developed. Based on the simulation results, an automated yard using LMCS/AGVS has almost double throughput of the manually operated yard. Thus, to implement LMCS/AGVS at marine container terminals to replace the conventional manual operation could be very useful. In addition, although LMCS and AGVS have roughly the same throughput, the high AIR rate of AGVs asserts that AGVS has more room for improvement. For loading operation in both systems, MADM approach gives the optimal number of vehicles, 21, that needs to be deployed.

**VII. REFERENCES**


