Integrated Scheduling of Quay Cranes and Automated Lifting Vehicles in Automated Container Terminal with Unlimited Buffer Space

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Abstract. Nowadays, role of sea port container terminals in national and regional transportation and economy cannot be omitted. To respond enormous and every increasing demand on sea transshipments within the same time frame, terminal managers require more and more efficiency in container performance and operations. Automation of the processes at the quays of the container ports is one the solutions to improve the performance and output of container terminals. For such purpose, using new generation of vehicles is unavoidable. Automated Lifting Vehicle (ALV) is one of the automatic vehicles that has been introduced during recent years and can be used in container terminals. In this paper, an integrated scheduling of quay cranes and automated lifting vehicles with unlimited buffer space is formulated as a mixed integer linear programming model. Our objective is to minimize the makespan of all the loading and unloading tasks for a pre-defined set of cranes. Obtained result from our scheduling model is compared with an Automated Guided Vehicle (AGV) inspired from the same problem.

Keywords: Automated container terminal, Quay crane, Automated lifting vehicle, Unlimited buffer space, Integrated scheduling.

1 Introduction

Maritime transport is one the essential supports for globalization and a huge portion of international trade is being transported through the ports. Due to the significant role of maritime transports major ports are expected to increase their cargo capacity to two or three times more by 2020 [1].

Containers are suitable, safe, secure and efficient carriers for storage and shipping of products and materials in sea transport. A shipping container is a box that is designed for door to door delivery of the goods without physical handling of the

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contents [2]. Container as a necessary part of a unit load concept has achieved a certain place in global sea cargo transportation. Nowadays, containers transport more than 60% of the world's deep-sea general cargo, especially between economically stable and strong countries [3]. As a result of the continuing increase of container trade, many sea terminals are equipped to serve the containerships and competition between major seaports and container terminals is becoming more and more. So it is important for port operators to develop different optimization algorithms and decision tools to improve their performance and competitiveness. The competitiveness of a container seaport is defined by different success factors, especially fastness of the loading and unloading activities. So it is essential that a terminal can receive, store, and dispatch containers efficiently and rapidly [4].

To increase efficiency of the container terminals, it is necessary to coordinate different terminal equipment to ensure a correct flow of containers within the terminal. Container activities can be categorized into: export, import and transshipment activities. In export activities, the containers are being shipped and stored at their predefined locations in the storage yard. For loading the containers, yard cranes (YC) will retrieve them from the stored locations and vehicles transport the containers to the quay side. Then quay cranes (QC) receive containers from the vehicles and load them into the vessels. The processes for import activities are performed in the same manner but in the reverse order. For transshipment activities, after unloading from the vessel, containers will be stored in the storage yard and finally be loaded onto other vessels.

Problems related to operations and activities in container terminals can be divided into several types of problems, such as assignment of vessels [5], loading or discharging and storage of the containers in marshaling yard [5], scheduling of quay cranes [6], planning of YCs [7] and assignment of storage places to containers [8].

In automatic container terminals, several types of vehicles can be used for handling and transferring the containers in the yard. Two different types of automatic vehicles that being used are: Automated Guided Vehicle (AGV) and Automated Lifting Vehicle (ALV). An AGV can receive a container from quay crane and transport it over a fixed path. In such situation, a yard crane should take the container off the vehicle. ALVs are capable of lifting a container from the ground by themselves. Because of such capability, in terminal, buffer areas are defined at QC in apron and transfer point (TP) in the yard to help loading and unloading process for ALVs. ALV receives the container from a buffer area and carries it to its destination.

Compared to AGVs, only few prior researches have involved ALVs. Vis et al. [9] has compared the performance of AGV and ALV, as two types of known automated vehicles, by a simulation study. They concluded that, by observing purchasing costs and initial essential investment for equipments, ALVs are the cheaper options than AGVs (in some cases 38% less ALVs need to be used than AGVs). Nguyen and Kim, [10] developed a mixed programming model for the optimal assignment of delivery tasks to ALVs. They have proposed a heuristic algorithm to solve their model. Le et al. [11] have used DCA for solving their model.

In this work, the authors consider some of constraints similar to the Nguyen's model [10]. Minimizing makespan is objective of our model that is also used by Homayouni et al. [12] for dispatching of AGVs in container's terminal. In the proposed mixed zero-one programming model of this study, unlimited buffer space for QCs is considered and so the delay of ALVs and QCs for lack of empty buffer space will not occur.

2 Problem Definition and Mathematical Model

2.1 Problem Definition

The handling activities can be divided into two parts, one portion of these activities which are performed by QCs are known as seaside operations, and another part that will be done by ALVs is called landside operations.

Before starting of ship operations, shipping agent prepares a guideline for loading and unloading operations based on the schedule of QCs. According to the guideline and work schedule, a sequence list will be issued that determines the sequence of unloading and loading operations for all the containers. In most of the times, actual ship operations follow the specified order in sequence list. So we can consider that sequence and delivery operations of ALVs are predefined and known in advance.

The function and duty of an ALV for unloading tasks is delivering a container from the apron to the yard, and for loading operations it should carry the container from the yard to the apron. During the unloading operation, QC picks up a container from the prow and delivers it into the buffer space. In container terminals with limited buffer spaces, when the buffer is full, ALV or QC must wait for releasing a container on buffer space. In our problem, we have considered unlimited buffer space for QCs and therefore delay of ALVs and QCs for lack of empty buffer space is eliminated. When QC delivered the container to the buffer, ALV picks up the container from the buffer and delivers it to the marshalling yard. In the marshalling yard, ALV releases the container to the specified and available transfer point (TP) of the yard. An AYC picks up and stacks container onto an empty and predefined place in bay. The loading operation is performed in the reverse order.

2.2 Mathematical Model

During developing the model, the authors assumed that YCs are not known as the bottle neck of the container terminal. It means that the vehicles can be served by the YCs immediately, and yard cranes are ready to pick up the imported containers without any delay. Also the exported containers are ready and available to be delivered to the ALV while it reaches the loading or unloading place.

The ALV's journey starts from predetermined loading/unloading station and finishes with coming back to the initial position. In the proposed model we have assumed that QCs are far enough from each other and there is enough and unlimited space for buffers in apron. In other words, quay cranes and ALVs can release the container to buffer as soon as reach the place. Some other assumptions in the formulation of the problem are as follows:

- Each ALV transports only one container at each time.

- All ALVs are same in capacity and shape, thus they are neither assigned to a specific kind of container nor to a crane.
- ALV's Congestions are not considered in the model.
- Operation time of ALV or QC for pick up and releasing the container is small enough and can be neglected.
- Travel times of ALVs, travel time of cranes between the quay and the vessel area (TQ) and its operation time (OQ) is deterministic and predefined.

The following notations are used in the proposed Mixed-Integer Programming (MIP) model for dispatching of ALVs:

V	The set of ALVs.
K	The set of QCs.
m_k	The number of tasks determined for QC_k , $k \in K$.
m_l	The number of tasks for ALV_l , $l \in V$.
T_i^k	The ith operation of QC_k , $k \in K$, $i = 1, \dots , m_k$.
y_i^k	The real completion time of T_i^k, $k \in K$, $i = 1, \dots , m_k$.
s_i^k	The earliest possible completion time of T_i^k, $k \in K$, $i = 1, \dots , m_k$.
K	$\{0\} \cup K$.
K''	$\{F\} \cup K$.
C_j	Cycle time of ALV_j , $j \in V$.
c_{ki}^{lj}	The travel time between QC_k and QC_l including required time for the ALV to be ready for T_j^l after it experiences T_i^k, $k \in K', l \in K''$, $i = 1,2, \dots , m_k$, $j = 1,2, \dots , m_l$.
x_{ki}^{lj}	The decision variable that becomes 1 if T_j^l be executed directly after T_i^k by the same ALV, $k \in K'$, $l \in K''$, $i = 1,2, \dots , m_k$, $j = 1,2, \dots , m_l$.
M	A big positive number.
OQ	The operational time of quay cranes.
TQ	The travel time of quay cranes between the ship and the quay area.
L	The set of loading tasks.
U	The set of Unloading tasks.

The problem of scheduling of lifting vehicle to transfer containers in an automated port container terminal with unlimited buffer space is a static scheduling and assignment problem for ALVs to accomplish all the delivery tasks without any limitation for buffer capacity. The objective function of the developed model is as below:

$$\text{Minimize } Z = Makespan \tag{1}$$

Different objective functions can be defined to improve the transfer and traveling of containers but in this model we have focused on minimizing the makespan of all loading and unloading tasks in a specific scheduling horizon (1). The makespan of tasks is the completion time for latest journey of the ALVs to the final destinations. Minimizing the makespan of ALVs will result in decreasing the completion time and delay of the quay cranes. Constraints for this model are described as follows:

$$\mathrm{C_j} - \left(\mathrm{y_i^k} - \mathrm{TQ} - \mathrm{OQ} + \mathrm{c_{ki}^{fj}}\right) \geq \mathrm{M}\left(\mathrm{x_{ki}^{fj}} - 1\right), \forall \mathrm{k} \in \mathrm{K}, \mathrm{j} \in \mathrm{V}, \quad \mathrm{i} = 1,2,\ldots,\mathrm{m_k}, \ \mathrm{T_i^k} \in \mathrm{L} \tag{2}$$

$$\mathrm{C_j} - \left(\mathrm{y_i^k} + \mathrm{c_{ki}^{fj}}\right) \geq \mathrm{M}\left(\mathrm{x_{ki}^{fj}} - 1\right), \forall \mathrm{k} \in \mathrm{K'}, \mathrm{j} \in \mathrm{V}, \mathrm{i} = 1,2,\ldots,\mathrm{m_k}, \ \mathrm{T_i^k} \in \mathrm{U} \tag{3}$$

$$\mathrm{Makespan} \geq \mathrm{C_j} \qquad \forall \mathrm{j} \in \mathrm{V} \tag{4}$$

$$\sum_{\mathrm{l} \in \mathrm{K''}} \sum_{\mathrm{j}=1}^{\mathrm{m_l}} \mathrm{x_{ki}^{lj}} = 1, \forall \mathrm{k} \in \mathrm{K'}, \mathrm{i} = 1,2,\ldots,\mathrm{m_k} \tag{5}$$

$$\sum_{\mathrm{k} \in \mathrm{K'}} \sum_{\mathrm{i}=1}^{\mathrm{m_k}} \mathrm{x_{ki}^{lj}} = 1, \forall \mathrm{k} \in \mathrm{K''}, \mathrm{j} = 1,2,\ldots,\mathrm{m_l} \tag{6}$$

$$\mathrm{y_i^k} \geq \mathrm{s_i^k}, \forall \mathrm{k} \in \mathrm{K'}, \mathrm{i} = 1,2,\ldots,\mathrm{m_k} \tag{7}$$

$$\mathrm{y_{i+1}^k} - \mathrm{y_i^k} \geq \mathrm{s_{i+1}^k} - \mathrm{s_i^k}, \forall \mathrm{k} \in \mathrm{K}, \mathrm{i} = 1,2,\ldots,\mathrm{m_{k-1}} \tag{8}$$

$$\mathrm{y_j^l} - \mathrm{A} \geq \mathrm{M}\left(\mathrm{x_{ki}^{lj}} - 1\right), \forall \mathrm{k} \in \mathrm{K'}, \forall \mathrm{l} \in \mathrm{K''}, \forall \mathrm{i} = 1,2,\ldots,\mathrm{m_k}, \quad \forall \mathrm{j} = 1,2,\ldots,\mathrm{m_l} \tag{9}$$

$$\mathrm{x_{ki}^{lj}} = 0 \text{ or } 1, \forall \mathrm{k} \in \mathrm{K'}, \mathrm{l} \in \mathrm{K''}, \mathrm{i} = 1,2,\ldots,\mathrm{m_k}, \mathrm{j} = 1,2,\ldots,\mathrm{m_l} \tag{10}$$

Constraints (2) and (3) define the cycle time of ALVs, including the time that the ALV delivers the last container to destination, and the travel time of its last journey to the assigned final location. In loading operations, the quay crane continues its task after receiving the container and the ALV is allowed to continue its travel, so for calculation of cycle time, *OQ* and *TQ* should be deducted. Depend on the current duty and previous assigned task to a specific ALV, c_{ki}^{lj} can be different. More details for calculation of c_{ki}^{lj} are presented in Table 1. In this table *S, F, L* and *U* represent the

Start, Finish, Loading and Unloading tasks and *a*, *b* and *c* are ALV traveling times between QCs and TPs.

Table 1. Calculation for c_{ki}^{lj}

T_i^k	T_j^l	c_{ki}^{lj}
S	L	$a+b$
S	U	a
L	L	$a+b$
L	U	a
L	F	a
U	L	$a+b+c$
U	U	$a+b$
U	F	$a+b$

Constraint (4) shows that makespan is the largest cycle time of the ALVs calculated through formula (2) and (3). Constraints (5) and (6) ensure a one to one relation between two sequential tasks including the initial and final journeys of the ALVs. Constraint (7) expresses that the actual completion time is always greater than or equal to the earliest possible completion time. Constraint (8) defines that between two tasks assigned to a specific QC, there should be enough time for the QC to perform all the required movements. Constraint (9) indicates that the y_j^l is depended on y_{j-1}^l and y_i^k. In other words, completion time of T_j^l on QC_j is related to previous duty of the ALV and completion time of prior assigned task to the QC. Based on current operation of QC and different characteristics of the T_i^k and T_{j-1}^l , this parameter varies. More detailed calculation for y_j^l is presented in Table 2. The "Max" function in this constraint can be separated into two inequalities to make a linear set of constraints. Constraint (10) defines x_{ki}^{lj} as binary decision variable.

In this model *Makespan*, C_j and y_i^k will be obtained during solving the model and through the calculations depend on which x_{ki}^{lj} s get 1 value and which one be 0. A feasible solution is a one to one assignment between all the start and finish sets, represented by a series of x_{ki}^{lj} s. The start set is included starting events of ALVs and events related to the transfer operations by ALVs. And the finish set includes the stopping events of ALVs and events for delivery tasks of ALVs.

Table 2. Calculation for Constraint (9) on *A*

T_i^k	T_{j-1}^l	T_j^l	A
L	L	L	$Max(y_{j-1}^l + TQ\ , y_i^k - TQ - OQ + c_{ki}^{lj}) + TQ + OQ$
U	L	L	$Max(y_{j-1}^l + TQ\ , y_i^k + c_{ki}^{lj}) + TQ + OQ$
L	U	L	$Max(y_{j-1}^l\ , y_i^k - TQ - OQ + c_{ki}^{lj}) + TQ + OQ$
U	U	L	$Max(y_{j-1}^l\ , y_i^k + c_{ki}^{lj}) + TQ + OQ$
U/L	L	U	$y_{j-1}^l + TQ + OQ$
U/L	U	U	$y_{j-1}^l + 2TQ + OQ$

3 Numerical Experiments and Discussion

For comparison of the proposed model for dispatching of ALVs with unlimited buffer space by the same problem with AGV, a set of test cases is considered. 10 test cases are planned in a typical automated container terminal containing six transfer points in yard and six quay cranes in apron. In the generated test cases, the number of operations for each QC, the number of QCs and the number of ALVs range from 4 to 7, from 2 to 3 and from 3 to 4, respectively.

The travel times of ALVs between all combinations of QCs and TPs shown in Table 3 are same as traveling times that presented by Lau and Zhao [13].

Table 3. ALV traveling times between combinations of QCs and TPs (s) [13]

	QCs						TPs					
	0	1	2	3	4	5	6	7	8	9	10	11
0	022	302	602	902	120	150	155	852	115	145	175	205
1	80	0	30	60	90	120	85	55	85	115	145	175
2	110	80	0	30	60	90	115	85	55	85	115	145
3	140	110	80	0	30	60	145	115	85	55	85	115
4	170	140	110	80	0	30	175	145	115	85	55	85
5	200	170	130	110	80	0	205	175	145	115	85	55
6	55	85	115	145	175	205	0	80	110	130	170	200
7	85	115	145	175	205	235	30	0	80	110	140	170
8	115	145	175	205	235	265	60	30	0	80	110	140
9	145	175	205	235	265	295	90	60	30	0	80	110
10	175	205	235	265	295	325	120	90	60	30	0	80
11	205	235	265	295	325	355	150	120	90	60	30	0

The *OQ* for unloading and loading tasks is set to 20 s and the *TQ* is equal to 10 s for loaded or empty journeys. Table 4 shows details of test cases and the comparative results for ALV and AGV. In the first column, number of tasks, number of QCs, number of TPs and number of ALVs for each case are presented. Defined sequence of loading and unloading tasks for each quay crane and objective value for ALV and AGV are shown in column 3, 4 and 5. Also, the objective values are compared in the last column. All the tests for the ALV and AGV were solve by branch and bound algorithm and programmed in Lingo® software.

Table 4. Test cases and comparative results

T-QC-TP-ALV	QC No.	Task Type	ALV (A)	AGV (B)	Ratio (=A/B)
8-2-2-3	1,2	U,U,U,L; U,L,U,U	150	315	0.47619
8-2-2-4	1,2	U,U,U,L; U,L,U,U	125	290	0.43103
10-2-2-3	4,5	U,U,L,L,L; L,U,L,U,L	190	245	0.77551
10-2-2-4	4,5	U,U,L,L,L; L,U,L,U,L	150	205	0.73171
12-2-2-3	2,3	U,U,L,L,U,L;U,L,U,L,U,L	290	435	0.66667
12-2-2-4	2,3	U,U,L,L,U,L;U,L,U,L,U,L	220	365	0.60274
12-3-2-3	2,3,4	U,U,L,L;U,L,U,L;U,L,U,L	160	395	0.40506
12-3-2-4	2,3,4	U,U,L,L;U,L,U,L;U,L,U,L	130	330	0.39394
14-2-2-3	2,3	U,U,L,L,U,L,U;L,U,L,U,L,L,U	250	360	0.69444
14-2-2-4	2,3	U,U,L,L,U,L,U;L,U,L,U,L,L,U	195	320	0.60937

From numerical results, and as it can be seen in Fig.1 we observe that in all the test cases, ALV with unlimited buffer space has better results than AGV and in each case, as we expected, by increasing number of ALVs we have better and less makespan.

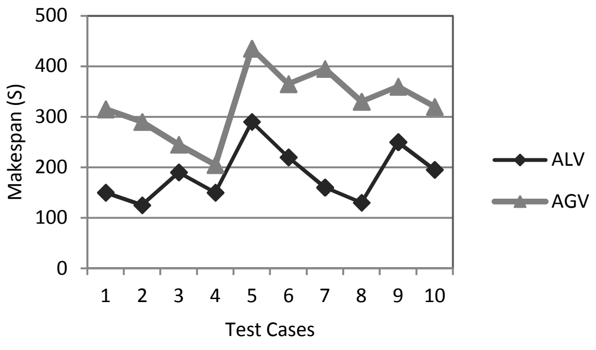

Fig. 1. Comparative results of test cases

4 Conclusion

This paper developed and discussed a static model for dispatching of ALVs to load or unload a predetermined number of containers in automated terminals with unlimited buffer spaces. The problem was formulated as a Mixed Integer Linear Programming (MILP) model to minimize the makespan of all transport tasks. The makespan is largest cycle time among the all ALVs to perform their assigned journeys from the initial locations to the final destinations. This objective function will decrease both the completion time of the QC tasks and ALV's traveling time. The authors considered test cases to evaluate performance of their model and compare the results by same problems with AGV. The obtained result shows that in all considered cases, ALV with unlimited buffer spaces has better performance than AGV.

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