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Research on the Planning of High-efficiency Shortcut Path for Rechargeable AGV

Siyu Zhao*, Jin Zhu

Institute of Logistics Science and Engineering, Shanghai Maritime University, Shanghai 201306, China
Email: 354025019@qq.com

Abstract: *To improve the loading and unloading efficiency of container terminals, the operation of the automated guided vehicle AGV is the key. However, the path planning, charging, resource allocation and other issues that exist in the operation of AGV have affected the efficiency of the automated terminal. Therefore, it is necessary to establish an effective data model, plan the best driving path, and realize the conflict-free charging and operation of the AGV. Experiments have proved that when charging is considered, it can reduce the running time of the AGV between the quay crane and the yard bridge, increase the operating speed of the AGV vehicle, and improve the operating efficiency of the automated terminal.*

Keywords: *automated container terminal, automatic guided vehicle (AGV), AGV charging, route planning, running time*

1. Introduction

In order to improve the efficiency of loading and unloading of automated terminals, Automated guided vehicles (hereinafter referred to as AGVs) are important equipment connecting quay bridges and field bridges, and play a key role in the operational efficiency of the terminal. AGV operating efficiency is related to the path planning, charging, and resource allocation of the AGV. How to take these factors into consideration and provide solutions is the key to improving the efficiency of the automated terminal.

In the horizontal transportation of automated container terminals, many domestic scholars have studied path planning. Ge Zhiyuan [4] took AGV as the research object and studied the AGV path planning and the dynamic coordination between multiple AGVs. Aiming at the AGV problem, firstly, an improved ant colony algorithm is used to solve the AGV path planning problem. Regarding collision avoidance, Yang Yajie [3] and others set the compatible and conflicting phases of intersections so that AGVs in compatible phases can pass through at the same time. Regarding the problem of AGV charging, Zhang Yaqi [5] and others considered the impact of the AGV charging process on the actual operation, with the goal of maximizing the AGV charging utilization rate, minimizing the completion time of the final task, and minimizing the AGV dead time. A scheduling model for automated terminal AGV operations in the charging process.

To sum up, in recent years, the research on AGVs has mainly focused on path planning and charging waiting time, but these studies have only solved a single problem in the operation of AGVs, and have not considered AGV path planning and charging. The innovation of this paper is to consider the number of charging piles and AGV vehicles and path planning in a unified way, and use algorithms to find the best value.

2. Problem description

The automated container terminal is composed of a quay crane operation area, an AGV horizontal operation area, and a yard container area. This article adds loading and unloading buffer and AGV charging area. The operation process of the entire container is shown in Figure 1. The AGV loads imported containers from the buffer zone of the quay crane to the buffer zone on the front side of the bridge for unloading. When the power is sufficient, it will return according to the planned route and process the next container. When the power is lower than the set value, go to the AGV charging area for charging operations. Then the AGV operates in accordance with the original working line. The problem

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that needs to be solved is the operation of multiple AGVs, the priority setting of loading and unloading tasks and charging, the path planning of the AGV, and the establishment of a mathematical model.

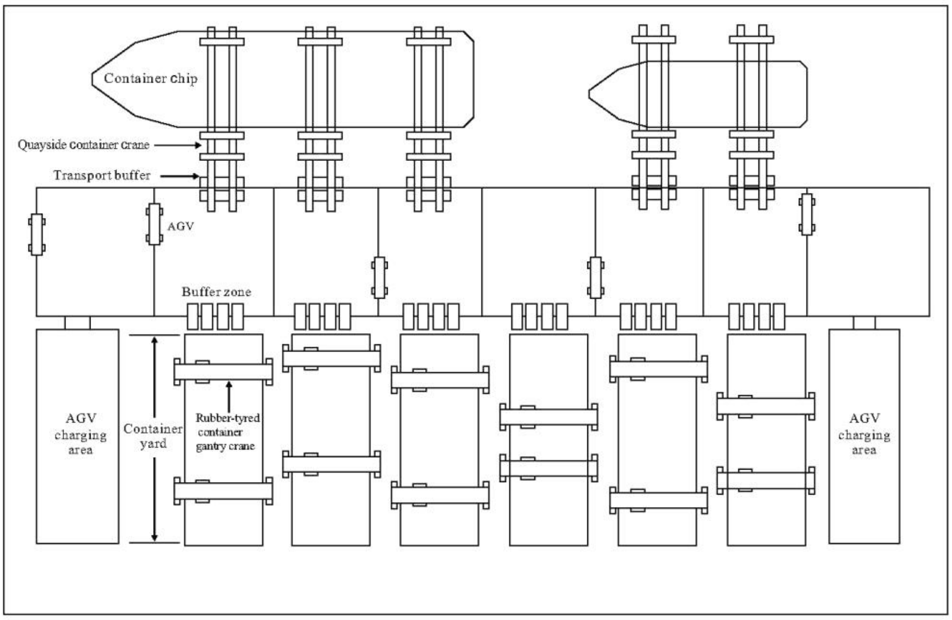

Figure 1. Aerial view of automated container terminal

3. Model establishment

Based on the shortest AGV driving path between the quay crane and the yard bridge, this model considers the charging of the AGV vehicle and plans the best path.

3.1. Model assumptions

In order to facilitate the solution and analysis of the problem and to comply with the container terminal operating rules, corresponding assumptions are made on the problem.

(1) The time for the quay crane to process a single container task is fixed.

(2) The time for the AGV to take the container from the quay crane and the yard bridge is negligible.

(3) The AGV travels at a uniform speed in the determined driving path; for a two-lane path, only its collision at the path node is considered.

(4) The storage location of the imported container task in the yard is known.

(5) After the AGV is placed in the waiting area in front of the bridge, it can leave and return to the shore to perform the next task.

3.1.1 Prioritization of task allocation

Follow the following principles when assigning tasks.

(1) The start address and target address of each task cannot be the same.

(2) Any two AGVs cannot start at the same address at the same time.

(3) An AGV cannot receive two different tasks at the same time.

(4) The assignment of tasks shall not exceed the load-bearing range of AGV.

(5) AGV must obey the task assignment.

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The tasks are divided into transportation tasks and charging tasks. Set the priority according to the priority of the task. Tasks with higher urgency have higher priority, and tasks with higher priority are assigned first. Divide tasks into 4 different priorities: 1, 2, 3, 4. The size of the number is inversely proportional to the priority. 1 has the highest priority, and then decreases sequentially, and 4 has the lowest priority.

The whole process is as follows. After completing the transportation task C1, the system checks whether there is a transportation task and whether the power is below the threshold. If the power is sufficient, perform task C2; if the power is lower than the threshold and not enough to return to the charging station after completing C2, then immediately return to the charging station for charging.

3.1.2 AGV priority

AGV priority has different regulations in task allocation and execution. The regulation of AGV priority is conducive to the realization of coordinated operation among multiple AGVs. Therefore, the priority of AGV is defined as follows.

(1) In task allocation, the AGV priority is determined according to the size of the free AGV number. The higher the number, the lower the priority.

(2) During task execution, the AGV priority is determined according to the priority of the task accepted by the AGV. The higher the priority of the task, the higher the priority of AGV.

(3) AGVs performing charging tasks have higher priority than AGVs performing transportation tasks.

(4) When there are multiple AGVs performing charging tasks at the same time, the AGV far away from the charging station has a higher priority.

(5) When the AGV that has completed the charging task performs the transportation task, the task is assigned to the AGV first.

(6) Under special circumstances, AGV should give priority to the manual intervention path.

(7) Regardless of the transshipment process, if the ship's loading and unloading lines are balanced, the shortest path is selected when considering idle trolleys.

3.1.3 AGV driving path planning

When the AGV is driving, problems such as queue congestion, insufficient battery stop, node conflict, and pursuit conflict should be dealt with as follows.

(1) Queuing congestion problem, AGV queue congestion when loading and unloading waiting, use the loading and unloading buffer to solve, the AGV charging area queuing congestion is solved by charging priority.

(2) The problem of AGV vehicle charging is solved by setting up an AGV charging area beside the bridge and setting up a dedicated charging lane.

(3) The two types of conflicts are resolved as follows.

(a) Node conflict

As shown in Figure 2, under normal circumstances, at the route node, vehicles with high priority pass first, and vehicles with low priority stop and wait. In order to avoid waiting for the installation of a distance sensor in front of the AGV vehicle, it is necessary to predict whether a conflict or collision occurs. When the safety distance between the vehicle and the node is d_0, it is determined whether there is a vehicle within the safety distance on the other side of the node that needs to pass. If the vehicle on the other side is greater than or equal to the safety distance, it can pass successively without waiting.

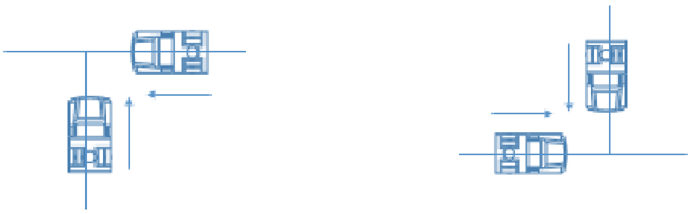

Figure 2. Node conflict

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(b) Pursuit of conflict

As shown in Figure 3, the two AGVs have the same driving path and the same direction during the driving process. Since it is stipulated that the AGV travels at a constant speed, no pursuit collision will occur. However, when the AGV needs to stop and avoid collisions in handling conflicts, the pursuit collision will easily occur. Set the safety distance d_m. When the distance between the two AGVs is less than d_m, the vehicle behind will stop and wait until the safety distance is met again, and then resume driving.

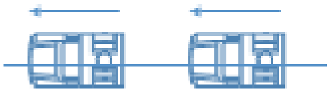

Figure 3. Pursuit of conflict

3.2 Symbol description

3.2.1 Model parameters

I: The set of all tasks, i=1,2,...,N.

I^+: The set of all tasks and the next task, i=1,2,...,I,N+1,N+2, where N+1, N+2 are the start and end points of the next task, respectively

V: A collection of AGVs, v=1,2,...,V.

K: The set of nodes in the path

α: AGV passes the node number after node i and node j

Q_v: the current remaining power of the AGVv;

Q_0: AGVv minimum remaining power threshold

T_{ij}: the time from completing task $i \in I$ to starting task $j \in I$;

S_{ij}: the distance from the delivery point of task $i \in I$ to the loading point of task $j \in I$;

R_v: the earliest time when $AGVv \in V$ can be used;

T_i: the time required to perform task $i \in I$;

T_{v0}: AGVv parking waiting time

S_i: the distance required to perform task $i \in I$;

B_i: the earliest effective start time of task $i \in I$;

z_i: the time when the task $i \in I$ was started;

$L_{i,v}$: The distance traveled by AGVv when it completes the task $i \in I$;

d_{kv}: the distance between AGVv and node K

d_0: the buffer distance between the AGV and the node

d_m: the safe distance of AGV driving in the same direction

d_{vw}: the distance between AGVv and AGVw traveling in the same direction

F_i: The time to complete all tasks, that is, the time when the last task was completed.

O_b: Virtual start position

O_e: Virtual end position

3.2.2 Decision variables

$$k_{ij} = \begin{cases} 1, \text{AGVv} \in \text{V visit node j after visiting node i. i, j} \in \text{K} \\ 0, \text{otherwise} \end{cases}$$

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$y_{iv} = \begin{cases} 1, \text{AGVv} \in V \text{ is responsible for the execution of tasks } i \in I \\ 0, \text{otherwise} \end{cases}$

$x_{iv} = \begin{cases} 1, \text{AGVv} \in V \text{ immediately performs task } j \in I \text{ after completing task } i \in I \\ 0, \text{otherwise} \end{cases}$

$Q_{v0} = \begin{cases} 1, Q_v < Q_0 \\ 0, \text{otherwise} \end{cases}$

$d_{kv0} = \begin{cases} 1, d_{kv} < d_0 \\ 0, \text{otherwise} \end{cases}$

$d_{vwm} = \begin{cases} 1, d_{vm} < d_m \\ 0, \text{otherwise} \end{cases}$

$E_{vwk} = \begin{cases} 1, \text{there are two cars at the same time within the buffer distance of node K} \\ 0, \text{otherwise} \end{cases}$

3.3 Model establishment

Combining the collision avoidance model proposed in Section 3.3.1, the AGV collision avoidance is added to the AGV transportation and charging model to establish a mixed integer programming model that minimizes the maximum completion time of the total task.

The specific model and its meaning are as follows:

(1) $\min = \{\max\{F_i\}, i \in I\}$ is the objective function, which means to minimize the end time of the last task.

(2) $F_i = z_i + T_i$ represents the completion time of all tasks.

(3) $z_j + (1 - x_{ijv})M \geq z_i + T_i + T_{ij}, \forall i \neq j, v \in V$ means that if tasks i and j are executed successively by any AGV, the conditions met by the start execution time of tasks i and j.

(4) $z_j \geq B_i, \forall i \in I$ means that the start time of task i∈I is carried out after its earliest scheduled start time.

(5) $z_j \geq R_v + T_{N+1,i} + (y_{iv} - 1)M, \forall i \in I, v \in V$ means that the task i ∈ I assigned to the vehicle v ∈ V is performed within the effective working time of the AGV.

(6) $L_{j,v}q + (1 - x_{ijv})Q_V \geq (L_{i,v} + S_j + S_{ij})q, \forall i \neq j, v \in V$ represents the condition that if tasks i and j are executed successively by any AGV v, the power consumption is satisfied.

(7) $(L_{i,v} + S_{i,N+2})q \leq Q_0, \forall i \in I, v \in V$.

(8) $\sum_{v=1}^{V} Q_{v0} < 1, v \in V, w \in V$ means that each AGV can complete the task and return to the charging station when the power is lower than the threshold.

(9) $\sum_{i=1}^{K}\sum_{j=1}^{K} X_{ij} = 1$ limit that when at time t, AGVv needs to perform task k and the power is sufficient, AGVv can complete the task and return to the charging station, and AGVv will go to perform the task.

(10) $\sum_{v=1}^{V} y_{iv} = 1, \forall i \in I$ means that if the AGV can complete the target task at time t, it does not need to be charged, otherwise it must go to the charging station to charge.

(11) $\sum_{i=1}^{N} y_{iv} = 1, \forall v \in V$ means that each AGV can only be assigned one container task at any time.

(12) $\sum_{j=1,i\neq j}^{N} x_{jiv} = \sum_{j=1,i\neq j}^{N} x_{jiv} = y_{iv}, \forall i \in I, v \in V$ means that for any AGV and all tasks, the flow constraint of the task in the task network is satisfied.

(13) $\sum_{w=1,w\neq v}^{V}\sum_{k=1}^{K} d_{kv0} \cdot E_{vwk} < 1, v \in V, w \in V, k \in K$ means to avoid two AGVs below the buffer distance d_0 from passing through the node at the same time.

(14) $\sum_{w=1,w\neq v}^{V} d_{vwm} < 1, v \in V, w \in V$ indicates that the distance d_{vw} between two AGVv and AGVw traveling in the same direction in the same node should maintain a safe distance d_m.

(15) $t_{r_1k_1c_k} > t_{r_2k_1c_k} \rightarrow P_{r_1k_1} < P_{r_2k_2}$ means AGV priority, assign tasks according to higher priority.

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(16) $F_i \geq 0, z_i > 0, L_{i,v} > 0, \forall i \in I, v \in V$ is a non-negative limit on the parameter.

4. Algorithm design

Dijkstra algorithm is a typical shortest path algorithm. It is used to calculate the shortest path from one node to other nodes. Its main feature is to extend the starting point to the outer layer until it reaches the end point. Utilizing the above-mentioned characteristics of the Dijkstra algorithm and applying it to the planning of the horizontal transportation path of the automated container terminal, the AGV path can be planned effectively and reasonably, and it is helpful to improve the efficiency of loading and unloading.

5. Experimental analysis

5.1 Experimental setup

Table 1. Equipment test parameter settings for container terminal scenarios

Parameter	**Setting**
Container terminal width	276M
Container terminal depth	110M
Number of quayside container crane	3
Number of rubber-tyred container gantry crane	3
Transport buffer depth	30M
Total number of containers	300
Number of containers per quayside container crane	100
Time for quayside container crane to unload an imported container/s	50s
Time for rubber-tyred container gantry crane to unload an imported container/s	55s
Waiting time when encountering obstacles at the intersection/s	1s
Length of AGV	15m
Distance between two AGVs Dm	4m
AGV speed V	3m/s

5.2 Experimental scenario

In the analysis part of this article, three sets of experiments are done, and the specific scene settings are shown in Table 2.

Table 2. Experimental scene settings

Serial number	Experimental purpose	Experimental settings
1	Verify the impact of the number of AGV vehicles and the number of tasks on the transportation time	Let the number of AGV vehicles n=1,2,3,4,5,6,7,8; Let the number of tasks be 20, 40, 60, 80, 100; Run the algorithm, and according to the different number of AGV vehicles, get the experimental results corresponding to the loading and unloading time.
2	Verify the impact of route planning and collision avoidance strategies on loading and unloading tasks and transportation time	On the basis of Experiment 1, consider the use of path planning and collision avoidance strategies to do experiments to obtain the number of conflicting nodes, the number of conflicts and the required time.
3	Verify the impact of the location and number of charging piles on the improvement of AGV usage	On the basis of Experiment 2, the number of quay crane transportation tasks is 100. Set the charging piles and compare the conflicting nodes and congested road sections on different working roads at different positions to obtain the location and number of charging devices, which can improve the congestion situation.

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5.3 Experimental results and analysis

5.3.1 Experiment One

Table 3. Number of loading and unloading tasks AGV number and loading and unloading time (time: minutes)

Number of vehicles Number of tasks	20	40	60	80	100
1	40	80	120	160	200
2	20	40	60	80	100
3	13.33	26.67	40.00	53.33	66.67
4	10	20	30	40	50
5	8	16	24	32	40
6	6.67	13.33	20.00	26.67	33.33
7	5.71	11.43	17.14	22.86	28.57
8	5	10	15	20	25

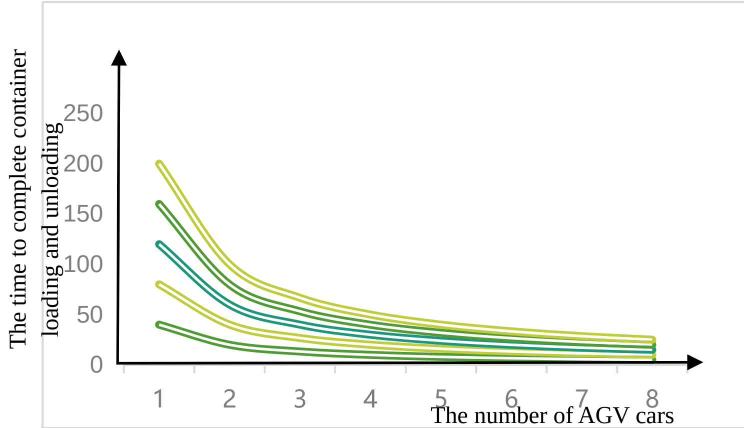

Figure 4. The relationship between the number of AGV vehicles and the loading and unloading time

Figure 4 shows the relationship between the number of AGV vehicles and the loading and unloading time when the loading and unloading tasks are certain. From the above picture and table, it can be seen that series 1 to 5 are graphs of loading and unloading 20 to 100 containers with 1 to 8 AGV vehicles respectively. When 4 to 5 AGV vehicles are loaded and unloaded at the same time, although the loading and unloading tasks increase, the time curve gradually approaches. It can be concluded that the number of AGV vehicles should be 4 units.

5.3.2 Experiment Two

According to the results of experiment 1, the safety distance between the two AGVs is set to 4m in the model formula (13) (14), and the waiting time when the two AGVs meet at the node is 1.5 minutes. , Figure 5 is a diagram of the AGV loading and unloading operation path, the nodes are marked as shown in the figure.

As shown in Figure 5, three quay cranes A, B, and C are selected to have loading and unloading buffer areas, corresponding to the 3 yard bridge a, b, and c box areas, and loading and unloading buffer areas are set at the same time. A total of 300 containers were loaded and unloaded. There are 3 quay cranes; each quay crane operates 100 containers; each quay crane is equipped with 4 AGV vehicles and 2 operating routes. The operation method is loading and unloading at the same time, leaving the lane for charging, regardless of the quay crane waiting, and continuous operation. Each AGV runs according to the planned route. The number of conflicting nodes is as follows.

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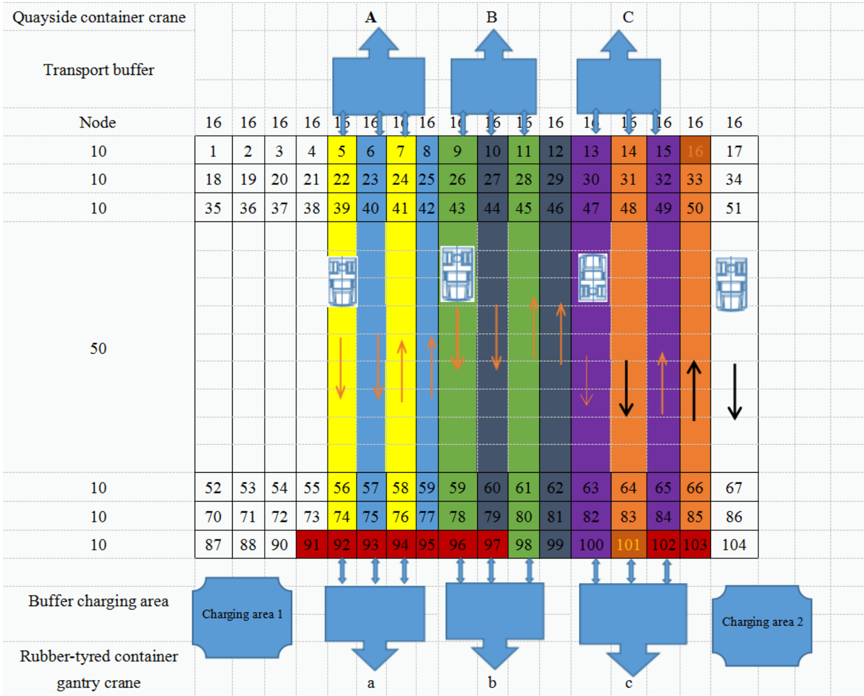

Figure 5. AGV working path diagram

Table 4. AGV working path nodes, conflict nodes, and waiting time summary table

Working type	Quayside container crane-Rubber-tyred container gantry crane	Working path	Path and node number	Conflict nodes	Conflict node number	Node waiting time	Waiting time
Loading and unloading	A-a	1: A-a-A	5-22-39-56-92-93-94-76-58-41-25-7	7,93,94	3	1.5	4.5
		2: A-a-A	6-23-40-57-75-93-94-95-77-59-42-25-8-7				
	B-b	3: B-b-B	9-26-43-59-78-96-97-98-80-61-45-28-11	11,97,98	3	1.5	4.5
		4: B-b-B	10-27-44-60-79-97-98-99-81-62-46-29-12-11				
	C-c	5: C-c-C	13-30-47-63-82-100-101-102-84-65-49-32-15	15,102,103	3	1.5	4.5
		6: C-c-C	14-31-48-64-83-101-102-103-85-66-50-33-16-15				

As shown in Table 4, the number of conflict nodes for each two working roads is 3, and there are 9 conflicting nodes in total. The waiting time for each node is 1.5 minutes, and the waiting time for each loading and unloading is 2.25 minutes. It can be concluded that path optimization can reduce collisions and improve efficiency.

5.3.3 Experiment Three

On the basis of the second experiment, charging devices are added. The number, location and path nodes of the electrical devices are shown in Figure 5.

As shown in Figure 5, this experiment shows several scenarios. The location and number of charging devices have an impact on the efficiency of loading and unloading in the work area. Set up dedicated charging lanes and make a statistical comparison of the conflicts between the dedicated lanes and the original loading and unloading lanes.

The experimental conditions are as follows.

(1) There are two charging devices on the left and right sides of the loading and unloading buffer

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area of the bridge, and two charging places are equipped with dedicated charging lanes.

(2) The loading and unloading lanes (routes) of each quay crane to the on-site bridge are marked in the figure, and the loading and unloading lanes are also used as charging lanes.

(3) See Table 5 for the statistics of driving paths and conflicting nodes.

Table 5. AGV charging path node, conflict node and data waiting time summary table

Working type	Quayside container crane-Rubber-tyred container gantry crane	Charging location	Path number	Path and node number	Conflict nodes	Conflict node number	Node waiting time	Waiting time
Loading, unloading and charging	A-a	Charging area 1	1 Charging area 1 A-a-A	91-92-93-94-76-58-41-24-7	7,91,92,93,94	5	1.5	7.5
			2 Charging area 1 A-a-A	93-92-91-92-93-94-95-77-59-42-25-8-7				
	B-b		3 Charging area 1 B-b-B	96-95-94-93-92-91-90-91-92-93-94-95-96-97-98-80-61-45-28-11	91,92,93,94,95,96,97,98	8	1.5	12
			4 Charging area 1 B-b-B	97-96-95-94-93-92-91-90-91-92-93-94-95-96-97-98-99-81-62-46-29-12				
	C-c	Charging area 2	5 Charging area 2 C-c-C	100-101-102-103-104-103-102-84-65-49-32-15	102,103	2	1.5	4.5
			6 Charging area 2 C-c-C	16-17-34-51-67-86-104-103-102-103-85-66-50-33-16-15-14				

From Table 5, the following comparison chart can be drawn (Figure 6).

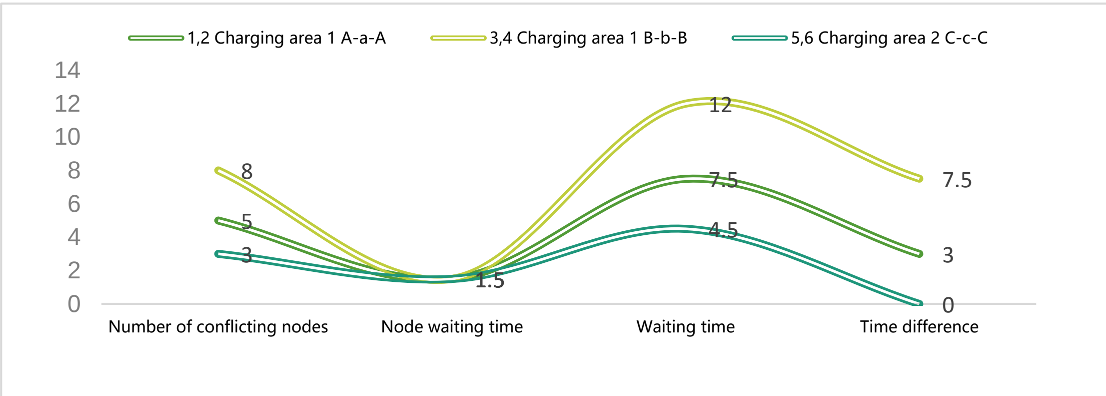

Figure 6. Time difference between charging and loading and unloading of different lines

(1) In Figure 6, lines 1, 2, 5, and 6 have fewer conflicting nodes, and lines 3 and 4 have the most conflicting nodes. Among them, line 1 is a lane close to charging 1, and line 6 is a dedicated charging lane. The location of the AGV car and the charging device is different, which will affect the number of conflicting nodes.

(2) Figure 6 shows the time difference between charging and loading and unloading of different lines. The time difference between lines 5 and 6 is 0; the time difference between lines 1 and 2 is 3 minutes; the time difference between lines 3 and 4 is 7.5 minutes. It can be concluded that the most time it takes to charge AGV vehicles on different lines is 7.5 minutes.

(3) AVG vehicles should be charged when unloading. The charging conditions are: a when the vehicle is unloaded, b reaches the charging range, and c detects the situation of AGV vehicles on congested road sections to reduce conflicts.

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6. Conclusion

This paper studies how to improve the loading and unloading efficiency of automated container terminals from the aspects of AGV vehicle path planning and resource allocation. First, start with path planning, combined with priority setting, and build a model based on time minimization. Then use the algorithm to get the best path. On the basis of the best route, equipped with an appropriate amount of AGV vehicles. Based on the least number of conflicting nodes, the configuration of charging devices is considered, including the location and number of charging devices and the setting of charging lanes. Experiments prove that the combination of resource allocation and model algorithm can improve the efficiency of loading and unloading.

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