Research on Integrated Scheduling Optimization of Double-trolley Quay Crane and AGV in Automated Terminal

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Abstract. With the upsizing of ships, the operating efficiency of automated container terminals is becoming increasingly important. Based on the operation mode of loading and unloading synchronization, we first established an integrated scheduling optimization model of Double-trolley Quay Crane (QC) and AGV. Secondly, we designed a genetic algorithm embedded in tabu search to improve its local optimization ability. Finally, we conduct an empirical analysis. In the same case size, compared with the traditional genetic algorithm, the genetic algorithm embedded in tabu search has shorter model solving time and lower model optimal solution fitness. The maximum difference of the model solving time and the optimal solution fitness value can reach 165.113% and 7.71%, respectively. The results verify the rationality of the model and the effectiveness of the algorithm.

Keywords: Integrated scheduling; loading and unloading synchronization; Double-trolley QC; Genetic Algorithm Embedded in Tabu Search.

1. Introduction

With the development of large-scale container ships, how to accurately arrange ship schedules, reasonably formulate scheduling plans, and improve operational efficiency will become a serious problem that traditional container terminals need to face. The integration and optimization of Double-trolley QC and AGV for automated terminals have become the focus of research. Reference[1] proposed a multi-criteria scheduling strategy for automated container terminals, and optimized the scheduling strategy using a multi-objective evolutionary algorithm (MOEA). Reference[2] compares the terminal operation productivity of four different types of QC combined with AGV and ALV. AGV can be moved freely and flexibly in horizontal transportation areas. The study found that when the number of AGV configurations is sufficient, the difference in operating performance between AGV and ALV will be significantly reduced. Reference[3] established four cooperative optimization models for the coordinated operation scheduling plans of different loading and unloading equipment. Reference [4-5] describes the operation process under the loading and unloading process system of "single-trolley Quay Crane--AGV", and establishes a mixed integer programming model for the integrated scheduling problem of single-trolley Quay Crane and AGV. Reference [6] proposed a mixed integer programming model for the scheduling problem under the "quay crane -truck-gantry crane" loading and unloading process. A numerical example is used to verify the effect of different quantity ratios between the truck and the gantry crane on the operation time required for the handling system to complete all tasks.
References [7] and [8] studied AGV scheduling problems and compared the results of CPLEX and traditional genetic algorithms with different number of tasks. Reference [9] uses a Markov chain model to prove that the genetic algorithm embedded in tabu search can converge to the global optimal solution with probability 1. Reference [10] uses a genetic tabu search algorithm to solve the traveling salesman problem in transportation networks, and proves that the algorithm is more robust, more efficient, and more stable.

Based on the above research status and theoretical background, considering the operational efficiency of automated terminals, this paper establishes an integrated scheduling optimization model of double-trolley QC and AGV, and proposes a genetic algorithm embedded in tabu search algorithm to solve the model. Finally, an empirical analysis is performed.

2. Operation Scene
The terminal adopts the handling technology of "Double-trolley QC-AGV-ARMG". The front of the terminal is operated by double-trolley QC for container loading and unloading, the horizontal transportation area is handled by AGV, and the rear yard is handled by ARMG. The specific operation scene is shown in Figure 1.

![Figure 1. The specific operation scene.](image)

As shown in Figure 1, the horizontal transportation area of the terminal adopts a square road network structure. The AGV driving environment at the intersection is simple, which facilitates the organization and control of the multiple AGV system. Each section of the road network is a one-way single lane, and multiple AGV are not allowed to pass in parallel.

3. Model Building

3.1. Model assumptions and parameter definitions
This paper is mainly based on the following assumptions:
- The "quality guaranteed" scheduling mode is adopted in the horizontal transportation area;
- Do not consider the movement speed of AGV under no-load or heavy-load conditions;
- Operating time delay due to unexpected factors such as equipment failure are not taken into account.

The symbol description is shown below:

- $Z/X$: Collection of actual container loading/unloading tasks;
- $D_{det}/D_{act}$: Estimated/actual departure time;
- $c_i/c_j$: Penalty cost factor due to ship departure delay / AGV system operation energy consumption;
- $x_j$: 0-1 Decision variables for AGV task execution sequence;
- $y_j$: 0-1 Decision variables for AGV task assignment;
- $T_{vt}^{1/2/3}$: Total time of no-load/heavy-load on-transit / stationary state of the vth AGV;
- $w_{vt}^{1/2/3}$: Weight per unit time of each AGV under no load / heavy load / stationary state;
- $\mu$: Weight coefficient;
- $T_{ms}$: Time required for single container handling operation of main trolley/mast trolley;
- $t_{no}/t_{lh}$: Travel time of AGV during no-load / heavy-load state when performing task j.
$t_{n_j,v}$: Sequence number of the predecessor of task $j$ in the task execution sequence of the $v$th AGV;
$pt_j$ / $yt_{j,v}$: When AGV executes task $j$, the time when it reaches corresponding quay crane / yard transfer area;
$qm / qs_j$: When quayside main trolley/mast trolley performs the task $j$, the time of picking/putting the container at the transfer platform;
$m / s_j$: 0-1 variable of the task execution status of quay crane main trolley / mast trolley at the transfer platform.

3.2. Integrated scheduling optimization model of Double-trolley QC and AGV

The goal of the solution in this section is to minimize the weighted total value of ship departure time delay cost and energy consumption cost of multi-AGV transportation system operations. The following mathematical model is established, and the objective function is:

$$f = \min \left\{ \mu \cdot c_1 \cdot f_1^1 + (1 - \mu) \cdot c_2 \cdot f_1^2 \right\}$$  \hspace{1cm} (1)

$$f_1 = \max \{ D_t \cdot t_i - D_t \cdot t_0 \cdot 0 \}$$  \hspace{1cm} (2)

$$f_2 = \sum_{k=1}^{N_{max}} \left[ T_{m} - w^{1}_{k} + T_{n} - w^{2}_{k} + T_{s} - w^{3}_{k} \right]$$  \hspace{1cm} (3)

Among them:

$$D_t = \max\{qm_j + T_m | j \in Z\}$$  \hspace{1cm} (4)

$$T_{s}^{1/2} = \sum_{j=1}^{N_{max}} to / th_j \cdot y_{n, j}$$  \hspace{1cm} (5)

$$T_{j}^{v} = \max\{qm_j \cdot y_{n, j}, qs_j \cdot y_{n, j} | \forall j \in Task\} - T_{s}^{1} - T_{s}^{2}$$  \hspace{1cm} (6)

Equation (1) represents the total cost of the terminal operating system to complete the current task. Equation (2) represents the cost of delay in departure time. Equation (3) represents Cost of operating time for multi-AGV transportation systems. Equation (4) indicates that the actual departure time of the ship is the completion time of the last task in the handling operation of quay crane. Equation (5) represents the total length of no-load/heavy-load transportation for AGV to complete all tasks. Equation (6) indicates the total time for AGV to wait in line or receive quay crane services at quay crane transfer area.

The constraints are as follows:

3.2.1. Constraint of operation time between the quay crane mast trolley and AGV:

$$y_t / pt_j \geq qs_{m_j}, -T_s + t_0 \left( j \in Z, \ t_{n, j, v} \in Z \right)$$

$$y_t / pt_j \geq yt_{m, j}, + t_0 \left( j \in Z, \ t_{n, j, v} \in X \right)$$  \hspace{1cm} (7)

$$pt_j \leq qy_j - T_s \left( j \in Z \right)$$  \hspace{1cm} (8)

$$pt_j \leq y_t \left( j \in X \right)$$  \hspace{1cm} (9)

$$yt_j \geq qy_j + T_s + th_j \left( j \in X \right)$$  \hspace{1cm} (10)

$$pt_j \geq yt_j + th_j \left( j \in Z \right)$$  \hspace{1cm} (11)
Equation (7) shows the connection between the start time of the loading / unloading task of the same AGV and the end time of the previous task in the task sequence. Equation (8) and Equation (9) show the relationship between the time when the AGV arrives at the Quay Crane and the time when the bridge mast trolley to pick up and places the container at the transfer platform during the loading / unloading task. Equation (10) represents the time when the AGV arrives at the corresponding field bridge during the AGV performs the unloading task. Equation (11) indicates the time when the AGV arrives at the corresponding Quay Crane during the AGV performs the loading task.

3.2.2. Restrictions on the operating time between quay crane main trolley and mast trolley:

\[
\begin{align*}
qs_j - T_j &\geq qs_{m_j}, \quad (j \in Z, \text{tn}_j \in X) \\
qs_j - T_j &\geq qs_{m_j} + T_m, \quad (j \in Z, \text{tn}_j \in X) \\
qs_j &\geq qs_{m_j}, \quad (j \in X, \text{pre}_j \in Z) \\
qs_j &\geq qs_{m_j} + T_m, \quad (j \in X, \text{pre}_j \in X)
\end{align*}
\]

Equations (12) and (13) respectively indicate the connection relationship of the operating time at the transfer platform when the bridge mast trolley performs the current loading or unloading task. Equations (14) and (15) are respectively the connection relationship of the operating time at the transfer platform when the Quay Crane main trolley performs the current loading or unloading task. Equation (16) indicates the connection between the main trolley operation time and the mast trolley operation time at the transit platform when the Quay Crane performs the same loading and unloading task.

3.2.3. Restrictions on decision variables:

\[
x_i = \begin{cases} 
1 & \text{tn}_{j_i} = i \\
0 & \text{tn}_{j_i} \neq i
\end{cases}
\]

\[
m_j = \begin{cases} 
1 & t \geq qm_j \\
0 & t < qm_j
\end{cases}
\]

\[
s_j = \begin{cases} 
1 & t \geq qs_j \\
0 & t < qs_j
\end{cases}
\]

\[
y_{n,j} = \begin{cases} 
0 & \\
1 &
\end{cases}
\]

Equation (17) indicates that when task \( i \) and task \( j \) are executed by the same AGV, and task \( i \) is the predecessor task of task \( j \), the decision variable takes the value 1, otherwise it takes the value 0. Equation (18) indicates that when the main trolley of the Quay Crane has performed the task \( j \) container pick-up / places operation at the transit platform at time \( t \), the decision variable takes the value 1, otherwise it takes the value 0. Equation (19) indicates that when the mast trolley of the Quay
Crane has performed the task \( j \) container pick-up/places operation at the transit platform at time \( t \), the decision variable takes the value 1, otherwise it takes the value 0. Equation (20) indicates that when task \( j \) is assigned to the \( v \)-th AGV for execution, the decision variable takes the value 1, otherwise it takes the value 0.

4. The Genetic Algorithm Embedded in Tabu Search

The traditional Genetic algorithm is a method of searching the optimal solution by simulating the natural evolution process. It has strong global optimization ability, but the convergence rate is slow in the later stages of evolution [10].

The tabu search algorithm has the advantages of strong local development ability and fast convergence speed, strong "climbing" ability, but the global development ability is weak, and the pros and cons of search results are highly dependent on the initial solution and the neighborhood mapping relationship [10].

Therefore, combined with the characteristics of the automatic container terminal’s Double-trolley QC and multi-AGV integrated scheduling, a genetic algorithm embedded in tabu search is used in this paper. The algorithm framework is shown in Figure 2. This paper introduces the short-term memory and local development capabilities of the tabu search algorithm, transforms the mutation operator in the traditional genetic algorithm into a tabu search algorithm for neighborhood optimization, and improves the local search ability of genetic algorithms by using the tabu criteria and the amnesty criterion of tabu search algorithm.

![Figure 2. The algorithm framework.](image)

The genetic algorithm embedded in tabu search has made three improvements based on the traditional genetic algorithm. First, the evolutionary reversal operation is introduced to increase the probability that the offspring can inherit the superior genes from the parent. Second, the tabu mutation operation is introduced to improve the local optimization of the algorithm. Finally, an elite retention strategy was introduced to ensure that individuals with high fitness in the parent generation would not be lost due to crossover operations or mutation operations.

4.1. The evolutionary reversal operation

Considering the applicability of the reversal operator to the model in this paper, it is stipulated that the break point of the reversal operator must be located inside the close demarcation point "0"; the genetic information on both sides of the break point is exactly the same as that of the parent individual, ensuring that the remaining AGV perform the tasks, and the order does not change. In addition, the reversal operator is unidirectional, and only accepts reversal operations that increase the fitness value after reversal, otherwise the segment is rejected for reversal and the reversal is invalid.

4.2. Tabu mutation operation

In the chromosome mutation operation, the mutation operator in the traditional algorithm is converted into a tabu search algorithm for neighborhood optimization. The specific steps are as follows:

4.2.1. Initialize
Determine the individual who produces the mutation through the mutation probability, and use this individual as the initial individual;

4.2.2. Generate neighborhoods
That is, two points are randomly selected and their positions are swapped. If the chromosome code does not meet the requirements after swapping positions, the mutation is rejected and the position nodes are randomly selected again.

4.2.3. Calculate the fitness of each individual in the neighborhood
Update current solution, aspiration level, and tabu table based on fitness values. Among them, the tabu table mainly includes two indicators: the tabu object and the tabu step. When the non-empty tabu table needs to be updated, in addition to updating the current candidate solution mapping information, the tabu steps of all tabu objects in the table should also be updated. When the tabu step size is 0, the tabu object is deemed to have been freed.

4.2.4. Determine whether the current convergence effect meets the stopping criteria.
If not, stop criterion, return to step 2 to generate current solution neighborhood after updated to continue searching; if it is satisfied, output the updated current solution as a new individual generated by the initial individual after mutation operation.

4.3. Elite retention strategy
After the offspring population is generated, the parent with highest fitness is reinserted into the offspring population to make the number of individuals in the new species is consistent with the number of individuals in the original population. According to this, the optimal individual in the offspring population is never inferior to the optimal individual in the parent, ensuring that the superior genes of the parent are not lost due to crossover or mutation operations.

5. Empirical Analysis

5.1. Experiment and scene parameter settings
The research scenario of this paper is shown in Figure 1 and the road network layout of the frontier horizontal transport area of the terminal is shown in Figure 3. The specific scene and experimental parameters are shown in Table 1 below.

5.2. Comparative experiment of traditional genetic algorithm and genetic algorithm embedded in tabu search
Case sizes are 24, 48 and 96. The number of trolleys in the multi-AGV system is 4, 6, and 8. Other parameters are shown in Table 2.

In order to reduce the random error in the solution results of the genetic algorithm, MATLAB runs ten times in every example. The average solution time and the optimal solution in the objective function value are recorded, as shown in Table 3.

**Figure 3.** Road network layout in the horizontal transportation area.

**Table 1.** Parameters settings.

| Scene parameters | Experimental parameters |
|------------------|-------------------------|
| name             | value                   | name     | value |
| \( T_m \)        | 70(s)                   | GA-size  | 100    |
Table 2. Set value of $D_{t_i}$.

| Number of tasks | $D_{t_i}(s)$ |
|-----------------|--------------|
| 24              | 960          |
| 48              | 1920         |
| 96              | 3840         |

Table 3. Comparative analysis of algorithm solution effects under different case sizes.

| Number of containers | AGV number | traditional genetic algorithm | genetic algorithm embedded in tabu search | Degree of difference (%) |
|----------------------|------------|-------------------------------|-------------------------------------------|---------------------------|
|                      |            | The optimal value ($) | Computing time (min) | The optimal value ($) | Computing time (min) | The optimal value difference | Computing time difference |
| 24                   | 4          | 12.53            | 6.31             | 12.12              | 2.38              | 3.38%                        | 165.13%                   |
| 24                   | 6          | 12.23            | 6.57             | 11.89              | 3.77              | 2.86%                        | 74.27%                    |
| 24                   | 8          | 12.69            | 7.13             | 12.60              | 4.71              | 0.71%                        | 51.38%                    |
| 24                   | 10         | 12.78            | 9.24             | 12.73              | 6.60              | 0.39%                        | 40.00%                    |
| 24                   | 12         | 13.79            | 11.58            | 12.97              | 9.60              | 6.32%                        | 20.63%                    |
| 48                   | 4          | 34.82            | 18.74            | 32.44              | 14.95             | 7.34%                        | 25.35%                    |
| 48                   | 6          | 26.05            | 19.45            | 25.68              | 16.15             | 1.44%                        | 20.43%                    |
| 48                   | 8          | 28.25            | 17.65            | 26.46              | 16.45             | 6.76%                        | 7.29%                     |
| 48                   | 10         | 29.10            | 23.41            | 27.85              | 18.82             | 4.49%                        | 24.39%                    |
| 48                   | 12         | 31.71            | 23.91            | 29.49              | 19.35             | 7.53%                        | 23.57%                    |
| 96                   | 4          | 76.95            | 31.16            | 77.01              | 26.66             | -0.08%                       | 16.88%                    |
| 96                   | 6          | 60.80            | 32.94            | 56.45              | 31.14             | 7.71%                        | 5.78%                     |
| 96                   | 8          | 61.17            | 36.96            | 58.18              | 32.38             | 5.14%                        | 14.14%                    |
| 96                   | 10         | 62.62            | 37.75            | 60.74              | 33.10             | 3.10%                        | 14.05%                    |
| 96                   | 12         | 67.39            | 43.25            | 65.38              | 38.97             | 3.07%                        | 10.98%                    |

At different case sizes, this paper uses the genetic algorithm embedded in tabu search proposed in this paper and traditional genetic algorithms to solve the model respectively, and then conducts in-depth comparison and analysis from two aspects: solution time and solution accuracy.

5.3. Results and discussion
The traditional genetic algorithm has a slow convergence speed in the later stage of evolution\cite{10}. The genetic algorithm embedded in tabu search proposed in this paper introduces the short-term memory
and local development capabilities of the tabu search algorithm. The "memory" function of the tabu table guides the search direction of the algorithm and improves the convergence speed. Therefore, the model solving time can be greatly reduced. The results of model solving time are shown in Figure 4 below.

![Figure 4](image)

**Figure 4.** Model solving time results of the two algorithms at different case sizes.

As can be seen from Figure 4, in terms of model solving time, the bar graph represents the solution result of the genetic algorithm embedded in tabu search, and the line chart graph represents the solution result of the traditional genetic algorithm. The legend shows the different container operations, with values of 24, 48, and 96. The model solving time of the genetic algorithm embedded in tabu search is generally lower than the model solving time of the traditional genetic algorithm. But the larger scale of the example, the larger number of AGV, and the smaller difference in solving time. The maximum difference between the model solving time obtained by the genetic algorithm embedded in tabu search and the model solving time obtained by the traditional genetic algorithm can reach 165.13%. When the number of containers is 24, the accuracy difference of the average solving time is 70.28%; when the number of containers is 48, the accuracy difference of the average solving time under the medium-scale example is 20.21%; when the number of containers is 96, the accuracy difference of the average solving time under large-scale examples is 12.37%.

Traditional genetic algorithms are performed by three operators: selection, crossover, and mutation. Due to defects such as poor local search capabilities, traditional genetic algorithms often have difficulty converging to optimal solutions\[^9\]. The genetic algorithm embedded in tabu search is based on the use of the tabu mutation operator for neighborhood optimization. The tabu criteria and the amnesty criterion of tabu search algorithm are used to improve the local search ability of the genetic algorithm, thereby improving the optimal solution fitness of the model. The results of model optimal solution fitness are shown in Figure 5 below.

![Figure 5](image)

**Figure 5.** Model optimal solution fitness of the two algorithms at different case sizes.

As can be seen from Figure 5, in terms of model optimal solution fitness, the bar graph represents the solution result of the genetic algorithm embedded in tabu search, and the line chart graph represents the solution result of the traditional genetic algorithm. The legend shows the different container operations, with values of 24, 48, and 96. The model optimal solution fitness of the genetic algorithm embedded in tabu search is generally lower than the model solving time of the traditional genetic algorithm. The
maximum difference between the optimal value obtained by the genetic algorithm embedded in tabu search and the optimal value obtained by the traditional genetic algorithm can reach 7.71%. When the number of containers is 24, the accuracy difference of the average optimal value is 2.73%; when the number of containers is 48, the accuracy difference of the average optimal value under the medium-scale example is 5.51%; when the number of containers is 96, the accuracy difference of the average optimal value under large-scale examples is 3.79%.

The results show that the genetic algorithm embedded in tabu search is effective for solving the integrated scheduling optimization model of Double-trolley QC and AGV based on loading and unloading synchronization. The algorithm can significantly reduce solving time of the model under the different case size while ensuring accuracy.

6. Conclusions

This paper starts with the operating system commonly used in current automated container terminals, establishes an optimized scheduling model based on loading and unloading synchronization of Double-trolley Quay Crane and AGV, and uses a genetic algorithm embedded in tabu search algorithm to solve the problem. An example analysis verifies the rationality of the model and the effectiveness of the algorithm. In the same case size, compared with the traditional genetic algorithm, the genetic algorithm embedded in tabu search has shorter model solving time and lower model optimal solution fitness, which means lower total cost. The maximum difference between the model solving time and the optimal solution fitness value obtained by the genetic algorithm embedded in tabu search and the model solving time and the optimal solution fitness value obtained by the traditional genetic algorithm can reach 165.13% and 7.71%, respectively.

This paper comprehensively considers the efficiency of terminal operations and the cost of terminal operations delays, which not only has the great significance for improving the utilization rate of terminal handling equipment, shortening the stay time of ships at the port, and promoting the upgrading of port berths, but also provides a certain theoretical support for the development of automation terminal to promote the sustainable development of the domestic shipping industry. In the following research, the specific parameters of the container on the ship will be introduced to make the problem more relevant to the actual operation of the container terminal. The scheduling optimization under the conflict of AGV paths will also be considered to make the unmanned terminal more intelligent.

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