Joint configuration and scheduling optimization of the dual trolley quay crane and AGV for automated container terminal

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Abstract. This paper proposes a method to optimize the configuration and scheduling of dual trolley quay crane and AGV so as to reduce the cost in automated container terminal. A two-phase model is constructed to minimize cost during handling operation considering the relevant constraints such as laytime allowable in the contract, AGV's endurance time and buffer platform for quay crane and blocks, which will be solved by the proposed genetic algorithm. Yangshan Phase IV automated container terminal’s data was used to demonstrate the validity and applicability of the proposed model. By the results of the experiments, it is found that the proposed method can reduce cost while ensuring that the completion time is not delayed.

1. Introduction
As early as 1993, in order to improve handling efficiency and reduce energy consumption in terminal, the Rotterdam Port of the Netherlands began to construct automated container terminals. After more than 20 years, the current automated dock technology has gradually matured and improved. This paper will consider the joint configuration and scheduling of quay crane and AGVs for the purpose of reducing cost during loading and discharging.

Some scholars pay attention to the effect of dual-trolley quay crane scheduling. Liang (2018)[1] studied the dual-trolley quay crane scheduling problem by analyzing the earliest workable time and required completion time of each container. Zhang (2018)[2] considered the longitudinal stability of the ship during loading and discharging, established a quay crane scheduling optimization model with stability constraints. Some scholars studied the coordinated dispatching of quay crane and AGV. Peng (2018)[3] established a simulation model based on complex queuing networks to optimize the ratio of quay crane, yard crane and AGVs. Some scholars considered the impact of uncertain environment in the process of AGV transportation. For example, Singgih (2016)[4] studied the AGV route planning problem and considered the waiting time due to traffic congestion.

It can be seen from the existing research that the gaps in the research are as follows: (1) The impact of the ship's allowable laytime is not considered. (2) The impact of the endurance time on the dispatch is not considered. (3) Insufficient research on the buffer zone. In summary, this paper will study the joint configuration and scheduling optimization with considering the ship's allowable laytime, AGV’s endurance time and buffer capacity.

2. Mathematical model
In this paper, the joint configuration and scheduling problem will be studied in two phases. In the first phase, the dual-trolley quay cranes are configured. All the deck containers or hold containers in the same bay are called a task. In the second phase, AGVs are scheduled and configured according to the
scheduled time of main trolley quay cranes, with a container as a unit. Since the delay of quay crane may cause higher losses, it is necessary to ensure that quay crane does not wait for AGV.

The research in this paper is based on the following assumptions: (1) All containers are same type; (2) The uncertain factors such as the path conflict are not considered; (3) There have buffer brackets under the blocks.

### 2.1 Phase I: Mathematical formulation for configuration and scheduling of quay crane

Sets and parameters as follows: $I$, the set of tasks, indexed by $i$. $N$, the set of containers, indexed by $n$. $K$, the set of QCs, indexed by $k$. $L_{safe}$, minimum allowable distance between two consecutive cranes. $t_f$, allowable laytime of the ship. $\tau_1$, the time required for the QCs to move a bay. $\tau_2$, the average time required for the QCs to complete the loading/discharging. $c_1$, $c_2$ and $c_3$, unit cost of AGVs, $w_{ijk}$, the operate time of container $c_k$ after task $t_i$, $n_{ik}$, the time QC $k$ needs to wait before starting the task $j$ after task $i$. $w_{ijk}$, whether QC $k$ performs task $i$ at time segment $t$. $x_{ijk}$, whether QC $k$ performs task $j$ after task $i$. $w_{ij}$, whether QC $k$ performs task $j$ after task $i$.

Decision variables are as follows: $x_{ijk}$, whether QC $k$ performs task $i$ at time segment $t$. $x_{ijk}$, whether QC $k$ performs task $j$ after task $i$.

Object1: Minimize the total cost of the QCs, including working cost, moving cost and waiting cost.

\[
\text{min } f_c = C_c \times \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 + C_c \times \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 + C_c \times \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1
\]

s.t.

\[
\sum_{t=1}^{T} x_{ij} = 1 \quad \forall i \in I, t \in T
\]

(2)

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij} = N_i \quad \forall i \in I
\]

(3)

\[
\sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} = 0 \quad \forall i \in I, \forall k \in K
\]

(4)

\[
\sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 + \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 + \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 \leq t_f \quad \forall i \in I, \forall k \in K
\]

(5)

\[
\sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{t=1}^{T} x_{nj} \tau_1 \geq L_{safe} \quad \forall k, k' \in K, t \in T
\]

(6)

\[
x_{nj} \in \{0, 1\} \quad \forall i, j \in I, \forall k \in K
\]

(7)

Constraints (2) ensure that each task is performing by one QC. Constraints (3) guarantee that all container will be handled. Constraints (4) guarantee that each task has one and only one predecessor task and a dummy task. Evidently, the completion time cannot exceed allowable laytime, which is ensured through constraints (5). Constraints (6) enforce the safety margin between QCs. Finally, the binary nature of the decision variable is specified by constraints (7).

### 2.2 Phase II: Mathematical formulation for AGV scheduling

Through the optimization results of the first phase, we can know the operated time of tasks. In this phase, loaded and discharged containers are assigned to AGV.

Sets and parameters as follows: $L$, the set of loading containers. $D$, the set of discharging containers. $C$, the set of yard cranes, indexed by $c$. $A$, the set of AGVs, indexed by $a$. $T_{nk}^c$, the planned completion time of container $c$ by the main trolley of quay crane $k$. $T_{nk}$, the actually completion time of container $n$ by the main trolley of quay crate $k$. $S_{mc}$, the operate time of container $c$ by yard crane $c$. $T_{mc}$, the start time of container $n$ by AGV $a$. $C_4$, the waiting cost per unit of time of gantry trolley for AGV. $C_5$, $C_6$ and $C_7$ means the cost of AGV by delivery containers, no-load moving and waiting in unit time. $P_1$, the capacity of the transit platform at dual-trolley quay crane. $P_2$, the capacity of buffer bracket in blocks. $\tau_3$, the average time required for gantry trolley to pick up or put down a container. $\tau_4$, the average time required for the yard crane to pick up or put down a
container. \(v_1\), the speed of AGV with containers. \(v_0\), the speed of AGV without containers.

Decision variables: \(x_{na}\), whether container \(n\) is assigned to the AGV \(a\); \(x_{na'a}\), whether the AGV transport container \(na'\) after completed the transportation of container \(n\); \(u_{na}\), whether is remaining power less than the safe power after completed the transportation of container \(n\).

Object2: Maximizing the proportion of cost.

\[
 f_2 = \max \left[ C_1 \times \sum_{a \in A} \sum_{n \in N} x_{na} + C_0 \times \sum_{a \in A} \sum_{n \in N} x_{na'a} + C_1 \times \left(\sum_{a \in A} \sum_{n \in N} w_{na} + \sum_{a \in A} \sum_{n \in N} w_{na'a}\right) + C_2 \times \sum_{a \in A} \sum_{n \in N} \left(T_{a} - T_{a}^0\right) \right]
\]

s.t.

\[
 \sum_{a \in A} x_{na} = \sum_{a \in A} x_{na'a} = 1 \quad \forall n \in N
\]

\[
 T_{a}^0 = \max\{T_{a} + t_{a}, T_{a}^0\} \quad \forall a \in A, \forall n \in N
\]

\[
 T_{a}^0 = \max\{T_{a}^0\} \quad \forall n \in N
\]

\[
 T_{a} = T_{a}^0 + t_a \quad \forall n \in N, \forall a \in A
\]

\[
 E_{a} = S_a, LT_{a} = S_a + p_t \times t_s \quad \forall n \in L, \forall c \in C
\]

\[
 w_{na} = \max\{T_{na} - T_{na}, 0\} \quad \forall a \in A, \forall n \in N
\]

\[
 w_{na} = \max\{E_{na} - T_{na}, 0\} \quad \forall n \in N, \forall a \in A, \forall c \in C
\]

\[
 T_{na} + t_{na} + w_{na} + t_{na'a} + w_{na'a} + \tau_s \times u_{na} \leq T_{na'} + M (1 - x_{na'a}) \quad \forall n \in L, n' \in L
\]

\[
 T_{na} + t_{na} + w_{na} + t_{na'a} + w_{na'a} + \tau_s \times u_{na} \leq T_{na'} + M (1 - x_{na'a}) \quad \forall n \in L, n' \in L
\]

\[
 T_{na} + t_{na} + w_{na} + t_{na'a} + w_{na'a} + \tau_s \times u_{na} \leq T_{na'} + M (1 - x_{na'a}) \quad \forall n \in D, n' \in L
\]

\[
 T_{na} + t_{na} + w_{na} + t_{na'a} + w_{na'a} + \tau_s \times u_{na} \leq T_{na'} + M (1 - x_{na'a}) \quad \forall n \in D, n' \in D
\]

\[
 x_{na}, x_{na'a}, u_{na} \in [0, 1] \quad \forall n, n' \in N, \forall a \in A
\]

\[
 T_{na} \geq 0 \quad \forall n \in N, \forall a \in A
\]

Equation (9) indicates that a container is transported only by one AGV. Equation (10) and (11) indicates that the actual operation time of the main trolley is not later than the planned operation time. Equations (12) indicates the relation between actual operating time of the gantry trolley and the arrival time of the AGV. Equations (13) and (14) respectively indicate the time window when AGV transports loaded containers or discharged containers at blocks. Equations (15) and (16) respectively represent the waiting time at quay and AGV delivers loaded container or picks up discharged containers. Equations (17) and (18) respectively represent the waiting time at blocks. Equations (19)- (22) respectively represent the constraint about the time when AGV start next loaded container or discharged container. Equations (23) and (24) respectively represent the type and value range of variables.

3. Algorithms

3.1 Enumeration Algorithm for solving the first phase model

The above optimization model is nonlinear based on the discrete independent variables, therefore is a NP-hard problem, which cannot be solved with CPLEX. Therefore, a simplified Enumeration Algorithm (EA) is adopted to get the optimal solution, and the detailed steps are as follows:

1) Arranging all tasks according to the sequence. The sequence of the tasks as follows. To the task operated by same quay crane, the bay with smaller number is earlier, and the discharging task is earlier than the loading task. To the tasks located at same bay, the discharging container on-deck is earlier than in-hold, and the loading container in-hold container is earlier than on-deck.
2) Calculating the values of the objective function under different number of quay cranes with the constraints of impossible cross and safe distance between quay cranes. All the quay crane scheduling schemes under different configuration are listed and valued. The scheme with minimum value is best.

3) Selecting the optimal quay crane configuration and scheduling scheme. Under the premise of satisfying laytime of ship, the optimal solution can be obtained by comparing the objective function values of different configured scheme.

3.2 Extended genetic algorithm for solving the second phase model

In this paper, the extended genetic algorithm based on population evolution is improved to solve the second phase model according to the problem characteristics. The steps of the algorithm as follows.

(1) Chromosome representation

A two-line chromosome is designed by matrix coding, which length is the number of containers. The gene value in the first line represents the sequence of container, and the gene value in the second line means the AGV assigned to each container. According to the stowage plan and the results of the first phase, the quay crane index and yard crane index of each containers can be known. For example, there are 3 quay cranes to load or discharge containers at the same time, and 4 AGVs participate in the transportation of delivery containers. The chromosomes shown in figure 1 means that the container with index 27 will operated by yard crane 7 and quay crane 2, assigned to AGV 1.

![Fig1. The chromosome](image)

(2) Generating the initial population

A certain number of individuals are generated by random numbers under the constraint of equations (9).

(3) Evaluation and selection

The reciprocal value of the objective function is taken as the fitness function, and the individual with the highest fitness value will be selected into the next generation.

(4) Crossover and mutation

All the individuals in the population were randomly grouped in which eight individuals are as a group. The individuals with the highest fitness in each group were regarded as the local optimal solution which can reserved to next generation. Through the crossover operation, 4 new individuals can be generated, which is shown in figure 2 (a). The mutation of the local optimal chromosome was conducted by means of gene inversion, gene exchange and updating the breakpoints. The remaining three new individuals were generated as shown in figure 2(b), (c) and (d). Each generation of Crossover and mutation operation can produce a new set of individuals.

![Diagram of Crossover](image)
Handling of individuals that don’t meet the constraints
In the process of gene mutation, the individual’s value is set to infinitesimal and will not be inherited to the next generation, which may cause delay of the main trolley.

(6) Termination
The algorithm terminates when the algorithm reaches the maximum number of iterations.

4. Case studies

4.1 Experimental setting
The date of container’s location distribution reference to Luo[5], with 20 bay to be loaded and discharged. The speed of loaded, no-load AGV is set to 210 and 350 m/min. There are nine blocks for stacking containers and the real date of layout form Yangshan Phase IV automated container terminal. The capacity of the transfer platform in dual-trolley quay crane is 2. The safe distance between two quay cranes is set to one bay. The capacity of the buffer bracket at each blocks is 4. The cost of quay crane reference to Chen[6]. Some other inputs are shown in Table 1.

| parameters         | value  | parameters         | value  | parameters         | value  | parameters         | value  |
|--------------------|--------|--------------------|--------|--------------------|--------|--------------------|--------|
| $C_{i}/[kw·h]$     | 91.24  | $C_{i}/[kw·h]$     | 49.6   | $C_{i}/[kw·h·veh]$ | 9      | $r_{i}/[min]$      | 1      |
| $C_{i}/[kw·h]$     | 70.18  |                    |        | $C_{i}/[kw·h·veh]$ | 21     | $r_{i}/[min]$      | 1      |
| $C_{i}/[kw·h]$     | 49.6   |                    |        | $C_{i}/[kw·h·veh]$ | 14     | $r_{i}/[min]$      | 2      |

4.2 Optimization results of the first phase
The programming and calculation process are completed by Matlab2016. The laytime of the anchored ship is set to 44 hours. The near optimal solutions is shown in figure 3. It can be seen from the figure that the route of the quay cranes has no intersections at any time. The minimum operating cost of quay cranes is 11505 kw·h, and the finished time is 2597 min. The optimal scheduling scheme under this configuration scheme is as follows: during discharging, quay crane 1 discharges bay 1-3, quay crane 2 discharges bay 3-10, and quay crane 3 discharges bay 11-20. During loading, quay crane 1 loads bay 1-13, quay crane 2 loads bay 14-18, and quay crane 3 loads bay 19-20. Quay crane 1 finished discharging at the 486th min, and the quay crane 3 finished discharging at the 2323th min. The synchronous time of loading and discharging was 1837 min, which was conducive to reducing the AGV’s no-load time.
4.3 Optimization results of the second phase

Based on the results of quay crane scheduling optimization in the first phase, MATLAB programming was used to solve the scheduling problem for 3769 containers. The population size was set as 120 with the maximum iterations 1500. The result of scheduling scheme is shown in Table 2. The optimal solution 7 AGVs configured with the cost of 3857, and the utilization rate of AGVs is 55.5%.

![Fig.3. Path of the dual-trolley quay cranes](image)

| Tab.2. The scheduling results of AGV |
|-------------------------------------|
| AGV | Number of containers delivered by AGV |
|-----|--------------------------------------|
| 1   | 1→7→11→16→22→25→36→47→54→59→63→70→78→83→86→89→96→107→113→131→…→3530→3537→3545→3548→3555→3562→3567→3572→3575→3580→3585→3588 |
| 2   | 2→5→8→13→17→18→21→27→31→37→48→58→61→67→74→80→82→90→94→98→115→…→3336→3344→3348→3354→3355→3361→3367→3377→3382→3393→3398 |
| 3   | 3→4→9→14→20→23→29→32→40→44→46→49→56→62→72→85→87→92→102→11 |
| 4   | 4→…→3747→3750→3751→3753→3754→3755→3757→3758→3760→3761→3762→3767 |
| 5   | 5→6→10→12→24→34→38→42→51→60→64→69→73→76→84→88→93→99→100→105→110→…→3653→3655→3658→3661→3664→3665→3668→3674→3677→3680→3687→3691→3697 |
| 6   | 6→…→3610→3614 |
| 7   | 7→30→41→52→57→66→68→77→81→103→106→111→117→121→138→142→167→170→185→…→3702→3703→3707→3709→3710→3712→3716→3718→3721→3727→3730→3733→3738 |

4.4 Analysis and comparison of results

In order to verify the effectiveness of the model and algorithm, experiments were carried on with different AGV configuration principles. Principle 1: minimum cost of AGV. Principle 2: minimum the number of configured AGVs. Principle 3: configure quay cranes and AGVs according to the ratio of 1:3[7]. The comparison of these strategies are shown in table 3.

| Tab.3. The results of different laytime and different AGV configuration principles |
|------------------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Text | $t_f / h$ | $T_{run} / h$ | $K$ | $f_1 / kw\cdot h$ | $f_2 / kw\cdot h$ | $min\{f_1, f_2\} / (kw\cdot h)$ | Principle 1 | Principle 2 | Principle 3 |
|-----|-----------|-------------|----|-----------------|-----------------|-----------------|-------------|-------------|-------------|
| 1   | 48        | 46.46       | 3  | 11499.1         | 15374.6         | 7               | 3875.5      | 4417.4      | 4198.1      |
| 2   | 44        | 43.28       | 3  | 11505.3         | 15362.3         | 7               | 3857.0      | 4030.4      | 4168.6      |
It can be seen from table 6 that joint dispatching of quay cranes and AGV with the objective of minimizing cost (principle 1) can be optimized without any delay of the quay crane. In text 2, the cost of AGV in principle 1 can be reduced by 4.5% and 8.08% respectively compared with principle 2 and principle 3.

5. Conclusions
The two-phase scheduling optimization model proposed in this paper can optimize the joint scheduling problem between dual-trolley quay crane and AGV. The shorter the available laytime, the more the dual-trolley quay crane configuration. The solution obtained by solving the model can complete operations within laytime. In this paper, considering the decoupling effect between the buffer platform and the buffer bracket, under the constraint of AGV endurance time, the optimal configuration ratio of the QC and AGVs is about 1:2.33. Considering this problem under uncertain factors will be the future research direction.

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