Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Multi-resource collaborative scheduling problem of automated terminal considering the AGV charging effect under COVID-19

Baofeng Sun a, *, Gaoshuai Zhai a, Shi Li b, Bin Pei c

a College of Transportation, Jilin University, Changchun, 130022, China
b China FAW Group Corporation, Manufacturing Department, Changchun, 130013, China
c China FAW Group Corporation, Engineering and Manufacturing Logistics Department, Changchun, 130013, China

ABSTRACT

Since the COVID-19 ravaged the global terminals, the Automated Container Terminal (ACT) has become one of important approach to promote the stronger quick response capacity to deal with the uncertainty that COVID-19 brought to the terminal. This research takes Automated Guided Vehicle (AGV) and their effects into account the multi-resource collaborative scheduling model to tradeoff ACT operational efficiency and energy savings. Firstly, the dual-cycle strategy of QC and the pooling strategy of AGV are given, which coordinates the scheduling of Quay Cranes (QCs), Yard Cranes (YCs) and other equipment. Furthermore, a multi-resource collaborative scheduling optimization model is proposed which roots from the principle of the Blocking-type Hybrid Flow Shop Problem (B-HFSP) with the objectives of minimizing the makespan of QC and the transportation energy consumption. And simultaneously, a mixed algorithm SA-GA is designed for solving this mixed integer programming model by an optimizing effect of Simulated Annealing on Genetic algorithms. Numerical experiments show that the model in this research is effective. The convergence of SA-GA is effective for small-scale cases and superior for large-scale cases. Considering both goals of high efficiency and energy saving, the Pareto solution set and collaborative scheduling solution take a priority to ensure that the bottlenecked QC runs efficiently. Here and now the average idle rate of QC is about [14%, 35%] lower than that of other equipment. The collaborative scheduling model constructed above not only has reference value for other multi-device and multi-stage scheduling problem, but also enhance the integrated decision-making ability of the ACT in the post-epidemic era.

1. Introduction

The COVID-19 pandemic, which began in early 2020, has adversely affected the manufacturing, agriculture and service industries at varying degrees, creating stagnation and regression (Gupta et al., 2022). Global Maritime Supply Chain (MSC) faces increasing risks of uncertainty in the post COVID-19 era, ports disruptions and congestion are becoming common (Huang et al., 2022). Due to the high infectivity, long incubation period, high incidence, and asymptomatic infections of COVID-19, some shipping companies have made preparations for long-term coexistence with the pandemic (Stewart, 2021). Because the ACT holds the characteristics of unmanned and efficient, it has become an effective tool to improve port productivity during the period of COVID-19 and reduce the risk of infection among workers even from goods to workers. As important hubs of international trade, ports are significantly influenced by public health emergencies. Therefore, strict quarantine and prevention measures must be taken (Fa et al., 2021) to prevent the spread of the global epidemic. However, these measures have extended the berthing time and turnover rate of containers, as well as lowered the efficiency of cargo handling operations, and eventually reduced service satisfaction. The Automated Container Terminal (ACT), the advanced technology innovation mode of the terminal, has successfully implemented examples such as Yangshan Port IV, Qingdao Port and Rotterdam Port. During the epidemic period, the ACT has shown obvious advantages such as intelligent technology, personnel and cargo safety, and high-quality service, which enable to reduce the risk of uncertainty caused by COVID-19. However, ACT needs a huge investment in the early stage, and there are many types of large equipment such as Quay Crane (QC), Automated Guided Vehicle (AGV), and Yard Crane (YC), which lack the coordination scheduling optimization of multiple types of resources. At the same time, automation equipment brings about both high operation cost and great pressure on energy saving and
emission reduction. Those means to enhance the level of joint and smart decision making for ACT operating system systematically are urgently needed to face with the rapid changes in the new stage of the terminal. This paper therefore focuses on the multi-resource collaborative scheduling problem in ACT scenarios to offer the systematical optimization model and its high-performance algorithm to increase ACT’s capabilities of artificial intelligence in the post-pandemic era.

Therefore, this study intends to solve two problems. First, based on the objective of systematically improving the operation efficiency of the ACT, the multi-resource collaborative scheduling optimization of the QC, AGV and YC is studied to realize the integration of the scheduling plan along with AGV pooling strategy and AGV charging effects. Second, it aims to realize the energy saving of the terminals, identify and quantify energy consumption, and make full use of the function of various critical equipment, in order to obtain a scheduling solution with an obvious global energy-saving effect.

2. Literature review

Generally, the ACT system is composed of QC, AGV, and YC subsystems, which jointly complete loading and unloading tasks, transporting and stacking. ACT system collaborative scheduling refers to the terminal being regarded as a whole in the operation process, where all operation links closely cooperate to realize the optimal scheduling of all links, improve the overall scheduling effect of the system, and realize the efficient operation of ACT. These tasks are mostly attributed to the HFSP (Lee et al., 2008; Luo and Wu, 2015; Li et al., 2020; Ahmed et al., 2021). They establish the objective function of operational efficiencies, such as minimizing the makespan, energy consumption, total operational cost, and maximizing resource utilization, to build the ACT scheduling model.

On the one hand, many factors affect the efficiency of ACT. In addition to the uncertainty of ships and containers, there are also factors of the ACT system itself, such as the QC scheduling mode, that is, dual-cycle or single-cycle (Luo and Wu, 2015; Li et al., 2020; Ahmed et al., 2021); moreover, the AGV charging (Bian et al., 2015; Zhang et al., 2017) and its scheduling strategy also influence the efficiency of ACT (Schmidt et al., 2015; Ding and Chen, 2020). Among them, the dual-cycle mode refers to the QC dealing with the import and export container alternately at the same time. Compared with the single-cycle mode where the QC only deals with one kind of container when working, the advantages of dual-cycle are that it can effectively improve the efficiency of QC as a bottleneck resource and reduce the waiting time of ships in berth (Goodchild and Daganzo, 2006; Lau and Zhao, 2008). However, the ACT multi-resource collaborative scheduling problem in dual-cycle mode has high complexity. To simplify this problem, it is assumed that multiple resources have homogeneity (Xing et al., 2014; Chen et al., 2012; Zhang, 2018). In fact, the QC and YC are powered directly, while the AGV needs to charge frequently, which needs to be considered in collaborative scheduling decisions. At the same time, existing studies also assume that the battery of the AGV is sufficient when working, and there is no need to consider the problem of AGV charging. However, as the number of AGVs increases, charging becomes inevitable. In the works of Bian et al. (2015) and Zhang et al. (2017), the endurance capacity of AGV is characterized based on the remaining battery. Ding and Chen (2020) took the influence of AGV charging strategy and the makespan of the system into account when constructing the model of ACT scheduling, where the constraints such as capacity and endurance of AGV are refined. However, the scheduling policy between AGV and QC was not considered. Therefore, the collaborative scheduling of QC, YC and AGV resources based on the dual-cycle mode and considering the influence of AGV charging would be conducive to improving the operational efficiency and service level of ACT.

On the other hand, as a large transportation hub, the port needs a lot of energy to maintain its operation, which have produced a lot of industrial pollution (Wang et al., 2022). Therefore, it is necessary to try to save energy at the terminal. There have been many studies on the optimization of energy consumption. For example, Li et al. (2021) indicated that ACT configured with bilateral-cantilever ARMGs under perpendicular layout are more energy-saving than ACT with non-cantilever ARMG by means of simulation. But it could hardly avoid investing heavily in YC. Yang et al. (2019) constructed an integrated terminal scheduling model aimed at minimizing the makespan of the terminal and the energy consumption of AGV and YC, but the energy consumption of QC was not considered (Liu and Ge, 2018). proposed a convex mathematical programming model for the optimal allocation of QC and AGV. One of their objectives was to minimize CO2 emissions during the unloading of containers from QC to AGV, but they did not consider the reduction of energy consumption of AGV in the dispatching process and the carbon reduction in YC. The AGV moves between QC and YC, and its energy consumption is sensitive to the impact of ACT on the whole system, which requires in-depth analysis (He et al., 2015). Yang et al. (2019) attempted to balance the two objectives of efficiency and energy consumption by studying the ACT multi-resource integrated scheduling optimization under the dual-cycle mode. Peng et al. (2019) determined the allocation strategy of On-shore Power Supply (OPS), to realize the trade-off between total cost of OPS and carbon emissions of ships. However, from the perspective of integrated scheduling, it does not consider the energy consumption and energy replenishment methods of QC and YC. The energy consumption was based on the equipment operation time, including RMGC (Rail-Mounted Gantry Crane), AGV and YC. However, the waiting time and idle time of RMGC were ignored. Obviously, the energy-saving and emission reduction process of the terminal can be achieved from a global perspective, and the energy consumption should be identified and quantified, in order to obtain a scheduling solution with apparent energy-saving effects and solve the problem of unclear technical paths for reducing ACT energy consumption. Therefore, it is necessary to identify and quantify energy consumption from a global perspective to restore the path of energy conservation. In this way, the lack of a clear technical method to reduce ACT’s energy consumption can be addressed.

To sum up, the main contributions of this paper are as follows:

(1) Considering three heterogeneous resources with QC, AGV and YC in ACT, from the perspective of terminal collaborative scheduling, the dual-cycle mode is used to improve the utilization of key equipment, which is helpful to improve the integrated decision-making ability of ACT.

(2) To tradeoff the energy consumption and operation efficiency, a dual-cycle and multi-resource collaborative scheduling model was constructed rooting on the blocking type of hybrid flow shop problem (B-HFSP). The classical HFSP model was applied in ACT practice by considering both AGV pooling strategy and their charging effects. Based on the solution of commercial solver in small-scale examples, the effectiveness of SA-GA hybrid algorithm is verified by numerical experiments, and the superiority of SA-GA in large-scale cases is demonstrated. The SA-GA can solve NP hard problems in reasonable computation time.

(3) Taking AGV charging constraints into account of collaborative scheduling, AGV uses group scheduling to execute jobs while dealing with the multiple resources assignment and scheduling together. The impact of the number of AGVs on overall efficiency and energy consumption is quantified.

The remaining chapters are arranged as follows: Section 2 reviews the documented literature on the issues studied in this paper. Section 3 defines the question and basic assumptions. Section 4 establishes the ACT multi-resource collaborative scheduling model with minimum makespan and energy consumption under the dual-cycle strategy and clarifies the main constraints. In Section 5, an improved genetic algorithm (SA-GA) is designed. A numerical experiment is conducted in Section 6 to analyze the results of multi-resource scheduling and verify
the validity of the model and SA-GA. Section 7 summarizes the research conclusions.

3. Problem description and model design

In this section, the multi-resource collaborative scheduling problem of ACT proposed in this paper is described in detail. A mixed integer multi-objective programming model is formulated on the principle of the B–HFSP.

3.1. Problem description

The layout of the functional area and operation scenarios of the ACT studied in this paper are shown in Fig. 1. The area can be divided into shore working area, transportation area, yard handling area, and AGV charging area. Among them, the QC is located in the shore working area, which has determined sequences of operations for the container. The QC moves along the ship’s head and tail direction to complete the container loading and unloading on and off the ship.

The operation of QC in this paper is based on the dual-cycle strategy, that is, it handles the import and export tasks alternately. Compared with the single-cycle that handles only one type of container at work, the dual-cycle improves the utilization rate of the QC, which can bring better time reduction benefits and lower emissions for the terminal (Goodchild and Daganzo, 2006). The YC is set in the yard, which can be horizontally, covering all storage locations determined by the scheduling system. The yard is divided into import and export areas, which respectively house the containers entering and leaving the yard. Connected to the QC and YC systems by the transfer point, AGV moves along the guide rail in the transportation area and carries out terminal transport operations. Meanwhile, there is no temporary storage near the transfer point. What is more, the AGV charging area is set in a suitable place. The AGV adopts the pooling strategy, as shown in Fig. 1. A group of QCs (QC1–QCm) shares a resource pool (AGV1–AGVk), forming operation layer 1. Similarly, the EXYC and IMYC together with AGV form operation layer 2. The AGV can serve any QC in the operational area, but it cannot respond to the demand of other QC groups. Compared with the traditional non-pooling strategy, setting one AGV bind with a single QC improves its utilization rate, helps QC, the transportation equipment and YC to realize collaborative operation, and avoids the problem of the unbalanced workload of different AGVs.

According to Fig. 1, QC, AGV and YC complete the loading/unloading, transportation, storage/retrieval, and other operations of containers in succession according to the operation sequence of the task. For export containers, it is required to move containers from the yard to the ship in three successive stages: picking containers up from the yard, delivering them and putting them onto the ship. On the contrary, the workflow of import containers is the opposite of that of export containers. Each processing stage has certain parallel equipment, and the container can operate on any equipment. Moreover, it can be seen that the ACT multi-resource collaborative scheduling problem can be attributed to the B–HFSP (Wang et al., 2017).

In order to promote the development of the terminal in the post-epidemic period, this paper systematically optimizes the ACT operation system, while taking efficiency and energy consumption into account, to set up a collaborative scheduling optimization model. According to the principle of B–HFSP, the minimum of the makespan and transportation energy consumption is also considered, and the optimal scheduling solution for the synchronous coordination of multiple resources is obtained.

3.2. Assumptions

(1) The initial battery of AGV is known, and it can safely support it in driving from the current location to the charging area;
(2) Both the driving distance and the waiting time of AGV are proportional to the battery consumption;
(3) The QC scheduling plan is known, that is, the task sequence and the processing time of each QC are known. And the number of tasks for each QC is the same;
(4) Each type of equipment (including QC, AGV and YC) can only carry one container per operation;
(5) Neither the interference between QC and YC, nor the traffic congestion among the AGV are considered;
(6) The import and export yards are separated, and one YC (IMYC or EXYC) only serves one type of yard;
(7) External vehicles are not considered;
(8) The quantities of QC, AGV and YC are known;
(9) The travel speed of AGV with full load and no load is known to calculate the power consumption of AGV in different states;
(10) The yard has sufficient space to store the container;
(11) The weight of each container is known. That is, the power consumption rate of AGV loading containers of different weights is known;
(12) For QC, different AGVs are equivalent, and AGVs are not grouped in this study;
(13) The charging position of AGV is sufficient.

3.3. Notations

3.3.1. Description of sets

Description of variables and symbols:

\[ I_1: \text{Set of import tasks, } |I_1| = N_1; \]
\[ I_2: \text{Set of export tasks, } |I_2| = N_2; \]
\[ I:\text{Set of all tasks, } |I| = N_1 + N_2; \]
\[ I_s: \text{Set of all tasks added to the virtual starting task } (V,S), I_s = I \cup (V,S); \]
\[ I_f: \text{Set of all tasks added to the virtual ending task } (V,F), I_f = I \cup (V,F); \]
\[ I_{sv}: \text{Set of all tasks added to the virtual starting task } (V,S) \text{ and ending task } (V,F), I_{sv} = I \cup (V,S) \cup (V,F); \]
3.3.2. Description of parameters

(1) Parameters of QC

\[ \Omega_q; \quad \text{Task set of QC } q, \text{ indexed by } i, \]
\[ |\Omega_q| = N_q, \sum_{q \in Q} |\Omega_q| = N_1 = N_2, \quad \Omega_c \text{ and } \Omega_n \text{ are the same as } \Omega_q, \]
\[ q \in Q; \]

\[ X_{y(i,j)} = \begin{cases} 1, & \text{AGVa handles task } (q,i) \text{ and then } (r,j) \\ 0, & \text{otherwise} \end{cases} \]
\[ X_{y(i,j)} = \begin{cases} 1, & \text{AGVa goes to charge after completing task } (q,i) \\ 0, & \text{otherwise} \end{cases} \]
\[ \sigma_{r(i,j)} = \begin{cases} 1, & \text{YCc handles task } (q,i) \text{ and then } (r,j) \\ 0, & \text{otherwise} \end{cases} \]
\[ \sigma_{r(i,j)} = \begin{cases} 1, & \text{Task } (q,i) \text{ is stored in location } l \\ 0, & \text{otherwise} \end{cases} \]
\[ x_{r(i,j)} = \begin{cases} 1, & \text{task } (q,i) \text{ is handled by YCc} \\ 0, & \text{otherwise} \end{cases} \]

\[ \Omega_n; \quad \text{Task set of QC } n, \text{ indexed by } h, n \in Q; \]
\[ (q,i), (r,j), (n,h); \quad \text{These all represent different tasks, that is, a certain task processed by QC (loading or unloading).} \]
\[ u_{(q,i)}: \quad \text{The moment when YC } q \text{ begins to handle the task } (q,i); \]
\[ h_{(q,i)}: \quad \text{The time required for QC to process task } (q,i). \]

(2) Parameters of AGV

\[ D_{p_a}^{(i)}: \quad \text{Remaining battery of AGV after completing the task } (q,i); \]
\[ \eta: \quad \text{Travel speed of AGV under full load}; \]
\[ d_{r(j)}^{(i)}: \quad \text{Travel speed of AGV under no load}; \]
\[ d_{r(j)}^{(i)}: \quad \text{Distance of AGV from the destination of the task } (q,i) \text{ to the start of the task } (r,j); \]
\[ d_{r(j)}^{(i)}: \quad \text{For task } (q,i), \text{ the distance from its start to its destination}; \]
\[ p_{(q,i)}: \quad \text{The moment when AGV starts processing task } (q,i); \]
\[ T_{q,b}^{(i)}: \quad \text{Travel time of AGV from yard } b \text{ to the charging area}; \]
\[ T_{q,b}^{(i)}: \quad \text{Travel time of AGV from QC } q \text{ to the charging area}; \]
\[ T_{a,b}^{(i)}: \quad \text{Travel time of AGV from YC } c \text{ to the charging area}; \]
\[ T_{q,b}^{(i)}: \quad \text{Charging time of AGV}; \]
\[ \mu_a: \quad \text{Consumption of battery per unit time when AGV is running under no load; (Unit: kWh/s)} \]
\[ \mu_a: \quad \text{Consumption of battery per unit time while AGV is on standby; (Unit: kWh/s)} \]
\[ \mu_{(q,i)}: \quad \text{Consumption of battery per unit time when AGV performs tasks } (q,i). \]

(3) Parameters of YC

\[ d_{(q,i)}: \quad \text{The moment when YC } q \text{ starts processing task } (q,i); \]
\[ \varphi: \quad \text{The time for the YC to travel from the transfer point in front of the yard to location}; \]
\[ w_{(q,i)}: \quad \text{The time for the YC to travel from the location of the export task } (q,i) \text{ to the transfer point in front of its storage area.} \]

(4) Other parameters

\[ Z(x): \quad \text{0-1 function; when } x > 0, \quad Z(x) = 0, \text{ and when } x \leq 0, \quad Z(x) = 1; \]
\[ v_{(q,i)}: \quad \text{It is equal to 1 if } (q,i) \text{ is the import task, otherwise, it is equal to 0}; \]
\[ U: \quad \text{A number that is large enough}; \]

3.3.3. Description of decision variables

3.4. Mathematical model

3.4.1. Objective function

To ensure that the tasks can be completed as soon as possible so that the ship can leave the port earlier, the makespan of QC (denoted by M) should be minimized, as shown in Formula (1). Considering the energy conservation of terminals, it is necessary to achieve the minimization of transportation energy consumption (denoted by E) in the ACT joint scheduling process, as shown in Formula (2).

\[ \text{Min } f_1 = \max_q \left( u_{(q_N,i)} + h_{(q_N,i)} \right) \]  
(1)

\[ \text{Min } f_2 = E_w + E_q + E_m + E_p + E_a \]  
(2)

3.4.2. Constraint conditions

\[ E_a = \sum_{(q,i) \in I} \sum_{(r,j) \in I} \sum_{(n,h) \in I} X_{y(i,j)} \cdot d_{r(j)}^{(i)} \cdot \frac{\mu_a}{\eta} \]  
(3)

\[ E_{w_q} = \mu_w \cdot \sum_{(q,i) \in I} \sum_{(r,j) \in I} \left( u_{(q,i)} + h_{(q,i)} \right) - \left[ p_{(q,i)} + d_{r(j)}^{(i)} \cdot \frac{\mu_a}{\eta} + d_{r(j)}^{(i)} \cdot \frac{\mu_a}{\eta} \right] \sum_{(q,i) \in I} \left( q_{(r,j)}^{(i)} \right) 0 \]  
(4)

\[ E_{w_q} = \mu_w \cdot \sum_{(q,i) \in I} \left( p_{(q,i)} + d_{r(j)}^{(i)} \cdot \frac{\mu_a}{\eta} + d_{r(j)}^{(i)} \cdot \frac{\mu_a}{\eta} \right) \sum_{(q,i) \in I} \left( q_{(r,j)}^{(i)} \right) 0 \]  
(5)

\[ E_{w_q} = \mu_w \cdot \sum_{(q,i) \in I} \left( d_{(q,i)} - p_{(q,i)} - d_{(q,i)} - w_{(q,i)} \right) \]  
(6)

\[ E_{w_q} = \sum_{(q,i) \in I} \frac{d_{(q,i)}}{\eta} \mu_{(q,i)} \]
\[ E_o = \sum_{(q,i) \in \mathcal{D}} V_{o(q,i)} \chi_{o(q,i)} \mathcal{D}_{o(q,i)} \left\{ \sum_{(r,q) \in \mathcal{D}} \left[ T^{a}_{r} + (1 - v_{r}) \lambda_{o(q,i)} \right] \right\} \]

\[ = \sum_{(r,q) \in \mathcal{D}} V_{o(q,i)} \chi_{o(q,i)} \mathcal{D}_{o(q,i)} \left\{ \sum_{(r,q) \in \mathcal{D}} \left[ T^{a}_{r} + (1 - v_{r}) \lambda_{o(q,i)} \right] \right\} \]

\[ \sum_{a \in A, (r,j) \in \mathcal{D}_{o(q,i)}} x^{(r,j)}_{o(q,i)} = 1, \forall (q,i) \in I \]

\[ \sum_{a \in A, (q,j) \in \mathcal{D}_{o(q,i)}} x^{(r,j)}_{o(q,i)} = 1, \forall (r,j) \in I \]

\[ \sum_{(r,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (q,i) \in I; \forall c \in Y_{1} \]

\[ \sum_{(r,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (r,j) \in I; \forall c \in Y_{1} \]

\[ \sum_{(q,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (q,i) \in I; \forall c \in Y_{2} \]

\[ \sum_{(q,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (r,j) \in I; \forall c \in Y_{2} \]

\[ \sum_{(q,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (q,i) \in I; \forall c \in Y_{2} \]

\[ \sum_{(r,j) \in \mathcal{Y}(q,i) \cap \mathcal{A}(q,j)} d_{o(q,i)}^{(r,j)} = 1, \forall (r,j) \in I; \forall c \in Y_{2} \]

\[ d_{(q,i)} + x_{o(q,i)}^{(r,j)} \cdot (2 T_{b}^{a} + T_{b}^{a}) + \frac{d_{o(q,i)}^{(r,j)}}{\varepsilon} \leq p_{(r,j)} + U \left( 1 - x_{o(q,i)}^{(r,j)} \right) \forall a \in A, b \in B; \forall (q,i), (r,j) \in I \]

\[ u_{(q,i)} + x_{o(q,i)}^{(r,j)} \cdot (2 T_{b}^{a} + T_{b}^{a}) + \frac{d_{o(q,i)}^{(r,j)}}{\varepsilon} \leq p_{(r,j)} + U \left( 1 - x_{o(q,i)}^{(r,j)} \right) \forall a \in A, b \in B; \forall (q,i), (r,j) \in I \]

\[ u_{(q,i)} + x_{o(q,i)}^{(r,j)} \cdot (2 T_{b}^{a} + T_{b}^{a}) + \frac{d_{o(q,i)}^{(r,j)}}{\varepsilon} \leq p_{(r,j)} + U \left( 1 - x_{o(q,i)}^{(r,j)} \right) \forall a \in A, b \in B; \forall (q,i), (r,j) \in I \]

\[ u_{(q,i)} + x_{o(q,i)}^{(r,j)} \cdot (2 T_{b}^{a} + T_{b}^{a}) + \frac{d_{o(q,i)}^{(r,j)}}{\varepsilon} \leq p_{(r,j)} + U \left( 1 - x_{o(q,i)}^{(r,j)} \right) \forall a \in A, b \in B; \forall (q,i), (r,j) \in I \]
d_{(q,i)} + \chi_{a(q,i)}^{b} \cdot \gamma_{(q,i)} \cdot (2T_{b}^{k} + T_{b}^{k}) + \frac{d_{(r,j)}^{b}}{4} \leq p_{(r,j)} + U\left(1 - \chi_{a(r,j)}^{b}\right) \forall a \in A, b \in B, (q, i) \in I_{1}, (r, j) \in I_{2} \tag{30}

\begin{align}
    d_{(q,i)} + 2q_{i} & \leq U\left(1 - \rho_{(q,i)}^{c}\right) + \gamma_{(q,i)} \cdot \forall (q, i), (r, j) \in I_{1}, c \in Y_{1} \tag{31} \\
    d_{(q,i)} + \omega_{(q,i)} + d_{(r,j)} & \leq U\left(1 - \rho_{(r,j)}^{c}\right) + \gamma_{(q,i)} \cdot \forall (q, i), (r, j) \in I_{2}, c \in Y_{2} \tag{32} \\
    \chi_{a(q,i)}^{b} \cdot \gamma_{(q,i)} \cdot d_{(r,j)}^{b} & \in (0, 1), \forall a \in A, (q, i), (r, j) \in I_{1}, l \in L \tag{33} \\
    U_{(q,i), d_{(q,i)}, p_{(q,i)}, \Delta_{p_{(q,i)}}^{b}} & \geq 0, \forall a \in A, (q, i) \in I, q \in Q \tag{34}
\end{align}

\[
\begin{align}
    a_{(q,i)} + B_{(q,i)} \cdot T_{b}^{k} & \leq T_{b}^{k}, (q, i) \in I_{3}, a \in A \tag{35} \\
    \chi_{a(q,i)}^{b} \cdot \gamma_{(q,i)} \cdot d_{(r,j)}^{b} & \in (0, 1), \forall a \in A, (q, i), (r, j) \in I_{2}, l \in L \tag{36} \\
    U_{(q,i), d_{(q,i)}, p_{(q,i)}, \Delta_{p_{(q,i)}}^{b}} & \geq 0, \forall a \in A, (q, i) \in I, q \in Q \tag{37}
\end{align}
\]

(1) Constraints on the battery consumption of AGV

The AGV has five operating states of battery consumption: (1) From the previous task to the current task, the battery consumption of AGV is shown in Formula (3); (2) The standby battery consumption of AGV waiting for the task at the transfer point of QC is shown in Formula (4); (3) The standby battery consumption of AGV waiting for the task at the transfer point of QC is shown in Formula (5); (4) The battery consumption of AGV from the start of the current task to the destination is shown in Formula (6); (5) The battery consumption generated by AGV on its way to the charging area is shown in Formula (7).

(2) AGV charging constraints

During AICT loading and unloading operations, the battery capacity of AGV will be inevitably insufficient and needs to be supplemented. The existing studies lack analyses on the impact of the constraint of charging on collaborative scheduling. These studies generally regard AGV as the truck of general terminals, which does not correspond to the real situation. The efficiency will decrease significantly while the power of AGV is being replenished. Therefore, the influence of charging the AGV on the daily operation of AICT and collaborative scheduling cannot be ignored. This study therefore presents the constraints of AGV battery and introduces the variable $\Delta_{p_{(q,i)}}^{b}$ to record the battery of AGV after completing the task $(q, i)$. When AGV has completed the last task, we calculate and judge the value of $\Delta_{p_{(q,i)}}^{b}$. If it is less than that for the safe battery, AGV will not perform the task but drive to the charging area to replenish its power. When the battery is fully charged, AGV returns to work and AGV is unavailable during this period. The constraints are shown in Formulas (8)-(9).

(3) Task continuity constraint

AGV and YC cooperate with QC to complete the task. It is necessary to restrict the continuity of containers processed by AGV and YC. Equations 10 and 11 indicate that the task of an AGV is continuous. Equations 12-15 indicate that the tasks of a YC are continuous, and one YC can only serve one type of yard. Equations (12)-(14)-(15) represent the loading and unloading continuity of IMYC and EXYC, respectively. Formula (16) indicates that each import container is stored in a single storage location.

(4) Constraints on device resources

The number of device resources used cannot exceed their maximum number. The quantitative limitations of AGV and YC are described in Formulas (17)-(23). Formulas (17)-(18) represent the quantitative limitation of AGV. Equations (19)-(21)-(22) represent the restrictions on the quantity of IMYC and EXYC, respectively. Formula (23) indicates that each available storage location can store only one container.

(5) Constraints on the container operation time

Operated jointly by various equipment, the import container is finally stored in the yard, and the export container is loaded onto the ship. The operation time constraints of the import and export containers are shown in Formulas (24)-(25). For a single QC, the time to process two containers continuously is shown in Formula (26). AGV can

---

**Table 1**

| task | AGV | EXYC |
|------|-----|------|
| (1, 2) | 5   | 4    |
| (1, 4) | 3   | 4    |
| (1, 6) | 3   | 2    |
| (1, 8) | 5   | 3    |
| (2, 2) | 8   | 1    |
| (2, 4) | 8   | 4    |
| (3, 2) | 7   | 1    |

**Algorithm running process 1 SA-GA**

- **Input:** data  
  - **Output:** ST  
  - 1. **individuals** = Initialize(data)  
  - 2. [individuals,ST] = Non-domination-sort(individuals)  
  - 3. for $i = 1 \rightarrow \text{Maxgen}$ do  
  - 4. offspring1 = genetic-operator(individuals,ST)  
  - 5. [individuals, offspring2] = SA(individuals)  
  - 6. temp = [individuals, offspring1, offspring2]  
  - 7. individuals = replace(temp)  
  - 8. $T = T + q$  
  - 9. end for  
  - 10. [Pareto, ST] = Non-domination-sort(individuals)  

**Fig. 2.** Pseudo-code of SA-GA.
transport different types of containers. Formulas (27)-(30) respectively represent the time constraints for one AGV to continuously transport two export containers, two import containers, export-import container, and import-export container. Formulas (31)-(32) respectively represent the time constraints of processing two tasks by IMYC and EXYC.

(6) Logical constraints of variables

The ranges of values of decision variables and other related variables are presented by Formulas (33)-(34).

4. Algorithm design

The terminal integrated scheduling problem studied in this paper belongs to the B–HFSP and has the characteristic of bidirectional scheduling, which has no buffer zone for containers at any stage. This constitutes nonlinear Mixed-Integer Programming (MIP) and has been proved to be an NP-hard problem, which has higher complexity than single-direction scheduling. In some of the similar studies (Luo and Wu, 2015; Li et al., 2020), single intelligent algorithm is applied to solve the problem. In order to strengthen the effectiveness and persuasiveness of the algorithm, a Genetic Algorithm based on the operation of Simulated Annealing (SA-GA) is applied to solve the problem. The Simulated Annealing Algorithm (SAA) is not comprehensive enough for the overall search space; therefore, it does not easily enter the optimal search area. By incorporating the operation of Simulated Annealing (SA) into Genetic Algorithm (GA), falling into local optimum can be avoided and the efficiency of GA itself can be ensured. The improved algorithm will enhance the convergence and diversity of solutions.

4.1. Algorithm flow

In this paper, the SA-GA is designed to select suitable individuals for the SA operation after the evolution of the population in GA. As the number of iterations increases, the temperature gradually decreases and the optimization goal is finally achieved.

The SA-GA computing framework is constructed, and the pseudo-code of the algorithm running process is shown in Fig. 2.

4.2. Design of algorithm elements

4.2.1. Initial population setting

In this paper, the chromosome (genetic algorithm) in the SA-GA is taken as the scheduling solution, and a coding structure in matrix form is adopted. This can avoid splitting the integrated scheduling problem into the two-stage optimization problem of allocating AGV and YC, and can directly solve the overall problem of scheduling.

The unloading, loading and transportation processes of import and export containers are different; the former unloaded by QC needs to be transported to the yard through AGV, and then transported to the

| task | AGV | IMYC | SL |
|------|-----|------|----|
| (1,1)| 3   | 3    | 2  |
| (1,3)| 8   | 2    | 6  |
| (1,5)| 3   | 3    | 4  |
| (1,7)| 3   | 3    | 1  |
| (2,1)| 5   | 2    | 5  |
| (2,3)| 1   | 3    | 3  |
| (3,1)| 2   | 2    | 7  |

Table 2 Example of export task chromosome encoding.

Fig. 3. Pseudo-code of the objective function.

Table 2

| task | AGV | IMYC | SL |
|------|-----|------|----|
| (1,1)| 3   | 3    | 2  |
| (1,3)| 8   | 2    | 6  |
| (1,5)| 3   | 3    | 4  |
| (1,7)| 3   | 3    | 1  |
| (2,1)| 5   | 2    | 5  |
| (2,3)| 1   | 3    | 3  |
| (3,1)| 2   | 2    | 7  |

Example of export task chromosome encoding.

Fig. 4. Two-point crossover for AGV and YC.
designated storage location (denoted by SL in the chromosome) in the yard by YC. The processing flow of export containers is the opposite. As the QC assigned to the import containers is known in advance, the import chromosome is a matrix of three columns, which respectively indicate the AGV, YC and SL. Since the location of the export containers in the yard and the QC assigned to them is known, the export chromosome is a two-column matrix, which indicates the assigned AGV and YC. Each row in the matrix represents the equipment assigned to the task. The equipment assigned to each task is random, and the initial solution is generated accordingly. Different tasks cannot be assigned to the same SL, but they can be assigned to the same AGV or YC.

As shown in Tables 1 and 2, there are 7 import tasks and 7 export tasks, 3 QC, 8 AGV, and 12 YC (6 each for IMYC and EXYC) to complete the loading and unloading tasks. A pair of import and export chromosomes indicate a solution to the problem, and the population is initialized on this basis.

4.2.2. Calculation of objective functions

The sequence of QC handling containers and the location of import containers are known. Under these conditions, the objective function of the terminal scheduling model is to minimize $M$ and $E$. After the initial population has been formed, the equipment to process the container is successively allocated and the operation time is determined. The task is completed when the import container is placed in the storage location or the export container is loaded onto the ship. In this way, the loading and unloading of containers continues until all tasks are finished.

To obtain the scheduling solution efficiently and resolve the task conflict problem of ACT by a dual-cycle strategy, the concept of “task pair” is introduced here, that is, two consecutive tasks (one import task and one export task) of any QC are performed. This paper assumes that the order in which QC loads the containers is known, but this is unknown to IMYC and EXYC, and the strategy adopted to determine the order is crucial to the whole problem. The loading sequence of the IMYC container is determined by the completion time of AGV, which is the previous stage of the import task (i.e., the principle of ‘first come first served’ is adopted). EXYC is the first-stage equipment to deal with the export task. Given the uncertainty of the loading sequence of EXYC, the following method is adopted to solve the problem: for the multiple tasks assigned to EXYC, the shorter the task duration, the higher the service priority, thereby EXYC can release the current tasks more quickly and improve the utilization rate of QC and AGV.

Overall, the pseudo-code for solving the objective function is shown in Fig. 3.

4.2.3. Strategy of crossover

This paper applies the strategy of tournament selection, which is conducted according to the level of non-dominated sorting from selecting excellent individuals in a population to updating the parent. At the same time, the whole population is operated by Simulated Annealing (SA) to produce offspring. All offspring are sorted in a non-dominated order and crowding is calculated. The individuals with the highest-ranking are selected to enter the next iteration.

Since each container can be transported by any AGV and handled by any YC of the same type, the AGV and YC parts of chromosomes adopt a two-point crossover operator, that is, two crossover points are randomly set and gene segments between these two points are exchanged (as shown in Fig. 4). The uniform order-based crossover operator is applied for the SL part of the import chromosome (see Fig. 5).

4.2.4. Operation of SA

The SA-GA in this paper is referred to Czyzak and Jaszkiewicz (1998). To build the SA operator, the temperature update function is set to $h(q,i)$, and the SA operation is performed on each generation population. Compared with the NSGA-II, the SA operation performs a random interference on chromosomes (as shown in Fig. 6, taking imported chromosomes as an example), and accepts a new solution according to a certain probability, which is inferior to the current solution. Therefore, this algorithm can jump out of the local optimum more effectively and avoid premature convergence.

---

**Fig. 5.** Uniform order-based crossover for SL.

**Fig. 6.** Random interference of import task chromosomes by simulated annealing.

**Fig. 7.** GAP($M$) and GAP($E$) of different cases.
5. Numerical experiments

In order to verify the validity of the algorithm, a benchmark example and numerical experimental conditions are designed. The operation parameters of the terminal were set by referring to the literature (Wu et al., 2013; Luo and Wu, 2015); see (1)–(4), including the AGV operation parameters (Ding and Chen, 2020). Thus, 38 benchmark cases were generated in this paper, as shown in Appendix A.

(1) The time for QC to process tasks is related to its location on the ship or yard where the import and export containers are located, which follow uniform distribution, i.e., \( h(q_i) \sim U(30,180) \) s (Luo and Wu, 2015);
(2) We refer to the literature (Luo, 2013) when setting the distance and location parameters between the node, such as QC, YC, and storage location;
(3) The time for IMYC to load the containers at the transit point and store them in location 1 obeys uniform distribution, i.e., \( q_i \sim U(40,160) \) s (the time of EXYC to pick up the containers and deliver to the transfer point at the front of the yard is related to the storage location and obeys uniform distribution, i.e., \( w(q_i) \sim U(40,160) \) s (Luo and Wu, 2015);
(4) The AGV can be divided into two working states: no load and full load. In different states, the travel speed and power consumption parameters are different; refer to Appendix B (Ding and Chen, 2020).

The numerical experimental conditions are as follows: running times: 30; algorithm code based on MATLAB: R2018b; running environment: Intel i5-10210U 2.11Ghz 16.0 GB RAM.

5.1. Analysis of model validity

This chapter verifies the model validity by analyzing the influence of the AGV charging constraint on the optimal solution set of the model. Scenario with battery restriction: Before the task, all AGVs are fully charged and are on standby. During the execution of the task, if the battery level of any AGV is lower than safe, it moves to the charging area and continues to work until all tasks are completed.

Scenario without charging restriction: Before the task, all AGVs are restored to full power, the task plan is prepared. When all AGVs are restored to full power, the task plan is restarted.

Finally, the current task will be terminated for centralized device maintenance. When all AGVs are restored to full power, the task plan is restarted.

When considering the charging constraint, for the same set of initial solution X, the value of the set of optimal solution F1 is (M1, E1). Without the charging constraint, the value of the set of optimal solution F2 is (M2, E2). GAP (M), GAP (E) calculation method: GAP (M) = [(M2 - M1)/M1] * 100%, GAP (E) = [(E2 - E1)/E1] * 100%. The comparative results of GAP (M) and GAP (E) are shown in Fig. 7.

According to the figure above, when the case is small-scale (Examples 1 to 22), 77.27% (17/22) of GAP (M) values are positive. Meanwhile, in large-scale cases, 93.75% (15/16) of GAP (M) are positive. It can be seen that M1 has a more significant effect in large-scale cases than M2. Similarly, for GAP (E), 95.45% (21/22) and 100% (16/16) are positive in all cases. Obviously, solution set E1 is superior to E2. In general, the GAP (M) value of 84.21% (32/38) of solutions is positive, and the GAP (E) value of 97.37% (37/38) of solutions is positive among the 38 benchmark cases. The optimal solution set F1 considering charging constraints is better than set F2. Therefore, the corresponding solution for ACT multi-resource scheduling is superior to the traditional one. In conclusion, the model constructed in this paper is effective.

5.2. Analysis of algorithm validity

5.2.1. Algorithm parameter setting

The Taguchi experimental method was applied to optimize the parameters of SA-GA, NSGA-II and MOSA. Since large-scale solution is of more practical significance, here we all apply Case 30 to carry out experiments. For SA-GA, 5-parameter and 4-factor levels were considered, the orthogonal table \( L_{16}(4^5) \) was selected. For NSGA-II and MOSA, 4-parameter and 4-factor levels were considered, the orthogonal table \( L_{16}(4^5) \) was selected (see Table 3). We run 10 times for various combinations of parameters, and the algorithm performance under any parameter combination i was evaluated by a Response Variable (RV). The calculation method is expressed in Formula (5-1), where \( n \) represents the number of repeated runs under each parameter combination; RS represents the non-dominated solution set of all approximate Pareto solution sets; \( PA_i \) denotes the approximate Pareto solution set obtained by running the parameters for j time under combination i.

5.2.2. Solving small scale cases

Since there are some nonlinear expressions in the model in this paper, we introduce some auxiliary variables to perform transformation of linearization equivalently. For the part where binary variables and continuous variable are multiplied, as shown in Formula (4), auxiliary variables \( \theta_{a,h}^{(i)} \) and \( \theta_{a,h}^{(i)} \) are introduced to do the following equivalent linearization transformation.

\[
\theta_{a,h}^{(i)} \in [0, U] \forall a \in A, (q,i) \in I, (n,h) \in I
\]

\[
\theta_{a,h}^{(i)} \leq U \cdot x_{a,h}^{(i)} \forall a \in A, (q,i) \in I, (n,h) \in I
\]
The mean RV values and their ranking are shown in Table 5. The parameters of the NSGA-II were determined as follows: 

The mean RV values and their ranking are shown in Table 6.

The conversion process of $\theta_{\text{str}}$ is similar to that of $\theta_{\text{str}}$. Formula (4) is converted as follows:

For the part where binary variables are multiplied, as shown in Formula (7), auxiliary variables $t_{\text{q}ij}$ are introduced to do the following equivalent linearization transformation.

| Table 5 | Mean values and significance levels of RV (NSGA-II). |
|---|---|
| Level | $\text{staspop(RV)}$ | $\text{maxgen(RV)}$ | $\text{percross(RV)}$ | $\text{pmutation(RV)}$ |
| 1 | 0.264 | 0.451 | 0.719 | 0.563 |
| 2 | 0.389 | 0.752 | 0.466 | 0.484 |
| 3 | 0.621 | 0.684 | 0.342 | 0.395 |
| 4 | 0.547 | 0.182 | 0.310 | 0.272 |
| RV | 0.357 | 0.570 | 0.409 | 0.291 |
| RV (rank) | 3 | 1 | 2 | 4 |

The mean RV values and their ranking are shown in Table 6.

| Table 6 | Mean values and significance levels of RV (MOSA). |
|---|---|
| Level | $T_0$ (RV) | $T_\text{c}$ (RV) | $q_0$ (RV) | $t$ (RV) |
| 1 | 0.244 | 0.133 | 0.563 | 0.015 |
| 2 | 0.638 | 0.421 | 0.687 | 0.004 |
| 3 | 0.794 | 0.937 | 0.755 | 0.319 |
| 4 | 0.465 | 0.301 | 0.890 | 0.018 |
| RV | 0.550 | 0.804 | 0.327 | 0.315 |
| RV (rank) | 2 | 1 | 3 | 4 |

For other similar nonlinear parts in 3.4, the two linearization methods above are adopted, so that a linear MIP model can be obtained.

For other similar nonlinear parts in 3.4, the two linearization methods above are adopted, so that a linear MIP model can be obtained.

Firstly, SA-GA, NSGA-II, MOSA and the commercial solver Gurobi (Version of 9.5.2) were applied to solve small-scale cases 1–10 and the analysis of results is shown in Tables 7 and 8. By comparing the average of M, E and CPU (computing) time of Pareto solution sets, it can be found that the three heuristic algorithms have different gaps compared with the results obtained by Gurobi. For example, the minimum GAP (M) in MOSA is 0.19% and the largest is 3.39%, and the minimum GAP (M) of SA-GA is 0.41% and the maximum is 12.88%. But both the GAP(M) and GAP(M) vary within acceptable limits, which shows that these three heuristics are effective. For the CPU time of the two types of methods, Gurobi’s CPU time varies greatly and increases exponentially with the increase of the size of the case while the CPU time of the heuristic algorithm is very short. What’s more, the SA-GA we proposed can obtain the optimal/near-optimal solution in reasonable time.

Gurobi is not suitable for solving large-scale cases due to its long computing time, and the heuristic algorithm becoming more practical. The performance indicators of the three algorithms under large-scale cases are discussed in 5.2.3. 

5.2.3. Performance comparison of heuristic algorithms with large-scale cases

The NSGA-II and MOSA were selected for performance comparison with SA-GA. The performance of these algorithms was evaluated from many perspectives, including searchability, convergence ability, distribution of solution, running time, and comprehensiveness of the algorithm, which are respectively represented by the number of non-dominated solutions (Num), Error Rate-ER, Spacing indicator (S), Computing time (T), and Inverted generational distance (IGD). The effectiveness of SA-GA, NSGA-II, and MOSA for cases with different scales was analyzed.

It can be seen that, in the small-scale cases, the Num of NSGA-II is large, whereas in large-scale cases, the complexity of the problem is greatly increased, and there is a large gap between the three algorithms (see Fig. 8). With the increase of complexity, the searching ability of MOSA and NSGA-II decreases significantly, while SA-GA can maintain good searching ability and find more Num. For instance, in Case 32, the Num of SA-GA is 13, which is 4.3 times and 1.4 times of MOSA and NSGA-II, respectively.

As shown in Fig. 9, for large-scale cases, the ER of SA-GA is generally smaller than that of the other two algorithms, that is, SA-GA can obtain

| Table 7 | Comparison of the results between heuristic algorithms and Gurobi under small-scale cases. |
|---|---|
| Index of case | SA-GA | NSGA-II | MOSA | Gurobi |
| | M(s) | E(kWh) | CPU(s) | M(s) | E(kWh) | CPU(s) | M(s) | E(kWh) | CPU(s) | M(s) | E(kWh) | CPU(s) |
| 1 | 345.6 | 23.4 | 20.16 | 316.8 | 22.8 | 60.52 | 311.0 | 24.6 | 7.75 | 309.1 | 22.2 | 0.05 |
| 2 | 410.7 | 29.0 | 67.84 | 404.8 | 29.0 | 65.49 | 397.4 | 29.0 | 10.64 | 386.3 | 29.0 | 2.35 |
| 3 | 511.8 | 34.2 | 64.60 | 460.2 | 33.4 | 101.33 | 460.6 | 33.9 | 7.97 | 457.8 | 32.8 | 0.06 |
| 4 | 527.5 | 37.0 | 90.34 | 493.4 | 36.8 | 102.20 | 484.4 | 35.4 | 18.27 | 468.5 | 35.4 | 56.45 |
| 5 | 557.9 | 41.6 | 120.35 | 548.4 | 40.5 | 130.16 | 538.4 | 43.2 | 17.92 | 524.7 | 39.6 | 0.12 |
| 6 | 698 | 45.6 | 41.81 | 639.8 | 43.7 | 128.24 | 628.2 | 45.7 | 11.46 | 618.4 | 42.9 | 1365.24 |
| 7 | 617.4 | 49.8 | 104.33 | 567.3 | 49.9 | 96.18 | 568.4 | 49.9 | 13.49 | 567.3 | 49.8 | 986.35 |
| 8 | 818.6 | 71.2 | 57.08 | 842.1 | 72.5 | 91.75 | 826.7 | 72.0 | 13.66 | 817.3 | 70.7 | 8649.21 |
| 9 | 1035.3 | 96.0 | 138.21 | 1085.7 | 98.4 | 185.85 | 1066.0 | 98.2 | 13.52 | 1031.1 | 96.0 | 14871.86 |
| 10 | 1402.7 | 112.9 | 67.28 | 1395.7 | 116.6 | 215.35 | 1366.2 | 108.7 | 19.91 | 1357.2 | 106.2 | 17658.65 |
more real Pareto solutions and its performance of convergence is good. However, SA-GA performs poorly in the small-scale cases. The \( ER \) of NSGA-II has the opposite trend to SA-GA, and the \( ER \) of MOSA does not change significantly in all cases.

As shown in Fig. 10, for small-scale cases, the differentiation ability of the three algorithms is low, which is because smaller cases mean fewer permutations and combinations. For large-scale cases, there are more permutations and combinations, as well as more Pareto frontier solutions, and the \( S \) of SA-GA is less than that of MOSA and NSGA-II in most cases, therefore, its solution distribution is better than that of the other two algorithms.

The smaller the \( T \) value, the lower the time complexity of the algorithm. Fig. 11 shows the \( T \) of the algorithms under different cases. In general, the \( T \) of SA-GA is greater than that of MOSA and smaller than that of NSGA-II. For example, for small-scale cases, the mean of \( T \) of the three algorithms are respectively 184.24 s, 43.71 s and 238.31 s. The \( T \) of SA-GA is larger than that of MOSA but smaller than that of NSGA-II. The SA-GA algorithm saves 45.48% of time compared with NSGA-II, but it takes 4.22 times longer than MOSA.

According to Fig. 12, the \( IGD \) of SA-GA is similar to that of NSGA-II, and the \( IGD \) of MOSA increases with the complexity of cases. The reason

### Table 8

|           | SA-GA | NSGA-II | MOSA |
|-----------|-------|---------|------|
| GAP(M)    | 11.83 | 6.32    | 11.80|
| GAP(E)    | 5.24  | 4.39    | 4.39 |
| GAP(M)    | 2.51  | 4.79    | 5.30 |
| GAP(E)    | 2.54  | 0.00    | 3.82 |
| GAP(M)    | 6.44  | 4.51    | 2.33 |
| GAP(E)    | 2.88  | 2.07    | 3.39 |
| GAP(M)    | 0.64  | 0.62    | 0.80 |
| GAP(E)    | 10.73 | 3.37    | 0.08 |
| GAP(M)    | 6.32  | 12.59   | 2.48 |
| GAP(E)    | 0.12  | 4.63    | 2.07 |
| GAP(M)    | 4.79  | 5.30    | 3.82 |
| GAP(E)    | 0.00  | 4.51    | 2.33 |
| GAP(M)    | 2.51  | 2.33    | 2.33 |
| GAP(E)    | 2.88  | 3.39    | 3.39 |

\( \text{GAP(M)} = (M \text{ from SA-GA or NSGA-II or MOSA} - M \text{ from Gurobi}) \times 100\% / M \text{ from Gurobi} \) (Unit: %).

\( \text{GAP(E)} = (E \text{ from SA-GA or NSGA-II or MOSA} - E \text{ from Gurobi}) \times 100\% / E \text{ from Gurobi} \) (Unit: %).
is that MOSA essentially only iterates continuously for an initial solution, and the algorithm collects excellent solutions during the process of iteration, which leads to low operational efficiency.

5.3. Analysis of operation effect of multi-resource collaborative scheduling

Compared with experiments on the resource allocation optimization of the terminal (Luo and Wu, 2015; Yue et al., 2019, 2021), from the perspective of ACT system optimization, this paper takes makespan, workload distribution, and resource utilization as indexes. Then, it analyzes the operation of QC, AGV and YC and their contribution to the ACT system.

5.3.1. Changes in the average idle rate of multiple resources

In order to describe the solution to the problem, Case 30 is taken as an example, and Fig. 13 presents the relevant Gantt diagram.

Taking Case 30 as an example, assuming that the working rate of each type of equipment = (total working time of equipment/final completion time of equipment) × 100%, the corresponding idle rate is: 1 − working rate. The variation of the average idle rate of various devices under Pareto frontier solution sets is shown in Fig. 14.

According to Fig. 14, it can be established that: (1) The average idle rate of QC [14%, 35%] is lower than that of other equipment because the...
Objective function $M$ is to minimize the makespan of QC, which gives priority to ensuring the efficiency of QC. (2) The average idle rate of AGV [54%, 67%] is higher than that of other equipment, and the overall utilization efficiency is low. The average idle rates of IMYC and EXYC are approximately [22%, 44%] and [26%, 45%], respectively.

5.3.2. Effect of number of AGVs and their charging constraints on the objective function

(1) According to Fig. 15 (a), set $\Delta M_i = \left[\frac{M_i^{X+1} - M_i}{M_i^i}\right] \times 100\%$ to represent the change of $M$ with the number of AGVs. As the number of AGVs increases, for feasible solutions ($X = 1$ to 11), $\Delta M_i$ is [-13%, -7%]. Increasing the number of the AGVs can significantly reduce $M$. For the solution ($X \geq 12$), $\Delta M_i$ is [-5%, 4%], where the increase in the number of the AGVs reduces its influence on $M$.

(2) According to Fig. 15 (b), set $\Delta E_i = \left[\frac{E_i^{X+1} - E_i}{E_i}\right] \times 100\%$ to represent the change of $E$ with the number of AGVs. As the number of the AGVs increases, $\Delta E_i$ ranges in [-7%, 8%], and this change is not obvious. The reason is that no matter to what extent the number of AGVs is increased, all ACT tasks need to be completed with the help of AGVs, which require a certain amount of work to operate. Affected by the different loading capacities of AGVs, there is a slight difference, but the total energy consumption fluctuates around 400 kWh.

(3) Fig. 16 shows the average charging rate and idle rate of AGVs in different numbers. As the number of AGVs increases, the average working rate of AGV decreases from 55% to 30%. After the feasible solution ($X = 9$), the decline rate of AGV average working rate slows down, because the number of AGVs is inversely proportional to the average number of tasks.

It can be seen that: (1) The average charging rate of AGV is positively correlated with their average working rate. When the average working rate of an AGV decreases, its charging rate also decreases. (2) With the increase of AGVs, their charging rate becomes progressively lower. When the number of AGVs exceeds 12 (in Case 30), the charging rate is about 0. Due to the large number of AGVs, the average number of operations and frequency to charge any AGV becomes reduced. If the number of AGVs continues to rise, the resources will be wasted.

6. Conclusions

In the post-epidemic era of COVID-19, it is of great significance to break through the technical bottleneck of automatic terminal operation optimization, which is one of the important strategies for smart ports of various countries to cope with the long-term coexistence of the epidemic and provide high efficiency, high quality and sustainability of the terminal. This research stands up the situation along with increased throughput and low efficiency of the port caused by the COVID-19 epidemic. Multi-resource collaborative scheduling of ACT affected by the charging operation of AGV is studied deeply in this paper, and the dual-cycle and pooling strategy are adopted, which synchronously dispatches the QC, YC, import & export tasks, and other resources.

The main conclusions are summarized as follows:

(1) The COVID-19 pandemic has exposed that the global port and shipping industries lack of systematic coordination in the management of operations not only among terminals but also among multiple heterogeneous resources inside of terminal. From the perspective of global scheduling, the scheduling problem of ACT (including the QC, AGV and YC operating systems) in the dual-cycle strategy is defined in this paper more comprehensively.
To obtain a scheduling solution with a satisfactory energy-saving effect, this paper optimizes both the efficiency target and energy-saving target to construct a dual-cycle multi-resource collaborative scheduling model based on the B-HFSP model. Those important constraints in model are improved, such as idle time, no-load time, waiting time, and conflict problems of the tasks of various key equipment. Thus, a model reference is provided for seeking the optimal ACT multi-resource collaborative scheduling solution to enhance the terminal rapid response capability and high-quality operation level in the post-COVID-19 era. At the same time, the model constructed based on the B–HFSP theory also showed a certain reference value for those multi-stage task scheduling problems, such as the warehousing process of auto parts, the supply of materials to workshop production, and so on.

(2) The ACT energy-saving and ACT transport energy consumption are deeply tracked and quantified. It is noted that the combined transport energy consumption of AGVs’ horizontal operations so-called AGV pooling strategy, is an important component of ACT’s combined energy consumption. Given that charging has been ignored in previous papers, this study lists the quantification method of energy consumption corresponding to the five working states of AGV, thus providing methodological support for the measurement of AGV dynamic energy consumption. In this way, a quantitative basis is established for revealing the exact impact of the charging constraints of AGV on dual-cycle multi-resource collaborative scheduling. Therefore, the model constructed in this paper is more consistent with the actual operation of ACT terminals.

(3) To solve the NP-hard problem of the multi-resource collaborative scheduling model and the task conflict in bidirectional operation, this study designs the SA-GA and redesigns the benchmark cases. SA-GA solving the mode is firstly proved effectively by analyzing the solution results of Gurobi and SA-GA under small-scale cases. And then, the SA-GA and MOSA and NSGA-II are compared with their performances such as the searchability, convergence ability, distribution of solution, running time, and comprehensiveness of the algorithm to the large-scale cases. The analysis of benchmark cases shows that SA-GA is able to get good solutions in a short time and outperforms MOSA and NSGA-II when solving the problem in this research.

In addition, the COVID-19 pandemic has exposed a lack of systematic coordination in the management of operations in the global port and shipping industries. This study provides a basis for considering the improvement of terminal operation efficiency, and has certain practical significance for improving the operation level of terminal management companies. Firstly, with the increasing uncertainty of the maritime supply chain, cargo accumulation and port congestion caused by delayed receipt of goods often occur at the terminals. How to mitigate such risks becomes a key issue for the industry. Based on more advanced theories, this paper describes the dispatching model of ACT work scenario, which can effectively improve the operation efficiency and provide solutions for the efficient operation and energy-saving of the terminal in the post-epidemic period. Second, because ACT’s efficient operation can replace a large amount of human labor, it can reduce the potential for port shutdown due to the pandemic, which is important for redesigning highly flexible global supply chain systems and networks and maintaining strong partnerships among shipping stakeholders.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant number 61873109]; the Natural Science Foundation of Jilin Province [grant number 20210101055JC]; and the FAW Technology Innovation Project [grant number KF2020-20006].

Appendix A

| Index | Number of containers | Number of AGV | Number of QC | Number of IMYC & EXYC |
|-------|----------------------|---------------|--------------|-----------------------|
| 1     | 5                    | 2             | 2            | 2                     |
| 2     | 6                    | 2             | 2            | 2                     |
| 3     | 7                    | 2             | 2            | 2                     |
| 4     | 8                    | 2             | 2            | 2                     |
| 5     | 9                    | 2             | 2            | 2                     |
| 6     | 10                   | 3             | 2            | 2                     |
| 7     | 10                   | 4             | 2            | 3                     |
| 8     | 15                   | 3             | 2            | 2                     |
| 9     | 20                   | 3             | 2            | 2                     |
| 10    | 25                   | 5             | 2            | 3                     |
| 11    | 30                   | 3             | 2            | 3                     |
| 12    | 30                   | 4             | 2            | 3                     |
| 13    | 30                   | 5             | 2            | 2                     |
| 14    | 40                   | 4             | 2            | 3                     |
| 15    | 40                   | 4             | 2            | 2                     |
| 16    | 40                   | 4             | 2            | 2                     |
| 17    | 50                   | 4             | 3            | 2                     |
| 18    | 50                   | 4             | 3            | 2                     |
| 19    | 50                   | 5             | 2            | 3                     |
| 20    | 60                   | 4             | 2            | 3                     |
| 21    | 60                   | 5             | 2            | 3                     |
| 22    | 60                   | 6             | 2            | 3                     |
| 23    | 70                   | 6             | 3            | 4                     |

(continued on next page)
Appendix B

AGV Parameter Setting

| Parameter | No-load | Full-load |
|-----------|---------|-----------|
| Speed (m/min) | 350.0 | 210.0 |
| Power consumption per 100 m(%) | 1.0 | 2.0 |

References

Ahmed, E., El-Abbasy, M.S., Zayed, T., Alfarah, G., Akass, S., 2021. Synchronized scheduling model for container terminals using simulated double-cycling strategy. Comput. Ind. Eng. 154, 107–118.
Bian, Z., Yang, Y., Mi, W., Mi, C., 2015. Dispatching electric AGVs in automated container terminals with long travelling distance. J. Coast Res. 73, 75–81.
Chen, Chao, Zhang, Zhe, Zeng, Qingcheng, 2012. Integrated scheduling model of mixed cross-operation for container terminal. Journal of Traffic and Transportation Engineering 12, 92–100.
Czyzak, P., Jaszkiewicz, A., 1998. Pareto simulated annealing - a metaheuristic technique for multiple-objective combinatorial optimization. J. Multi-Criteria Decis. Anal. 7, 34–47.
Ding, Yi, Chen, Ting, 2020. Charging scheduling of multi-loading AGV based on rolling time domain optimization strategy. Navigation of China 43, 80–85.
Fa, Zhancheng, Wang, Chongshan, Wang, Yuefeng, Liu, Yuwei, Zhang, Xiao, 2021. Establishment of COVID-19 prevention and control system at automated container terminals. Containerization 32, 5–8.
Goodchild, A.V., Daganzo, C.F., 2006. Double-Cycling strategies for container ships and their effect on ship loading and unloading operations. Transport. Sci. 40, 473–483.
Gupta, V., Santosh, K., Arora, R., Ciano, T., Kalid, K.S., Ca1, S.M., 2022. Socioeconomic impact due to COVID-19: an empirical assessment. Inf. Process. Manag. 59, 102810.
He, J., Huang, Y., Yan, W., Wang, S., 2015. Integrated internal truck, yard crane and quay crane scheduling in a container terminal considering energy consumption. Expert Syst. Appl. 42, 2464–2487.
Huang, L., Tan, Y., Guan, X., 2022. Hub-and-spoke Network Design for Container Shipping Considering Disruption and Congestion in the Post COVID-19 Era, vol. 225. Ocean & Coastal Management.
Lau, H.Y.K., Zhao, Y., 2008. Integrated scheduling of handling equipment at automated container terminals. Int. J. Prod. Econ. 112, 665–682.
Lee, D.-H., Wang, H.Q., Miao, L., 2008. Quay crane scheduling with non-interference constraints in port container terminals. Transport. Res. E Logist. Transport. Rev. 44, 124–135.
Li, H., Peng, J., Wang, X., 2020. Integrated resource assignment and scheduling optimization with limited critical equipment constraints at an automated container terminal. IEEE Trans. Intell. Transp. Syst. 22, 1–12.
Li, L., Peng, Y., Huang, J., Wang, W., Song, X., 2021. Simulation Study on Terminal Layout in Automated Container Terminals from Efficiency, Economic and Environment Perspectives, vol. 213. Ocean & Coastal Management.
Liu, D., Ge, Y.-E., 2018. Modeling assignment of quay cranes using queueing theory for minimizing CO2 emission at a container terminal. Transport. Res. Transport Environ. 61, 140–151.
Luo, J., 2013. Modelling of Quayside Logistics Problems at Container Terminals. Ph.D., University of Southampton.
Luo, J., Wu, Y., 2015. Modelling of dual-cycle strategy for container storage and vehicle scheduling problems at automated container terminals. Transport. Res. E Logist. Transport. Rev. 79, 49–64.
Peng, Y., Li, X., Wang, W., Wei, Z., Bing, X., Song, X., 2019. A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. Ocean Coast Manag. 167, 158–175.
Schmidt, J., Meyer-Barlag, C., Eisel, M., Kolbe, L.M., Appelrath, H.-J., 2015. Using battery-electric AGVs in container terminals — assessing the potential and optimizing the economic viability. Res. Transport. Bus. Manag. 17, 99–111.
Shi, M., 2021. Terminal keeps investing through Covid-19. Automot. Ind. 200, 74–75.
Wang, C., He, X., Ma, M., Xiong, L., Zhang, W., 2022. Assessing coastal ecosystem carrying capacity by a comprehensive economy-resources-environment system: A case study of South Korea. Ocean Coast Manag. 227.
Wang, Ling, Wang, Shengyao, Fang, Chen, 2017. Estimation of Distribution Algorithms for Scheduling. Tsinghua University Press, Beijing.
Wu, Y., Luo, J., Zhang, D., Dong, M., 2013. An integrated programming model for storage management and vehicle scheduling at container terminals. Res. Transport. Econ. 42, 13–27.
Xing, Xiwen, Mao, Jun, Zhang, Rui, Zhihong, 2014. Integrated scheduling optimization of container terminal loading and unloading Operations based on mixed flow scheduling. Chinese Journal of Management Science 22, 97–105.
Yang, Y., Zhuo, X., Haghani, A., 2019. Multiple equipment integrated scheduling and storage space allocation in rail–water intermodal container terminals considering energy efficiency. Transport. Res. Rec.: J. Transport. Res. Board 2673, 199–209.
Yue, L., Fan, H., Ma, M., 2021. Optimizing configuration and scheduling of double 40 ft dual-trolley quay cranes and AGVs for improving container terminal services. J. Clean. Prod. 292, 126019.
Yue, L., Fan, H., Zhai, C., 2019. Joint configuration and scheduling optimization of a dual-trolley quay crane and automatic guided vehicles with consideration of vessel stability. Sustainability 12, 24.
Zhang, Xiaoj, 2018. Optimization of Container Terminals with Double Cycling. Dr., Dalian Maritime University.
Zhang, Yaqi, Yang, Bin, Hu, Zhihua, Tian, Maojin, 2017. Research of AGV charging and job integrated scheduling at automated container terminal. Computer Engineering and Applications 53, 257–262, 270.