Ship appointment scheduling for lockage operations of waterway transport with non-punctual arrivals

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Abstract

The appointment scheduling of ships has been considered as an essential avenue for managing ship arrival pattern and mitigating waterway traffic congestion. This paper studies the ship appointment scheduling problem for lockage operations of waterway transport, and a new mathematical model is formulated to minimize the average waiting time of ships around the dam, in which the non-punctual arrival of appointment ships, the appointment adjustment level of ships in different arrival scenarios, and the rescheduling rate of ships for each period are explicitly taken into account. The waiting time of ships is estimated via an $M/M/C$ queueing method, and a hybrid particle swarm optimization-simulated annealing (PSO-SA) algorithm is applied to solve this model efficiently. The numerical experiments for the Three Gorges Dam (TGD) show that the proposed method is applicable to the management of ship arrival patterns and effective in improving the matching between ship arrivals and lockage capacity by shifting a small number of ships from peak to off-peak periods of the day. Thanks to these improvements, the waiting time of ships is significantly reduced, and the carbon emission of ships in the two arrival scenarios is reduced by 20.7 % and 17.4 %, respectively. Furthermore, the sensitivity analysis is conducted to investigate how other parameters, such as the proportion of non-punctual ships, ship appointment adjustment and rescheduling rate, affect the performance of the ship appointment scheduling system.

Keywords:

Ship appointment scheduling, Non-punctual arrivals, $M/M/C$ queueing method, Hybrid particle swarm optimization-simulated annealing, Three Gorges Dam

1. Introduction

Inland waterway transport is an important mode of transportation for bulk goods because it is cost-effective and environmentally friendly (Zhao et al., 2023). In general, some water conservancy projects are usually distributed on the inland waterway, and the corresponding locks are designed. These locks are an important infrastructure of the inland waterway, and ships usually have to pass through one or more locks that are commonly used to assist ships in overcoming water level differences caused by dams (Verstichel et al., 2014; Ji et al., 2021; Liu et al., 2024). The ever-increasing demand for inland cargo transport has led to the frequent use of locks by ships to pass through the dam, and the insufficient lockage capacity may cause the demand-capacity mismatch problem (Zheng et al., 2024; Zhang et al., 2024). Thus, the traffic congestion has further worsened due to the mismatch between the increasing demand for ship arrivals and the insufficient lockage capacity during the busiest period. To relieve the traffic congestion, the dam authority has tried some measures to manage ship arrival patterns, which are summarized as follows: (i) expanding and/or reconstructing the existing lock facilities (i.e., increasing the capacity of lock facilities), and (ii) establishing the ship appointment scheduling system (i.e., improving the operation and management level of ships). However, the expansion and/or reconstruction of infrastructure such as locks is very capital-intensive and time-consuming. Furthermore, an efficient matching mechanism between lockage capacity and ship arrival through infrastructure expansion and reconstruction is usually unachievable at most dams. Therefore, the improvement and innovation of the ship appointment scheduling system for better matching the ship arrivals and the lockage capacity would be a crucial avenue to relieve traffic congestion and reduce the waiting time of ships (Zhao et al., 2022).

This paper studies the ship appointment scheduling problem for lockage operations of waterway transport, where the arrival patterns of ships can be managed by shifting or adjusting a small number of ships from peak to off-peak periods of the day. Specifically, when the appointment scheduling of ships is not started, the arrival periods of ships can be divided into peak and off-peak periods. For the peak period, since each ship has its own preferred arrival time when many ships arrive in a short period, the limitation of lockage capacity may lead to the queuing of ships. As a result, some ships can only wait for the next appropriate period to pass the dam, resulting in a long waiting time and increased carbon emissions. For the off-peak period, ships can waste part of the lockage space (i.e., lock resources) and directly use the lock to pass the dam because the service capacity of the lock is sufficient, this situation usually occurs when the ship is sailing at night. The adjustment and shifting of uneven arrival of ships at different periods have been equipped in many famous dams worldwide. **Fig. 1** depicts the sketch of the Three Gorges Navigation Area, China. For instance, a set of ships is in charge of transporting cargo from the Shishou Bridge downstream of the Three Gorges Dam (TGD) to the Yunyang Bridge upstream of this dam. The Three Gorges Navigation Area is divided into the following four parts: (i) scheduling area, (ii) control area, (iii) near area, and (iv) core area. Ships coming from downstream of the Yangtze River can start the registration based on their time preference when they arrive at the Shishou Bridge, so that the original ship arrival scheme with peak and off-peak periods can be obtained. However, such unbalanced arrival of ships can lead to queuing of ships and waste of lock resources, which further causes the demand-capacity mismatch problem. As a result, to better manage the ship arrivals and facility utilizations, the arrival patterns of ships need to be adjusted and matched with lockage capacity in the core area of TGD. The development of the ship appointment system for matching the ship arrivals and lockage capacity at the TGD is extremely important, and the management of ship arrival patterns can play an important part in enhancing transportation efficiency and relieving waterway traffic congestion (Ji et al., 2022; Zheng et al., 2023).

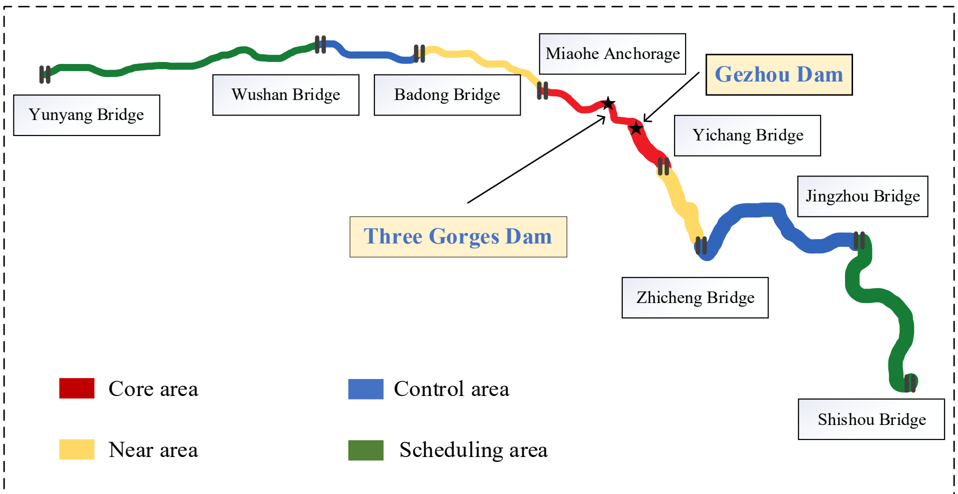


Fig. 1 The sketch of Three Gorges Navigation Area, China.

In addition, the non-punctual arrival of ships has seldom been taken into account. Due to the lack of strict penalty measures, the proposed ship appointment scheduling system can hardly ensure the punctuality of ship arrivals at the designated appointment period. In general, the unpunctual (i.e., non-punctual) arrival of ships can be divided into two categories: early arrival and late arrival at the appointed time. For ships that arrive early, they first wait at the anchorage and then pass the dam on time once the designated appointment time is reached. As a result, these early arrival ships do not affect the appointment scheduling scheme of ships and the scheduling of subsequent ships. For ships that arrive late, when the arrival of some ships needs to be delayed (i.e., non-punctual arrivals) due to some unexpected reasons (e.g., ship works improperly and security check failed), the uncertainty of ship arrival can complicate the ship appointment scheduling problem. This can further disturb the scheduling of subsequent and make the appointment scheduling system difficult to achieve the role of ship arrival pattern management. Moreover, the mismatched relationship between ship arrival and lockage capacity may be more obvious, which would increase the waiting time and carbon emissions of ships around the dam. The ship traffic congestion will be further intensified due to the disturbance of the disorderly arrival of unpunctual ships. Thus, the non-punctual arrival of ships can affect the ship scheduling scheme, which further influences the arrival schemes of subsequent ships. The interferences among ships are especially significant when the proportion of unpunctual ships reaches a certain scale (Creemers et al., 2021; Tan et al., 2022; Li et al., 2022). Consequently, it is very necessary to consider the impact of the non-punctual arrival of ships on the ship appointment scheduling system. It should be pointed out that the rescheduling strategy proposed in this paper is to reduce the impact of the non-punctual arrival of ships on the ship appointment scheduling system, the ships that miss their appointment periods need to be rescheduled and thus be adjusted to another appointment period, which can reduce the negative impact of the non-punctual arrival of appointment ships and alleviate the waterway traffic congestion. In addition, strict penalty measures are implemented by the dam operator to ensure the punctuality of rescheduled ship arrivals, so the late arrivals of rescheduled ships are not considered. Specifically, in this ship appointment scheduling system, the rescheduled ships are required to arrive at the lock on time, otherwise, a high penalty will be charged.

Another important problem is that the appointment scheduling of ships can be influenced by the ship appointment adjustment level, which is extremely relevant to the appointment adjustment rate, a proper appointment adjustment rate can improve the performance of the ship appointment scheduling system. Specifically, the ship appointment adjustment rate usually represents a numerical value, which refers to the proportion of ships that need to change the original arrival habit, and the ship appointment adjustment level reflects the negative impact of this rate on the appointment scheduling system, both of them are interrelated. In reality, the uneven arrivals of ships at different periods can cause the demand-capacity mismatch problem. The proposed ship appointment scheduling system is interactive, when the given appointment quota is not reached, ships can arrive during this period. Otherwise, the ship can be adjusted to another period. In principle, after the implementation of the ship appointment scheduling system, some ships during peak periods must be adjusted to other off-peak periods to arrive at the lock. Owing to the consideration of unpunctual arrival of ships, all ships that miss their appointment periods also need to be rescheduled and thus be adjusted to another appointment period. However, a higher appointment adjustment level may have a serious negative impact on the ship appointment scheduling system, because it means that more ships need to change their original arrival habits. Furthermore, frequent ship arrival adjustments may further exacerbate waterway traffic congestion and increase navigation risks. Thus, it is very necessary to consider the impact of the appointment adjustment level of ships. Setting the ship appointment adjustment level within a certain level is conducive to reducing the waiting time of ships and alleviating waterway traffic congestion.

This paper aims to address the ship appointment scheduling problem for lockage operations of waterway transport with non-punctual arrivals. Our contributions to this study can be summarized as follows:

(i) This study innovatively addresses the ship appointment scheduling problem for lockage operations of waterway transport, in which the non-punctual arrival of appointment ships, the appointment adjustment level of ships in different arrival scenarios, and the rescheduling rate of ships for each period are explicitly considered. A new mathematical model that minimizes the average waiting time of ships is proposed to manage the ship arrival pattern, which can improve the matching between ship arrival and lockage capacity by shifting or adjusting a small number of ships from peak to off-peak periods of the day.

(ii) The rescheduling strategy for unpunctual ships is introduced into this ship appointment scheduling problem. The change of arrival scenarios (i.e., on-time or non-punctual arrival scenarios) can affect the feasibility of the ship appointment scheduling scheme, and the proposed rescheduling strategy can significantly reduce the interference effects of unpunctual ships.

(iii) A hybrid particle swarm optimization-simulated annealing (PSO-SA) algorithm is presented to solve the proposed model, and the performance of the heuristic algorithm and mathematical model is verified by the real case study of the TGD. The experimental results reveal the impact of several factors (e.g., the queuing of ships, non-punctual arrival of ships, appointment adjustment level of ships, and ship rescheduling rate for each period) on ship appointment scheduling, and some significant insights can be concluded to help the scientific decision-making.

The rest of this paper can be structured as follows. In Section 2, the literature on appointment scheduling is reviewed. The development of the mathematical model and the description of the research problem are presented in Section 3. Section 4 proposes a hybrid PSO-SA algorithm. A real case study based on the TGD is conducted in Section 5, and Section 6 provides the summary of this study and suggestions for future research direction.

2. Literature review

The ship appointment scheduling problem proposed in this study involves scheduling and managing ships' arrival patterns in the presence of mismatches between ship arrivals and lockage capacities. Some attempts have been made in the literature to establish mathematical models and design heuristic algorithms to solve the demand-capacity mismatch problem and improve the transportation efficiency of appointment scheduling. Chen et al. (2013a) investigated the implementation scenario of different terminal appointment systems (TAS). A non-stationary queueing method was developed to model the terminal gate system, and a genetic algorithm (GA) was proposed to optimize the appointment quota and solve the demand-capacity mismatch problem (Chen et al., 2013b). Some other studies further extended the TAS. For instance, Zehendner and Feillet. (2014) proposed a TAS to improve the service quality of inland transport modes. A mixed integer linear programming (MILP) model was formulated to reduce the delay at the container terminal. Phan and Kim. (2015) investigated the TAS in container terminals. The authors proposed a new mathematical formulation for smoothing the peaks in arrivals while taking the inconvenience of the arrival adjustment and the waiting cost of trucks into account. A new decision-making model was developed to improve the level of operations of trucking companies and terminal operators. Torkjazi et al. (2018) further extended the same research problem by considering the services of terminal operators and haulage operators and presented a new method for designing the TAS. The above literature can lay a solid foundation for the development of appointment scheduling, which marks the preliminary construction of the appointment scheduling system. Furthermore, more appointment scheduling systems applied in other fields are studied in the literature. Li et al. (2018) investigated an appointment scheduling problem at container terminals while taking different levels of disruptions into account. A response strategy was presented to maintain the high resilience ability of the proposed system in neutralizing the impact of disruptions. Based on the analysis of an appointment scheduling problem arising from a Japanese container terminal, Azab and Morita. (2022) proposed a bi-objective optimization model with the lexicographical objective function, which efficiently coordinates truck appointments with container handling operations and avoids excessive delays. Zhao et al. (2022) further introduced the ship appointment problem in a bottlenecked navigation area that arises from the TGD. A new mathematical model was formulated to manage the ship arrival pattern and reduce the waiting time and carbon emissions of ships around the dam. However, this study is aimed at ship appointment scheduling in the on-time arrival scenarios, and appointment scheduling under complex situations (i.e., non-punctual arrival of ships) is not involved.

The impact of non-punctual arrivals on the appointment scheduling system has received much attention in recent related studies. Jiang et al. (2019) investigated the appointment scheduling problem considering unpunctuality. A stochastic programming model was developed to reduce the total waiting time. In the non-punctual arrival scenarios, Soltani et al. (2019) extended the same research problem by considering customer no-shows and developed an effective heuristic method to get a better appointment scheduling scheme. Creemers et al. (2021) formulated an analytical model to evaluate the performance of appointment scheduling rules. The model considers the customer's unpunctuality, no-shows, service interruptions, and delays in session start time. Shen et al. (2024) studied a multi-server time window allowance appointment scheduling problem considering the uncertainty of time-dependent no-shows. A mathematical model was formulated to optimize decision-making of appointment quota and time simultaneously. Different from the aforementioned studies that only considered unpunctuality, Chen et al. (2018) investigated a two-stage deterministic equivalent problem to optimize overbooking and scheduling decisions. Harris and Samorani. (2021) extended the model of Chen et al. (2018) by appointment overbooking. An appointment scheduling optimization model was developed to mitigate the negative effects of unpunctuality through appointment overbooking. In addition, to reduce the impact of the random arrival of walk-in patients on the appointment scheduling system, Pan et al. (2020) presented a finite-horizon Markov decision process model and established the optimal real-time scheduling policy under a given appointment schedule, which can significantly improve the performance of the department. However, the above studies focus on appointment overbooking in the case of unpunctuality and rarely involve rescheduling of unpunctual arrival. Li et al. (2017) further proposed a mathematical model based on the rescheduling strategy, and a hybrid artificial bee colony algorithm based on Tabu search was proposed to solve this model. For the scheduling problem with unpunctuality, Wang et al. (2024) presented a MILP model and two rescheduling strategies, and a population-based variable neighborhood search algorithm was used to solve the mentioned problem.

The consideration of appointment adjustment levels in the appointment scheduling system has become extremely important. Several studies in the literature studied the appointment scheduling problem with consideration of appointment adjustment. Chen et al. (2013a) established a bi-objective model that minimizes both truck waiting time and truck arrival adjustment, and a genetic algorithm was designed to aid in the optimization of the arrival pattern and the reduction of carbon emissions. Chen et al. (2013b) further extended the same research problem to a situation where the appointment adjustment level was also considered. A non-stationary $M(t)/E_k/c(t)$ queueing model and a B-PSFFA approximation method were developed. In addition, Zeng et al. (2019) proposed a novel method of optimizing the pickup sequence and the container re-handling strategy to reduce the re-handling (i.e., adjusting) of inbound containers. To the best of our knowledge, Zhao et al. (2022) is the only existing study modeling and optimizing ship arrival patterns at the dam using the appointment scheduling system. To optimize the use of lock facilities, a bi-objective appointment scheduling optimization model is developed to balance the waiting time and the arrival adjustment, which can efficiently manage the ship's arrival pattern and alleviate traffic congestion. It is crucial to note that all of the above mathematical models are bi-objective (i.e., waiting time and appointment adjustment level). In practice, the waiting time as well as the appointment adjustment level (i.e., the number of shifted arrivals) is mutually influenced, which further affects the effect of ship arrival optimization. Understanding this trade-off relationship (i.e., mutual influence) will help dam operators to better manage ship arrival patterns.

As can be seen from the above literature review, the optimization of appointment scheduling has been widely addressed by many scholars. **Table 1** presents an overview of the literature on appointment scheduling. However, the existing literature mainly focuses on the study of truck appointment scheduling at container terminals, the application of the ship appointment scheduling

Table 1 Overview of literature in appointment scheduling.

Citation	Appointment scheduling	On-time arrival scenarios	Non-punctual arrival scenarios	Rescheduling strategy	Appointment adjustment level	Solution method
Chen et al. (2013a, b)	√	√			√	GA
Phan and Kim. (2015)	√	√			√	Heuristic
Torkjazi et al. (2018)	√	√				IP
Li et al. (2018)	√	√				Heuristic
Azab and Morita. (2022)	√	√				Heuristic
Jiang et al. (2019)	√		√			Benders
Soltani et al. (2019)	√		√			Heuristic
Shen et al. (2024)	√		√			Benders
Harris and Samorani. (2021)	√		√			Heuristic
Pan et al. (2020)	√		√	√		Heuristic
Li et al. (2017)			√	√		HABC
Wang et al. (2024)		√	√	√		PVNS
Zeng et al. (2019)		√			√	Heuristic
Zhao et al. (2022)	√	√			√	NSGA-II
This paper	√	√	√	√	√	PSO-SA

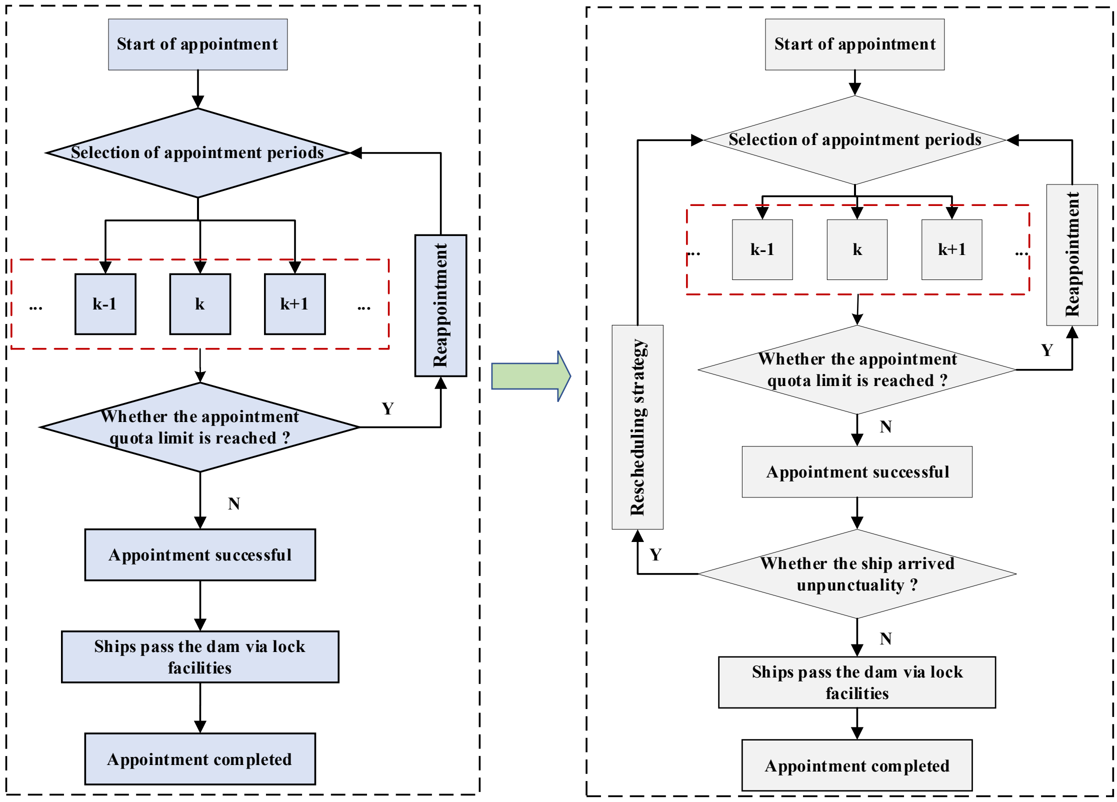
systems for better matching the ship arrivals and lockage capacity in waterway transport has rarely been studied. Furthermore, there is no existing literature that integrates ship appointment scheduling with the rescheduling of unpunctual ships, especially when considering the impact of ship appointment adjustment level. This paper thus studied the ship appointment scheduling problem for lockage operations of waterway transport with non-punctual arrivals, where the unpunctual arrival of appointment ships, the appointment adjustment level of ships in different arrival scenarios, and the rescheduling rate of ships for each period are comprehensively considered. A new mathematical model is presented, and the PSO-SA algorithm is designed to solve this model efficiently. This paper comprehensively expends the ship scheduling under on-time arrival scenarios to ship appointment scheduling with a rescheduling strategy in the non-punctual arrival scenarios, which is more realistic and innovative. The mentioned model can improve the matching between ship arrival and lockage capacity and alleviate the waterway traffic congestion.

3. Problem description and mathematical model

3.1 Problem description

The purpose of ship appointment scheduling for lockage operations of waterway transport is to manage the ship arrival pattern to improve the matching between ship arrivals and lockage capacity, which can enhance the transportation efficiency of ships and alleviate the waterway traffic congestion. A group of ships is required to transfer their cargo from one side of the dam to the other, and the lock is the main passing facility. Ships first start the registration (i.e., Start of appointment) based on positioning information provided by the navigation satellite system. The planning horizon can be divided into multiple appointment periods, ships can choose a preferred appointment period to arrive and pass through the dam once a lockage is available. Due to the limited capacity of the locks, each appointment period is configured with a corresponding appointment quota. Each ship needs to judge whether the appointment is successful according to the remaining status of the appointment quota. Once the appointment quota limit for a certain period is reached, appointments for subsequent ships are unsuccessful, and need to choose or adjust another free period to make an appointment again (i.e., reappointment). In contrast, the ship appointment is successful when the appointment quota limit is not reached, subsequent ships can continue the appointment scheduling for that period. Once the appointment is successful, ships can pass through the dam via the lock facilities and complete the appointment process. **Fig. 2(a)** illustrates the framework of the ship appointment scheduling system in the on-time arrival scenarios.

In addition to the appointment scheduling of ships in the on-time arrival scenario, during the planning horizon, dam operators also need to arrange a rescheduling scheme for the non-punctual arrival of appointment ships. For illustration purposes, **Fig. 2(b)** shows the framework of the ship appointment scheduling system in the non-punctual arrival scenarios. In general, the unpunctual arrival of ships often occurs in the process of ship appointment scheduling. To reduce the impact of the unpunctual arrival of ships on the ship appointment scheduling system, the ships that miss their appointment periods need to be rescheduled and thus be adjusted to another appointment period (i.e., rescheduling strategy). The unpunctual arrival of ships is divided into two categories: (i) ships arrive at the lock before their appointment periods, and (ii) ships arrive at the lock after their appointment periods. In principle, ships that arrive early can wait at the anchorage and then move the designated lock for passing the dam once their appointment periods are available, which has a negligible impact on the appointment system. However, when the arrival of some ships needs to be delayed (i.e., unpunctual arrival) due to some unexpected reasons (e.g., ship works improperly and security check failed), the ships need to be rescheduled to another appointment period (i.e., rescheduling strategy), which can reduce the negative impact of the non-punctual arrival of appointment ships. As a result, it is very necessary to consider the impact of the unpunctual arrival of ships. Furthermore, to ensure the punctual arrival of rescheduled ships, dam operators have implemented strict penalty measures (e.g., ship credit system and cancellation of appointment) during the ship rescheduling process, so the late arrival of rescheduled ships is not considered. For the sake of distinction, we refer to the adjusted arrival of unpunctual ships (i.e., non-punctual arrival of appointment ships) as the number of rescheduling of ships. Note that, for the sake of navigation rules, when the arrival of some ships is late at a specified period, dam operators can only arrange for the non-punctual arrival of ships to be rescheduled after a specified appointment period. As a result, in the ship appointment rescheduling process, we only need to collect real-time information about unpunctual ships before the specified appointment period. Specifically, by comparing the ship appointment scheduling scheme with the actual arrival scheme, dam operators can collect the real-time unpunctual arrival information of ships (i.e., the number of non-punctual ships) before the specified appointment period, based on which we generate a rescheduling scheme for non-punctual ships during the specified period.



(a) In the on-time arrival scenarios **(b) In the non-punctual arrival scenarios**

Fig. 2 Illustration of the ship appointment scheduling system framework.

The appointment adjustment level has an important influence on the arrival scheme of ships. In general, ships can register their preferred periods to pass the dam, which may result in uneven arrivals of ships at different periods. Such unbalanced arrival of ships can lead to queuing of ships and waste of lock resources, which further causes the demand-capacity mismatch problem. The proposed ship appointment scheduling system is interactive, when the given appointment quota of a period is not reached, ships can arrive during this period. Otherwise, the ship can be adjusted to another period. As a result, the appointment scheduling of ships can tackle the demand-capacity mismatch problem by shifting or adjusting the arrival pattern of ships in different appointment periods. Moreover, the arrival number of ships in each appointment period is planned and adjusted according to the appointment scheduling system, which is conducive to solving the waterway traffic congestion problem. Although the appropriate appointment adjustment of ship arrival pattern can effectively handle the demand-capacity mismatch problem and reduce the waiting time of ships, a higher appointment adjustment rate may have a serious negative impact on the ship appointment scheduling system, because it means that more ships need to change their original arrival habits. In addition, frequent ship arrival adjustments may further exacerbate waterway traffic congestion and increase navigation risks. The negative impact of ship appointment adjustments is particularly significant when non-punctual arrival ships are also rescheduled. Therefore, the appointment adjustment rate of ships should be controlled within a certain range, which is conducive to reducing the waiting time of ships and alleviating waterway traffic congestion.

Due to the demand-capacity mismatch problem caused by the unbalanced arrival of ships, the queuing of ships also has a significant impact on the arrival scheme of ships. At present, the lock facilities are used to pass the dam, which are managed by dam operators. In addition, ships need to queue at the anchorage when the lockage capacity is insufficient. Due to the increase in the queue length of ships, the waterway traffic congestion further worsens when many ships arrive in a short period. The carbon emission can be sharply increased with many ships waiting at the dam for a long time, which can further exacerbate the environmental pollution around the dam. **Fig. 3** shows a schematic diagram of the ship appointment scheduling process. As a result, it is very necessary to adjust the unbalanced arrival of ships by a ship appointment scheduling system, which helps to reduce the queuing length of ships and relieve the waterway traffic congestion (Bekker et al., 2024).

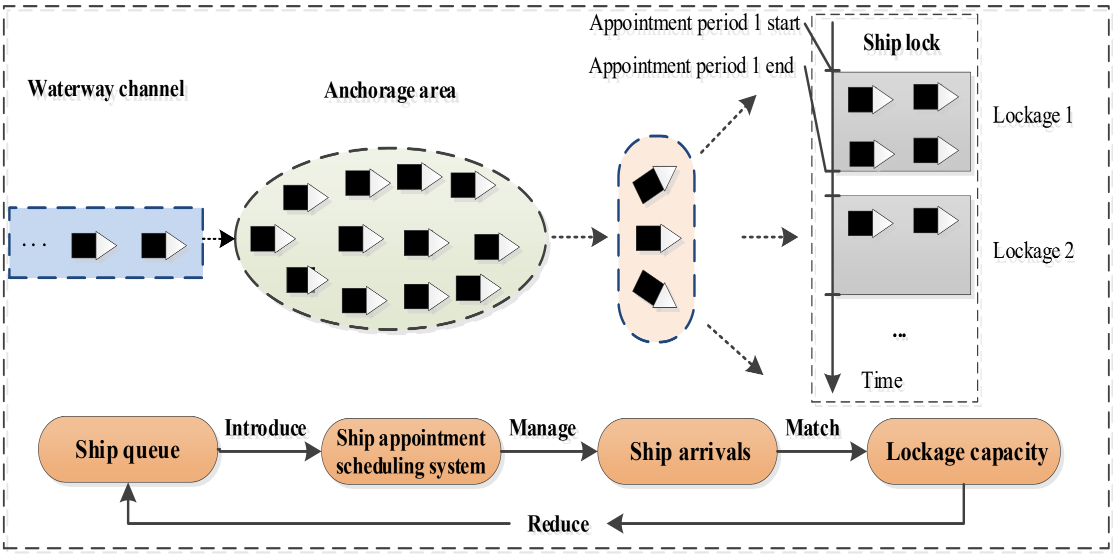


Fig. 3 Schematic diagram of the ship appointment scheduling process.

To solve the ship appointment scheduling problem for lockage operations of waterway transport in the on-time or non-punctual arrival scenarios, the framework of the ship appointment scheduling system is presented (see Fig. 2). Since the appointment scheduling of ships for lockage operations of waterway transportation involves the management of ship arrival pattern and lockage resource utilization, dam operators attempt to improve the matching between ship arrivals and lockage capacity by managing the ship arrival pattern at different appointment periods, which can also reduce the length of queuing and waiting time of ships around the dam. In addition, the rescheduling strategy of non-punctual arrival ships, the appointment adjustment level of ships, and the queuing of ships are comprehensively considered. The proposed method can effectively handle the demand-capacity mismatch problem by shifting or adjusting the arrival pattern of ships in different appointment periods, which can reduce the waiting time and queuing length of ships and improve the environmental pollution of ships at the dam.

3.2 An $M/M/C$ queueing method

The uneven arrival of ships at different periods will cause the demand-capacity mismatch problem, which may lead to the queuing of ships at the anchorage. Although the ship appointment scheduling system is effective in adjusting or shifting the ship arrival pattern and controlling the number of ships, it may not be able to estimate the waiting time and queue length of ships at the anchorage when waterway traffic congestion becomes worse (Zhao et al., 2022). In addition, since the waiting anchorage can accommodate all arriving ships in most cases, the queuing of ships waiting to pass the dam can be considered as a steady queuing process. It should be pointed out that during most of the year, the queuing system is in a steady queuing process. Therefore, a stationary queuing method should be applied to model this process and estimate the queue length of ships. To this aim, we applied an $M/M/C$ queueing method to estimate the queue length of ships under the ship appointment scheduling system.

In this section, we consider an $M/M/C$ queueing model with an arrival rate λ followed by Poisson process and a service time $1/\mu$ followed by a negative exponentially distributed process. The queuing of ships passing the dam is a complex problem, the queueing model proposed in this paper can be developed to analyze and evaluate the performance of the ship appointment scheduling system. In addition, an $M/M/C$ queueing model is capable of modeling the pattern of ship arrivals at the anchorage under the ship appointment scheduling system.

Specifically, in any state with n ships, the ship arrival rate and service rate can be calculated by Eqs. (1) and (2), respectively.

$$\lambda_n = \lambda, \ \ n \geq 0 \tag{1}$$

$$\mu = \begin{cases} n\mu, & n = 1,2,\dots,c \\ c\mu, & n = c+1, c+2, \dots \end{cases} \tag{2}$$

The probability of zero ships at the service stations (i.e., berths) can be expressed as follows:

$$P_0 = \left[\sum_{n=0}^{c-1} \frac{1}{c!} (\frac{\lambda}{\mu})^n + \frac{1}{c!} (\frac{\lambda}{\mu})^c \sum_{n=c}^{\infty} (\frac{\lambda}{\mu})^{n-c} \right]^{-1} \tag{3}$$

The probability distribution of queue length N can be denoted as $P_n = P\{N = n\}$ $(n = 0,1,2,\cdots)$, and the number of service stations is equal to c, indexed by n. The service strength ρ is equal to $\lambda/c\mu$. Thus, the probability of having n ships in a system with c service stations (i.e., berths) can be calculated by Eq. (4).

$$P_n = \begin{cases} \dfrac{1}{n!}\rho^n P_0 & (n \le c) \\ \dfrac{1}{c!\, c^{n-c}}\rho^n P_0 & (n > c) \end{cases} \tag{4}$$

Based on the actual ship arrivals ψ_{ik}, we can calculate the queue length of ships in a period, which can be expressed as follows:

$$L_{ik} = \frac{(c\rho)^c \rho}{c!\ (1-\rho)^2} P_0 = \frac{\rho^{c+1}}{(c-1)!\,(c-(\psi_{ik}-c))^2} P_0 \tag{5}$$

Eq. (5) establishes a function of the queue length, which can be applied to the mathematical model established in this paper (see Section 3.3) to analyze and evaluate the performance of the ship appointment system. Specifically, the proposed $\mathrm{M/M/C}$ queueing method is capable to model the pattern of ship arrivals at the anchorage, which can calculate the queue length and the average waiting time.

3.3 Mathematical model

3.3.1 Parameter meaning

To formulate the mathematical model of the ship appointment scheduling problem for lockage operations of waterway transport with non-punctual arrivals, the sets, parameters, and variables applied in the proposed model are defined:

Sets

A: set of planning horizons of ship appointment scheduling system (days), indexed by i.
B: set of daily appointment periods, indexed by k.

Parameters:

e_{ik}: expected number of ship arrivals at the k^{th} period in day i.
n_{ik}: expected number of ships unpunctuality at the k^{th} period in day i.
α: limitation of appointment adjustment level.
β: limitation of ship rescheduling rate for each period.
θ: the proportion of non-punctual arrival of ships.
t_{ik}: the average waiting time of ships calculated by the $M/M/C$ queue model (h).
L_{ik}: the ship queue length of the k^{th} period in day i.
μ_{ik}: number of ships serviced at the k^{th} period in day i.
ρ_{ik}: utilization of ship lock at the k^{th} period in day i .
d_{ik}: number of ship departures at the k^{th} period in day i.
L^{max}: maximum allowable queue length for a given appointment period.
S^{max}: maximum allowable service capability for a given appointment period.
W^{max}: maximum allowable queuing time for a given appointment period.

Variables

x_{ik}: appointment quota given to the k^{th} period in day i.
y_{ik}: number of initial ship arrivals at the k^{th} period in day i (without rescheduling of ships).
φ_{ik}: number of rescheduling of ships unpunctuality at the k^{th} period in day i.
ψ_{ik}: number of actual ship arrivals at the k^{th} period in day i (already rescheduling of ships).

3.3.2 Objective function

In the case of ship unpunctuality, dam operators determine the ship appointment quota and rescheduling rules for each period to optimize the arrival pattern of ships in different appointment periods, which can minimize the average waiting time of ships around the dam. Thus, we use the average waiting time of ships as the performance measure, which can ensure that the lockage operations of all ships are finished as soon as possible. The objective function (6) minimizes the average waiting time of ships, which can be expressed as follows:

$$minimize\ Z = \sum_{i\in A}\sum_{k\in B} t_{ik}\psi_{ik} \,/ \sum_{i\in A}\sum_{k\in B} \psi_{ik} \tag{6}$$

3.3.3 Constraints

$$0 < \sum_{i\in A}\sum_{k\in B} \psi_{ik} \le \sum_{i\in A}\sum_{k\in B} e_{ik} \tag{7}$$

$$0 < \psi_{ik} \le x_{ik}, \forall i \in A, \forall k \in B \tag{8}$$

Constraint (7) defines the conservation constraint of ship flow, which ensures that ships within the overall appointment period can be scheduled to pass the dam as much as possible. Constraint (8) guarantees that the given appointment quota is not surpassed by the actual number of ship arrivals in each appointment period.

$$\theta = \sum_{i\in A}\sum_{k\in B} n_{ik} \,/ \sum_{i\in A}\sum_{k\in B} e_{ik} \tag{9}$$

Eq. (9) specifies the proportion of unpunctual arrival of ships when they make an appointment scheduling, and the proportion of unpunctual arrival of ships is set to θ.

$$y_{ik} = f_{adjust}(e_{11}, e_{12}, \cdots, e_{IK}, x_{11}, x_{12}, \cdots, x_{IK}, n_{11}, n_{12}, \cdots, n_{IK}) , \forall i \in A, \forall k \in B \tag{10}$$

$$\varphi_{ik} = f_{reschedule}(n_{11}, n_{12}, \cdots, n_{ik}), \forall i \in A, \forall k \in B \tag{11}$$

$$\psi_{ik} = y_{ik} + \varphi_{ik}, \forall i \in A, \forall\, k \in B \tag{12}$$

Eq. (10) establishes a ship adjustment function and defines the ship adjustment rules (i.e., reappointment) for the case of unpunctual arrivals, which can balance the gap between expected ship arrivals and allocated quotas during each appointment period (Zhao et al., 2022). When $e_{ik} - n_{ik} \ge x_{ik}$, $y_{ik} = x_{ik}$, and it will mean this appointment period is fully booked, the number of initial ship arrivals can be equal to the given appointment quota. In this case, the exceeded amount of ship appointments can be shifted or adjusted to the nearest adjacent periods. However, when $e_{ik} - n_{ik} < x_{ik}$, y_{ik}equals to $e_{ik} - n_{ik}$ plus the adjusted appointment ships from other appointment periods. Eq. (11) establishes a ship rescheduling function and defines the rescheduling appointment rules for the case of non-punctual arrivals, which ensures that the rescheduling strategy can only be booked by ships that have missed appointments earlier in the period, and ships unpunctuality in subsequent periods cannot be booked. The comparison between the ship appointment scheme and the actual arrival scheme is used to collect the real-time unpunctual arrival information of ships, which is applied to count the number of non-punctual ships n_{ik}. Eq. (12) specifies the number of actual ship arrivals of each appointment period, which includes the number of initial ship arrivals and the rescheduling of ships' unpunctuality.

$$\sum_{i\in A}\sum_{k\in B} max\{\, e_{ik} - n_{ik} + \varphi_{ik} - x_{ik}, \varphi_{ik}\} \,/ \sum_{i\in A}\sum_{k\in B} e_{ik} \le \alpha \tag{13}$$

Constraint (13) ensures that the adjustable rate caused by ship reappointment and rescheduling cannot exceed the maximum appointment adjustment level α. Specifically, a larger parameter α indicates that more ships need to change their arrival pattern or habits, which means that the application of the appointment scheduling system has more negative effects. Thus, the ship appointment adjustment level reflects the negative impact of appointment adjustment rate (i.e., the proportion of ships that need to change the original arrival habit) on the appointment scheduling system.

$$0 < \varphi_{ik}/\psi_{ik} \leq \beta, \forall i \in A, \forall k \in B \tag{14}$$

Constraint (14) guarantees that the ship rescheduling rate for each period cannot exceed the maximum rescheduling rate β. The ship rescheduling rate for each period refers to the proportion of rescheduled ships when unpunctual ships are rescheduled at a specified appointment time. A large parameter β will prompt for a large number of ships to be rescheduled, which also has a negative effect on the appointment scheduling system.

$$L_{ik} = f_{queue}(\rho, c, P_0, \psi_{ik}), \forall i \in A, \forall k \in B \tag{15}$$

Eq. (15) establishes a function of the $M/M/C$ queuing method, and the specific formulation of the queuing model is given in Section 3.2 (i.e., Eq. (5)). The introduction of the queue theory makes the model nonlinearly constrained so that it cannot be solved using a commercial solver.

$$L_{i,k+1} = max\{L_{ik} + \psi_{ik} - d_{ik}, 0\}, \forall i \in A, \forall k \in B \tag{16}$$

$$0 \leq L_{ik} \leq L^{max}, \forall i \in A, \forall k \in B \tag{17}$$

$$d_{ik} = \mu_{ik}\rho_{ik}, \forall i \in A, \forall k \in B \tag{18}$$

$$0 \leq \rho_{ik} \leq 1, \forall i \in A, \forall k \in B \tag{19}$$

Constraints (16)-(19) calculate the change in ship queue, the queue length of ships (i.e., the upper bound of queue length), the ship departure rate, and the utilization of ship lock of each appointment period.

$$t_{ik} = L_{ik}/d_{ik}, \forall i \in A, \forall k \in B \tag{20}$$

$$0 \leq t_{ik} \leq W^{max}, \forall i \in A, \forall k \in B \tag{21}$$

Constraint (20) calculates the average waiting time of ships within each appointment period, and the upper bound can be given in constraint (21).

$$0 \leq x_{ik} \leq S^{max}, \forall i \in A, \forall k \in B \tag{22}$$

Constraint (22) specifies the upper bound of the allocated appointment quota in each period, which can be restricted by the capacity of lock facilities. The range of all variables can be specified in constraint (23).

$$x_{ik}, y_{ik}, \varphi_{ik}, \psi_{ik} \in Z^+, \forall i \in A, k \in B \tag{23}$$

It is worth pointing out that when $n_{ik}, \varphi_{ik}, \theta$ and β equal to 0, the model proposed in this paper can be transformed into a model for ship appointment scheduling without non-punctual arrival (i.e., in the on-time arrival scenario). When constraint (13) is removed, it becomes a model without the appointment adjustment level restriction of ships.

3.4 Ship carbon emission estimation

To evaluate and analyze the low-carbon and sustainability of the proposed ship appointment scheduling system, we calculate the carbon emissions of ships and compare the results with the original arrival scheme of ships. The ship appointment scheduling system proposed in Section 3.3 can reduce the average waiting time of ships (i.e.,Z) around the dam, which results in the reduction of ship idling emissions. Specifically, the ship will first wait at the anchorage in the idle state when the lock capacity is insufficient. The ship idle emission depends on the efficiency of the appointment scheduling system and can be reduced significantly through ship arrival adjustment. The carbon emissions from ships are related to fuel consumption, and this relationship can be linked by the carbon coefficient ∂. Many researchers, (e.g. Kontovas, 2014; Liu et al., 2024), set the carbon coefficient of ships to 3.082, which means each ton of fuel consumption can generate 3.082 tons carbon emissions. Several factors, such as ships' speed v_m, payload a_m, and weight ω_m can affect the fuel consumption of ships. M is the set of ships within the planning horizon, which can be indexed by m. Thus, the ship idle emissions can be estimated by Eqs (24)-(28).

$$g(v_m, \omega_m) = \tau \cdot (p + v_m^q) \cdot (a_m + \omega_m)^{2/3}, \forall m \in M \tag{24}$$

$$G_m = \tau \cdot (p + v_m^3) \cdot (a_m + \omega_m)^{2/3}, \forall m \in M \tag{25}$$

$$G_m^* = \tau \cdot p \cdot (a_m + \omega_m)^{2/3}, \forall m \in M \tag{26}$$

$$E = \frac{\partial}{24 \cdot M} \cdot \sum_{m \in M} G_m^* \tag{27}$$

$$R_{emission} = (T_s - Z) \cdot E \tag{28}$$

Eq. (24) formulated by Kontovas. (2014) is employed to calculate the fuel consumption of ships, where τ represents the ship-specific constant, p can be employed to adjust fuel consumption when ships' speed is low, and q can represent the correlation coefficient between fuel consumption and speed. Many studies, (e.g. Kontovas, 2014; Zhao et al., 2022), demonstrated that the fuel consumption during sailing is proportional to the cube of the average sailing speed, and the correlation coefficient q is commonly set to 3. Eq. (25) calculates the daily fuel consumption of ship m during sailing. Eq. (26) calculates the daily fuel consumption of ship m during waiting and berthing at the anchorage, which can be used to estimate ship idling emissions. Eq. (27) calculates the unit idling emission of ships, and reduced ship idle emissions can be calculated by Eq. (28), where T_s is the original average waiting time of ships (i.e., the ship appointment system is not applied).

4. Solution approach

The proposed ship appointment scheduling optimization model is an NP-hard problem, which needs to be addressed by the heuristic algorithm (Zhao et al., 2022; Liu et al., 2024). The particle swarm optimization (PSO) algorithm is widely used to solve the ship scheduling problems because of its strong robustness and fast convergence (Zhang et al., 2024). However, one of the disadvantages of the PSO is that when the local optimal solution is reached, all particles are clustered around it, and it is difficult to jump out of this local optimal solution. To overcome the disadvantages and shortcomings of the PSO algorithm, the method of reducing the probability of ignoring the optimal solution, as an approach of temperature adjustment in the simulated annealing (SA) algorithm, helps the PSO algorithm to jump from a local optimal solution to a globally optimal solution. The hybrid of the PSO and SA algorithm is an effective method to improve search convergence speed and avoid premature convergence. Therefore, this paper chooses a hybrid particle swarm optimization-simulated annealing (PSO-SA) to solve the model.

4.1 Basic PSO algorithm

The basic PSO algorithm was applied to simulate the large-scale flight of birds, which is an intelligent algorithm and has been proven to yield feasible solutions in a reasonable time. In the basic PSO algorithm, a group of particles is given in which each particle is considered to be a potential optimal solution. Particle position, velocity, and fitness values are used to represent the characteristics of each particle, which are also three important indicators to evaluate the quality of particles. In addition, the optimal solution is found by tracking two optimal values (i.e., personal optimal value P_{best} and group optimal value G_{best}). Specifically, a set of feasible solutions is randomly generated when the basic PSO algorithm is applied. Each feasible solution represents a particle in the D-dimensional search space, where the position and velocity of particle i can be expressed as $X_i = (X_{i1}, X_{i2}, \cdots, X_{iD})$ and $V_i = (V_{i1}, V_{i2}, \cdots, V_{iD})$. According to the objective function, the fitness value of each particle can be calculated. Thus, the formula for updating the particle position and velocity of the basic PSO at time $j+1$ can be as follows:

$$V_{iD}^{(j+1)} = \omega * V_{iD}^{j} + c_1 * r_1 * (P_{iD}^{(j)} - X_{iD}^{(j)}) + c_2 * r_2 * (P_{iD}^{(j)} - X_{iD}^{(j)}) \tag{29}$$

$$X_{iD}^{(j+1)} = X_{iD}^{(j)} + V_{iD}^{(j+1)} \tag{30}$$

$$\left|V_{iD}^{(j)}\right| \leq V_{max} \tag{31}$$

Where ω is the inertia weight of the particle velocity, r_1, r_2 represent the random number between 0 and 1, c_1, c_2 represent the cognitive and social parameters respectively, and V_{max} is the velocity vector limit constant.

4.2 SA algorithm

The simulated annealing (SA) algorithm seeks the global optimal solution of the optimization problem by a stochastic gradient method. In the SA algorithm, the technique simulates the gradual cooling of a physical system to reach a state of minimum potential energy. Specifically, the SA algorithm tries to replicate the crystallization process during cooling or annealing: when the material is heated, the particles have large kinetic energy and move randomly. As the material cools, more particles tend to flow in a direction that reduces the energy balance. Based on the above principles, the SA algorithm determines whether the new solution (X_n) will replace the old solution (X) by applying a probabilistic rule. For example, for a minimum optimization problem, if the fitness value ($f(X_n)$) is less than the previous fitness value ($f(X)$), the new solution will be accepted. Otherwise, the new solution can be accepted with the probability P. Thus, the probability of accepting a new solution P is calculated as below:

$$P = \begin{cases} exp(-\frac{\Delta f}{T}), & \Delta f > 0 \\ 1, & \Delta f \leq 0 \end{cases} \tag{32}$$

Where Δf is the change in the fitness function value (i.e., $\Delta f = f(X_n) - f(X)$), T is a controlling parameter which is called temperature.

4.3 Hybrid PSO-SA algorithm

One of the main disadvantages of the basic PSO algorithm is its early convergence and easy to fall into the trap of local optimal solutions. The method of reducing the probability of ignoring the optimal solution in the SA algorithm is considered an important way to jump out of the local optimal solution, the application of the above method can help the PSO algorithm to escape from the local optimal solution. To address the ship appointment scheduling problem, we proposed a hybrid particle swarm optimization-simulated annealing (PSO-SA) algorithm. Specifically, the proposed PSO-SA algorithm combines the PSO and SA algorithm to ensure the search converges faster and improves the local-search ability. Therefore, the hybrid PSO-SA algorithm is a heuristic combination approach that can provide high-quality solutions in a reasonable time (Sarbijan and Behnamian, 2022). The flowchart of the hybrid PSO-SA algorithm is illustrated in **Fig. 4**. The procedures of the hybrid PSO-SA algorithm implemented in this paper can be given as follows:

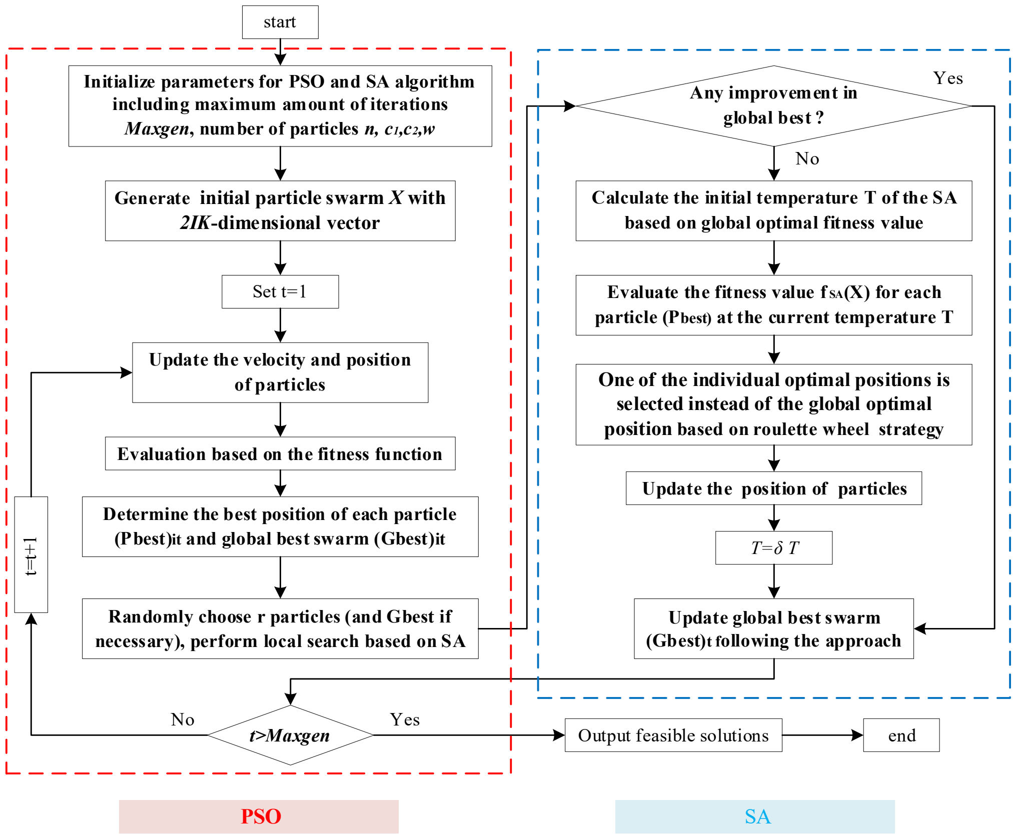


Fig. 4 The flowchart of the hybrid PSO-SA algorithm.

Step1: Population initialization. To apply the hybrid PSO-SA algorithm to solve the ship appointment scheduling problem, we can first encode the initial solution into a $2IK$-dimensional vector $X = (X_{11}, X_{12}, \cdots, X_{IK}, \cdots, X_{2IK})$ according to the relevant constraints of the model (i.e., Constraint (7)-(23)), and I, K are the number of planning horizons and daily appointment periods respectively. The first IK dimension can represent the appointment quota (x_{ik}) of IK appointment periods, the second IK dimension can indicate the number of rescheduling of unpunctual ships (φ_{ik}) of IK appointment periods, the initial vector should be restricted by the capacity of the lockage facility (S^{max}). According to each appointment quota and rescheduling allocation scheme, the initial arrival number of ships is calculated by Eq (10). Specifically, when $e_{ik} - n_{ik} \geq x_{ik}$, $y_{ik} = x_{ik}$, the excess of the appointment quota is reallocated to other available periods, which needs to meet the condition $e_{ik} - n_{ik} - x_{ik} = z_{11} + z_{12} + \cdots + z_{IK}, and\ z_{ik} = 0$. However, when $e_{ik} - n_{ik} < x_{ik}$, $y_{ik} = e_{ik} - n_{ik} + \sum z_{ik}$, which needs to meet the condition $y_{ik} \leq x_{ik}$. Where z_{ik} is the adjusted number of ships for the k^{th} period in day i, $\sum z_{ik}$ is the total number of ships adjusted to time period k^{th} on day i for other appointment periods. Thus, the actual arrival number of ships ψ_{ik} equals to $y_{ik} + \varphi_{ik}$, where φ_{ik} represents the number of rescheduling of unpunctual ships (i.e., rescheduling strategy). In addition, we initialize the parameters for PSO and SA, such as the inertia weight of the particle velocity (ω), the cognitive and social parameters (c_1, c_2) and the temperature controlling parameter (T).

Step 2: Fitness evaluation. The $M/M/C$ queueing method (see Section 3.2) is applied to model the ship arrival pattern at the anchorage, and the average waiting time of ships is also calculated to update the element in the objective function. The Eq. (6) is applied to evaluate and calculate the fitness of the individual particle (solution), the best position of each particle (P_{best}) and global best swarm (G_{best}) can be found.

Step 3: Particle and velocity update strategy. The generated particle swarm updates its historical optimal position in each generation. Thus, we can update the velocity and position for each particle in the population according to Eqs. (29) - (31).

Step 4: Perform the SA to the population. According to the global optimal fitness value, the initial temperature of the SA algorithm can be obtained. Based on the roulette wheel strategy, one of the individual optimal positions is selected to replace the global optimal position. Roulette wheel selection method is one of the selection operators, also known as proportional selection method. Its idea is to use the probability method to select the individuals with good fitness performance in the population. The higher the fitness of each individual, the higher the probability of being selected. When no improvement (i.e., $\Delta f < 0$) is achieved in a PSO cycle, a new position (i.e., solution) can be found and determined by SA algorithm (i.e., using temperature) and take place of old global best position in PSO algorithm. The new solution is accepted with the probability of 1 as the new feasible solution. Otherwise, the acceptance probability of new solution is calculated by generating a random number from a uniform distribution interval (0, 1). If $exp(-\Delta f/T) > rand$, the new position (solution) can be accepted as a new feasible solution (i.e., G_{best}) even through the current position is worse. Otherwise, the current position (solution) is kept.

Step 5: Update temperature. The temperature T is reduced by a certain annealing speed δ, say $T = \delta T$, and the annealing operation is completed.

Step 6: Termination criteria are determined. The search terminates if T is less than the end temperature and the feasible solution cannot be improved after some interactions (500 in this experiment). Otherwise, it can return to step 2.

4.4 Overall hybrid PSO-SA algorithm procedure

Algorithm 1 presents the hybrid PSO-SA algorithm procedure. Given the number of appointment ships and periods, and the initial solution can be randomly generated and evaluated by the fitness function (i.e., objective function). Then, the hybrid PSO-SA in Algorithms 1 can generate a particle with an initial state, we can update the velocity and position of each particle in the population according to Eqs. (29) - (31). The objective value should be estimated by the objective function of each particle and compared with its personal best value P_{best}. The swarm then gets the best solution from the particle as the global best solution G_{best}. To overcome the shortcoming of the PSO algorithm falling into local optimum, the SA algorithm inspires accepting the new solution. The proposed hybrid PSO-SA algorithm can calculate the probability based on Eq. (32), and new feasible solution will be accepted if the probability is larger than a random number between 0 and 1. This hybrid PSO-SA algorithm provides the possibility to get rid of one local optimum to find the global optimization result. Finally, the search terminates if T is less than the end temperature and the feasible solution cannot be improved after some interactions.

Algorithm 1: Hybrid PSO-SA algorithm

Input: ship arrival and lockage capacity information, appointment rules.
Output: good feasible appointment quota solution X
Population initialization
for iter $= 1 : \max gen$ do
    for particle $= 1 : sizepop$ do
        Particle and velocity update strategy
        Update position
        Evaluation by the objective function $f(X)$
        if $f(X)_i^t < f(X_n)_i^t\ (Pbest_i^t)$ then
            Update personal optimal value P_{best}
            if $f(X_n)_i^t (Pbest_i^t) < f(X_n)_i^t\ (Gbest_i^t)$ then
                Update global optimal value G_{best}
            end
        else
            $\Delta f \leftarrow f(X_n) - f(X)$
            $P \leftarrow exp(-\Delta f/T)$
            If $P > rand$ then
                New position (solution) is accepted as a new feasible solution
            end
        end
    end
    Update global best value G_{best}
    Update inertia weight ω
    $T \leftarrow \delta T$
end

5. Computational experiments

This paper uses a real-world case study to validate the effectiveness and application of the proposed ship appointment scheduling optimization model and solution algorithm. The proposed algorithm in this study is coded in MATLAB 2019b on a computer with Intel Core i5-1035G1 CPU and 8 GB RAM.

5.1 Data preparation

To verify the effectiveness and applicability of the proposed ship appointment scheduling system, we conduct a series of experiments based on the real-world data in the Three Gorges

Navigation Area, and the details of the ship appointment scheduling process are presented in **Table 2**. There is a 3-day planning horizon with 16 appointment periods per day (i.e., i = 16), and a total of 72 service stations (i.e., number of berths at the anchorage). Since a new lockage operation starts every 1.5 hours, the appointment period is set to 1.5 hours (i.e., 16 appointment periods per day). The service rate of ship queuing, maximum constraint information, and carbon emission parameters are also provided. With the strong support of the Three Gorges Navigation Authority, our research group conducted fieldwork in the navigation area located in front of the TGD in 2021 and 2023, and collected a large number of actual data. **Table 3** shows the original arrival pattern data of ships without the appointment scheduling system (i.e., the number of ships is 210), and registers the non-punctual arrivals data. According to the case of Three Gorges Navigation Area, we set the number of ships unpunctuality to 24 (i.e., the proportion of non-punctual arrival of ships θ is equal to 0.1), and the limitation of ship appointment adjustment rate (i.e., α) and ship rescheduling rate for each period (i.e., β) are set to 0.3 and 0.5 respectively. It should be pointed out that the unpunctual arrival of ships is random, and the number of unpunctual ships in each period can exceed two or more. However, due to the strict requirements of lockage operation and ship credit system, the concentration of non-punctual arrival of ships in a certain time period is avoided. Thus, the number of unpunctual ships in each period is limited, and it is rare for the number of non-punctual ships to exceed two or more in each period. Furthermore, strict penalty measures can only reduce the number of unpunctual ships in a certain period as much as possible, but the phenomenon of unpunctual arrival of ships is unavoidable because of some unexpected reasons (e.g., ship works improperly and security check failed). The uncertainty of ship arrival can complicate the ship appointment scheduling problem and disturb the scheduling of subsequent. Consequently, it is very necessary to consider the effects of unpunctual arrival of ships on the ship appointment scheduling. Then, based on the previous study (Sarbijan and Behnamian, 2022), the basic parameters of PSO-SA algorithm are set as follows: $\max gen = 500$, $sizepop = 100$, $c_1 = 2 \times sin(pi/2 \times (1 - t/maxgen))\string^2$, $c_2 = 2 \times sin(pi \times t/(2 \times maxgen))\string^2$, $w_{max} = 0.9$, $w_{min} = 0.4$, and we set $\delta = 0.8$, $T = -bestfitness/log(0.2)$, and random setting of the other algorithm parameters.

Table 2 Parameters of a real-world case study.

Parameter	Description	Data
J	No. of planning horizons	3 days
K	No. of daily appointment periods	16
c	No. of service stations	72
μ	Service rate of ship queuing	0.048
L^{max}	Maximum allowable queue length for a given appointment period	250
S^{max}	Maximum allowable service capability for a given appointment period	6
W^{max}	Maximum allowable queuing time for a given appointment period	60 h
τ	Ship-specific constant	0.0048
p	Adjustment parameters of fuel consumption	0.03
∂	Carbon coefficient	3.082

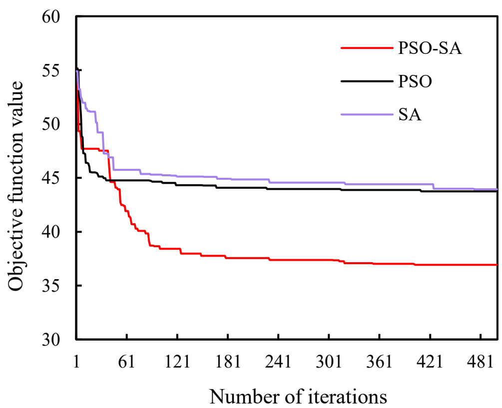
In this numerical experiment, we also consider two different arrival scenarios of ship appointment scheduling at the Three Gorges Navigation Area, namely on-time arrival scenarios and non-punctual arrival scenarios. Specifically, in the non-punctual arrival scenarios, some ships may arrive later than the designated period and can only be rescheduled to another appointment period. An important reason is that, if the non-punctual arrival of ships is not rescheduled, it will disrupt the original ship appointment scheduling scheme and cause serious waterway traffic congestion. Instead, in the on-time arrival scenarios, it is only necessary to reasonably arrange the arrival patterns of ships in each appointment period without considering the unpunctuality of ships.

Table 3 Detailed ship original arrival scheme and non-punctual arrival information.

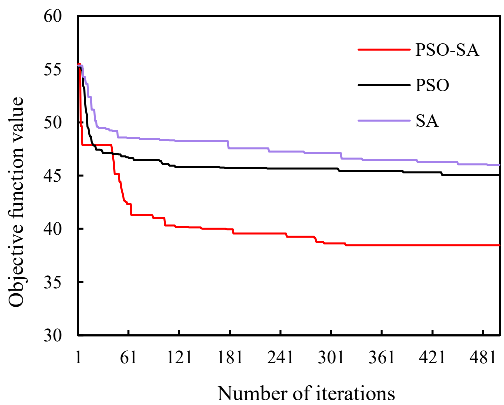
Daily appointment period k	Time	Original arrival No. [non-punctual arrival No.]		
		$i=1$	$i=2$	$i=3$
1	00:00-01:30	8 [0]	6 [0]	8 [1]
2	01:30-03:00	7 [0]	5 [1]	9 [0]
3	03:00-04:30	7 [1]	8 [0]	9 [0]
4	04:30-06:00	8 [0]	8 [1]	6 [0]
5	06:00-07:30	7 [0]	6 [0]	7 [1]
6	07:30-09:00	6 [1]	8 [1]	6 [1]
7	09:00-10:30	3 [0]	7 [0]	1 [0]
8	10:30-12:00	4 [1]	1 [1]	1 [0]
9	12:00-13:30	5 [1]	2 [0]	3 [1]
10	13:30-15:00	1 [0]	2 [1]	3 [0]
11	15:00-16:30	2 [1]	1 [1]	2 [0]
12	16:30-18:00	1 [0]	3 [0]	5 [1]
13	18:00-19:30	3 [1]	4 [1]	1 [0]
14	19:30-21:00	2 [0]	3 [0]	1 [1]
15	21:00-22:30	1 [1]	2 [1]	5 [0]
16	22:30-24:00	3 [1]	3 [1]	6 [1]

5.2 Algorithm contrast

In this section, the real-world case study and ship arrival data obtained in Tables 3 and 4 are applied to compare the computational efficiency and performance of the PSO-SA with the SA and PSO algorithms. **Fig. 5** shows the comparison results of PSO-SA with SA and PSO algorithms in different arrival scenarios. As can be seen, the numerical experiments have proved that the proposed PSO-SA can jump out of a locally optimal solution and has a better optimization ability than the SA and PSO. **Table 4** reports the computational results of three algorithms in different arrival scenarios.



(a) In the on-time arrival scenarios ($\theta = 0$)



(b) In the non-punctual arrival scenarios ($\theta = 0.1$)

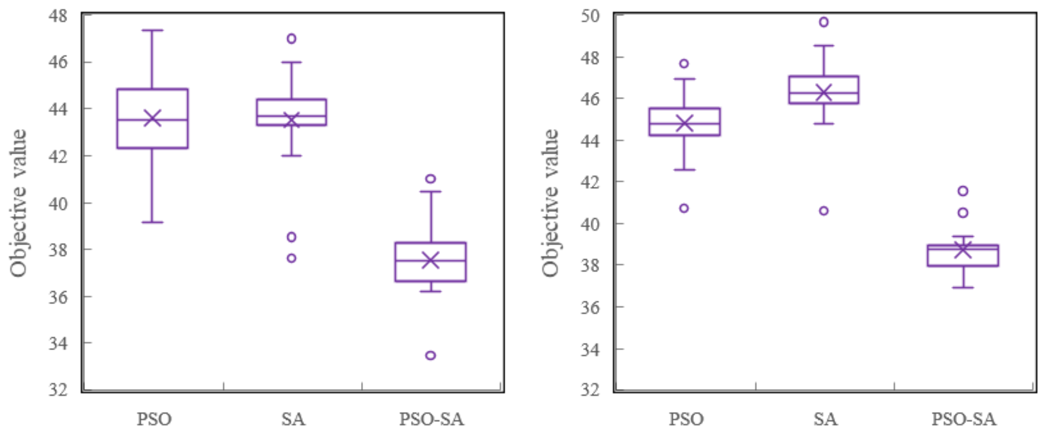
Fig. 5 Comparison results of PSO-SA with SA and PSO algorithms.

In terms of experimental results, the computational performance of the PSO-SA in the on-time arrival scenarios (i.e., $\theta = 0$) can be better than the SA and PSO by 15.96 % and 15.59 %, respectively. In addition, the computational performance of the PSO-SA in the non-punctual arrival scenarios (i.e., $\theta = 0.1$) can be better by 16.41 % and 14.66 % respectively.

To analyze the robustness between several heuristic algorithms in different arrival scenarios, we obtain the objective function value of the feasible solution of the experiment with 20 repetitions. **Fig. 6** shows the boxplot figure of the objective value from three algorithms. As can be seen, the objective value obtained by the PSO-SA algorithm has smaller median and range, which further verifies that the proposed PSO-SA algorithm significantly outperforms the PSO and SA algorithms.

Table 4 Computational results of three algorithms in different arrival scenarios.

Scenarios	In the on-time arrival scenarios			In the non-punctual arrival scenarios		
Methods	SA	PSO	PSO-SA	SA	PSO	PSO-SA
Objective function value (h)	43.94	43.75	36.93	46.00	45.06	38.45



(a) In the on-time arrival scenarios ($\theta = 0$) (b) In the non-punctual arrival scenarios ($\theta = 0.1$)

Fig. 6 The boxplot figure of the objective value from three algorithms.

5.3 Effectiveness of optimized ship appointment scheduling schemes

To further demonstrate the effectiveness of the proposed model and PSO-SA algorithm for managing the ship arrival pattern in different arrival scenarios, we compare the differences in ship arrival patterns between the original ship arrival scheme and the optimized ship appointment scheduling schemes. **Fig. 7** shows the ship arrival patterns (i.e., number of ships arriving) of the optimized and original schemes for different arrival scenarios. The result shows that the original ship arrival scheme is formulated based on ship arrival preference. It is very easy to cause uneven distribution of ship arrivals in different appointment periods. During the peak periods, the number of ships arriving largely exceeded the service capacity of the lockage facilities. Especially in the case of unpunctual arrival, the uncertain arrival of some ships may further aggravate the unbalanced distribution of ships over different appointment periods, the difficulty of ship arrival pattern management increases, which can result in long waiting time and increase the queue length of ships.

However, the ship appointment scheduling system proposed in this study achieves the optimal arrival pattern by shifting or adjusting the ship arrivals from peak time to no-peak time, which can level the arrival peak and alleviate the traffic congestion. Specifically, the proposed ship appointment scheduling system is applied to ships passing through the dam, the ship arrival pattern is flattened when more even quotas are allocated for different appointment periods, which can help to better match the service capacity of the lockage facilities. Considering the influence of unpunctual ships, the rescheduling strategy is applied to mitigate the negative impact of non-punctual ships and reduce the waiting time of ships around the dam. Therefore, it is very necessary to adopt the ship appointment scheduling system and obtain the optimized ship arrival scheme in different scenarios.

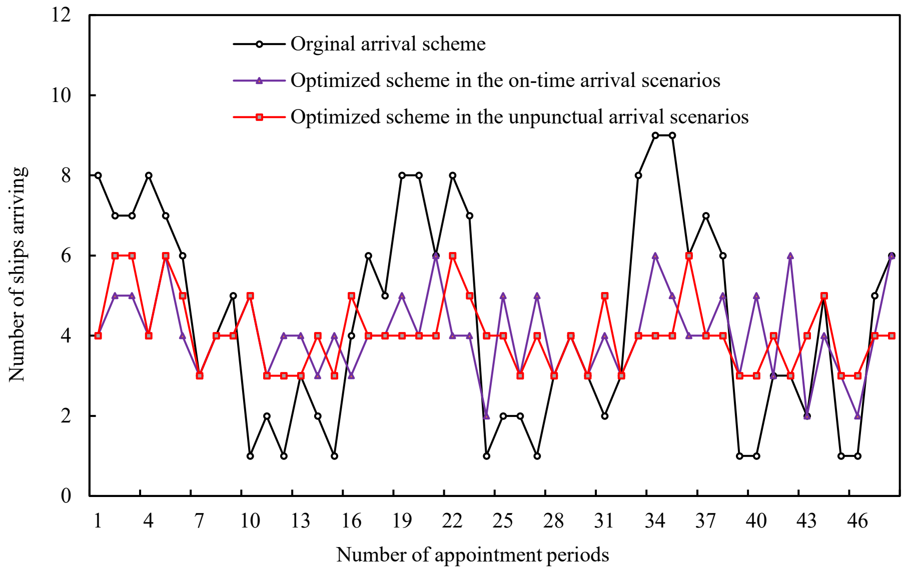


Fig. 7 Optimized and original ship arrival patterns for different arrival scenarios.

5.4 Analysis of carbon emission reduction of ship appointment scheduling system

In Section 3.4, the carbon emission reduction achieved by the optimized ship appointment scheduling schemes is calculated. Specifically, the emission in different arrival scenarios is calculated and compared with that of the original arrival scheme. **Fig. 8** presents the carbon emission reduction rate in the on-time and unpunctual (i.e., non-punctual) arrival scenarios.

Based on the observation of the Three Gorges Navigation Area from May 24th and May 26th, 2021, the average waiting time of ships is approximately 46.56 h (i.e., original ship arrival scheme) (Zhao et al., 2022). Additionally, this period is the most frequent and typical time of mismatch between ship arrivals and lockage capacity according to the historical data, we can obtain information about the number of ships, and the arrival patterns of ships can be managed. As can be seen, the proposed ship appointment scheduling system shows good effectiveness in improving environmental pollution, the carbon emission of ships in the on-time and non-punctual arrival scenarios can be reduced by 20.7 % and 17.4 % respectively. It is worth noting that the carbon emission reduction rate of ships decreased by 3.3 % in the non-punctual arrival scenarios. An important reason is that unpunctual arrival ships need to be rescheduled, which delays the appointment arrival time of these ships. As a result, the service resources of locks are wasted, resulting in increased waiting time and carbon emission of ships. The comparison results show that the proposed ship appointment scheduling system can promote the matching between the number of ship arrivals and the service resources of the lock at each appointment period, which can significantly reduce the carbon emission of ships. The results support the claim that appointment scheduling is an effective avenue to reduce ship idling emissions around the dam. Furthermore, the implementation effect of the ship appointment scheduling system is poor in the non-punctual arrival scenarios. Therefore, when the ship appointment scheduling system is implemented in different arrival scenarios, we need to pay more attention to the difference in carbon emission reduction effects.

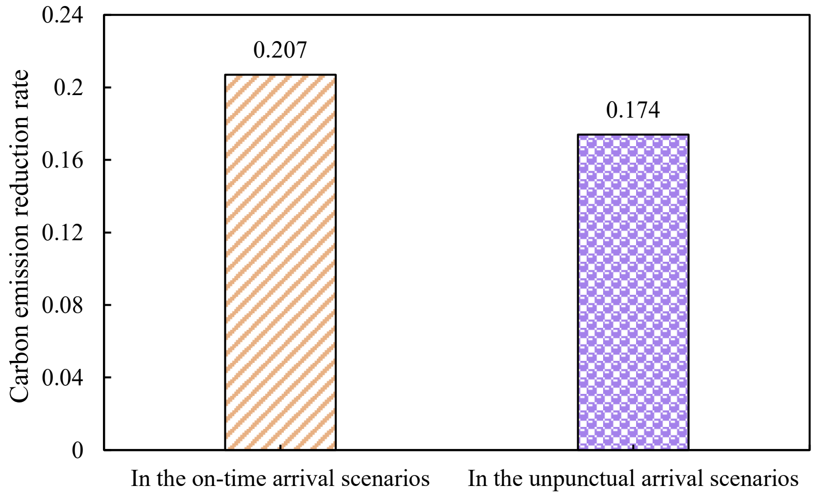


Fig. 8 Carbon emission reduction rate in different arrival scenarios.

5.5 Sensitivity analysis

5.5.1 Analysis of the proportion of non-punctual ships

This paper investigates the ship appointment scheduling problem for lockage operations of waterway transport, where the non-punctual arrival of ships is also considered. In addition, we apply the rescheduling strategy to reduce the negative effects of the non-punctual arrival of ships. Numerical experiments are conducted to analyze the effect of the proportion of non-punctual ships (i.e., θ) on the objective value and computational performance. In the numerical experiments, we select the instance group of 210 ships in 3 days as the benchmark instance. Such a ship appointment scheduling scale is acceptable for lock arrangements with more than 16 lockages per day. In this section, we generate some new instances by setting the proportion of ship unpunctuality to $\{0, 0.05, 0.10, \ldots, 0.50\}$, thus constructing a total of 11 new test instances. Since the total number of ships in the benchmark instance is 210, we can calculate the number of non-punctual ships in each instance based on the proportion of unpunctual ships, which can be set to $\{0, 11, 21, \ldots, 105\}$. According to the distributive law of unpunctual arrival of ships at the Three Gorges Dam, we randomly generate the number of non-punctual ships in each time period. In addition, to maintain the stability of the ship appointment scheduling system, we require that the proportion of non-punctual ships does not exceed 50%, so its upper bound is set to 0.50. The detailed results are presented in **Table 5,** where "Obj_value" and "Time" refer to the objective function value (i.e., the average waiting time of ships) and computational time of the proposed algorithm, respectively. **Fig. 9** presents the objective value and computational time curve.

Some of the important insights in **Table 5** and **Fig. 9** are summarized as follows. First, when the non-punctual arrival rate of ships is set to 0, the appointment scheduling of ships can be considered to be carried out in the on-time arrival scenarios. All ships can arrive on time according to the appointment period, which avoids interference to the scheduling of ships. The proposed PSO-SA algorithm takes only 0.69 s to solve the ship appointment scheduling problem for lockage operations of waterway transportation in the on-time arrival scenarios. In terms of operational efficiency, the proposed algorithm is suitable for efficient decision-making of ship appointment scheduling in the on-time arrival scenarios. Second, when the proportion of non-punctual ships increases, the computation time of the PSO-SA algorithm also increases, which indicates that the

Table 5 Detailed results with varying ship unpunctuality arrival rate.

Instances.	Proportion of unpunctual	Averages	
No	arrival ships θ	Obj_value (h)	Time (s)
1	0	36.93	0.69
2	0.05	37.85	0.76
3	0.10	38.45	0.91
4	0.15	39.66	1.08
5	0.20	39.80	1.09
6	0.25	41.25	1.80
7	0.30	43.68	2.12
8	0.35	45.38	2.26
9	0.40	47.02	2.58
10	0.45	49.82	2.79
11	0.50	52.19	3.17

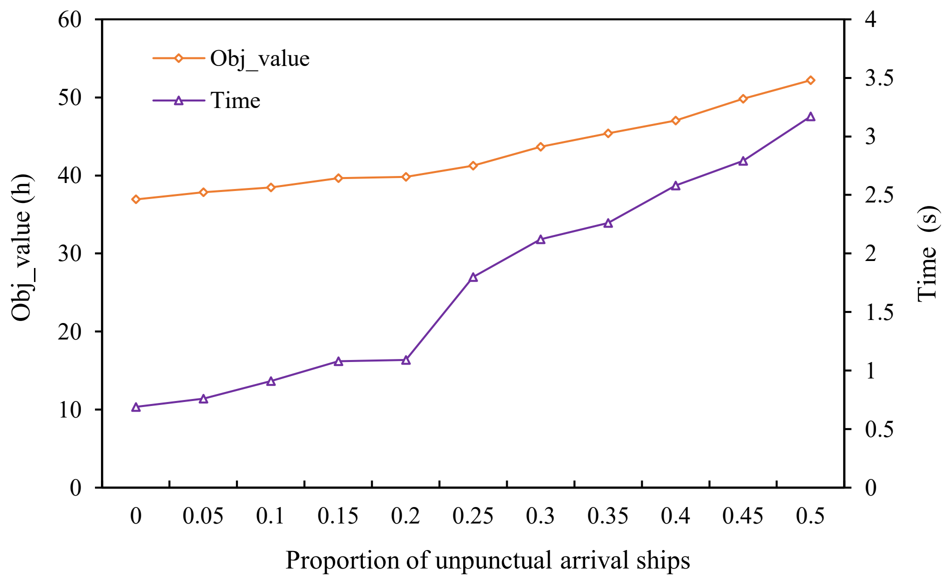


Fig. 9 Sensitivity analysis of the proportion of non-punctual arrival ships.

operating rules of the ship appointment scheduling system become more and more complicated when more unpunctual arrival ships interfere with the scheduling of on-time arrival ships. In addition, the growth of the objective function value gradually increases with the increase of the proportion of unpunctual ships. An important reason is the continuous increase in the proportion of unpunctual ships, more ships have to be rescheduled (i.e., rescheduling strategy), so that ships cannot arrive at the original appointment period, resulting in lower efficiency of ship scheduling and long waiting time for ships. Third, when the proportion of non-punctual ships grows to a certain level, the function of the ship appointment scheduling system will be reduced until it becomes invalid. This is because the continuous increase in the proportion of non-punctual ships may lead to the loss of the function of ship arrival pattern management. This is, when the proportion of unpunctual ships reaches a specified value (possible 0.40), the effect of implementing the ship appointment scheduling system is worse than that not implementing the proposed system (i.e., original ship arrival scheme), which indicates that the increase of the proportion of non-punctual ships will affect the implementation effect of the proposed ship appointment scheduling system (i.e., the rescheduling strategy is invalid). Therefore, dam operators should pay more attention to controlling the number of non-punctual ships during the implementation of the appointment scheduling system.

In addition, the above analysis can help dam operators to better reduce the waiting time of ships around the dam when controlling the proportion of non-punctual ships. For instance, the ship appointment scheduling system may be ineffective when the number of unpunctual ships is still dominant. Increasing efforts to control the number of non-punctual ships, which can lead to a significant decrease in the objective function value (i.e., the average waiting time of ships) and thus bring better implementation effects of the ship appointment scheduling system. Therefore, dam operators can decide whether to control the proportion of non-punctual ships to a lower level to obtain the maximum benefit of navigation and the minimum waiting time of ships.

5.5.2 Analysis of ship appointment adjustment rate

In this section, the sensitivity analysis on the ship appointment adjustment rate is performed to determine the optimal ship appointment adjustment rate level and investigate the trade-off relationship between the appointment adjustment rate (i.e., negative effects of ship appointment scheduling system) and waiting time of ships (i.e., objective function value). Numerical experiments are carried out to analyze and discuss the effects of the ship appointment adjustment rate on the objective function value and the computational performance. In the numerical experiments, we generate new instances based on the group of instances with 210 ships, where the limitation of the ship appointment adjustment rate (i.e., α) varies from 0, 0.1, 0.2, …, 0.5. We further select three ship arrival patterns, namely $\theta \in \{0, 0.05, 0.1\}$, where θ represents the proportion of unpunctual ships. It is worth noting that since unpunctual ships need to be adjusted, the value of the ship appointment adjustment rate must be higher than the value of the proportion of unpunctual ships (i.e., $\alpha \geq \theta$). There is a total of 16 new instances with different ship appointment adjustment rates and the proportion of unpunctual ships. When the proportion of non-punctual ships and ship appointment adjustment rate is set to 0, it means that the ship appointment scheduling system is not applied, and all ships were scheduled according to the original ship arrival scheme (i.e., Instance 1). In instances 1~6, all ships can arrive on time and there are no unpunctual ships that need to be rescheduled and adjusted. However, the introduction of the appointment scheduling system can manage the ship arrival pattern by shifting a small number of ships from peak to off-peak periods of the day, which means that the arrival patterns of some ships still need to be adjusted. In addition, a larger parameter α indicates that more ships need to change their arrival pattern or habits, which means that the matching between ship arrivals and lockage capacity can be better, and the average waiting time of ships can be reduced. Thus, for the instances 1~6, the limitation of ship appointment adjustment rate (i.e., α) still has a significant impact on the average waiting time of ships. The detailed results with varying the ship appointment adjustment rate are presented in **Table 6**.

As can be seen, as the ship appointment adjustment rate increases under different arrival scenarios, the computational time of the PSO-SA algorithm is slightly decreased. That is because more appointment adjustments lead to an increase in its adjustment space, increasing the adjustment amplitude of the ship's arrival pattern and the flexibility of the ship appointment scheduling system. As a result, the algorithm can obtain the feasible solution in a relatively short time. Furthermore, we also observe a decrease in the objective value with an increase in the rate of ship appointment adjustment. The results verify the trade-off relationship between the objective function value and the ship appointment adjustment rate, which indicates that appropriate arrival pattern adjustment can reduce the average waiting time and carbon emission of ships around the dam. However, when the ship appointment adjustment rate is set too large, it means that more ships need to change their arrival habits, which has a greater negative impact on the ship appointment scheduling system. Therefore, the implementation of a ship appointment scheduling system requires a balance between reducing the waiting time of ships and reducing the negative impact caused by ship appointments. A proper setting of the ship appointment adjustment rate will help to manage the ship arrival pattern and play the role of the ship appointment scheduling system.

Table 6 Detailed computational results with varying the ship appointment adjustment rate.

Instances. No	Proportion of unpunctual ships θ	Ship appointment adjustment rate α	Average Obj_value (h)	Time (s)
1	0	0	46.56	0
2		0.10	39.41	1.53
3		0.20	38.07	1.42
4		0.30	36.93	0.69
5		0.40	36.90	0.67
6		0.50	36.71	0.67
7	0.05	0	-	-
8		0.10	40.22	1.81
9		0.20	38.87	1.54
10		0.30	37.85	0.96
11		0.40	37.76	0.80
12		0.50	37.59	0.79
13	0.10	0	-	-
14		0.10	40.73	1.97
15		0.20	39.14	1.71
16		0.30	38.45	1.01
17		0.40	38.42	0.90
18		0.50	37.98	0.95

5.5.3 Analysis of ship rescheduling rate for each period

To further investigate the impact of the ship rescheduling rate for each period (i.e., β) on the ship appointment scheduling system, we further test the ship appointment scheduling optimization model with various ship rescheduling rate levels for each period. Specifically, the sensitivity analysis on the ship rescheduling rate for each period is performed to determine the optimal rescheduling scheme, as the effect of the rescheduling strategy is related to the size of the rescheduling rate for each period, and has a significant impact on the whole appointment scheduling system. We select one ship arrival pattern, namely $\theta = 0.1$, where θ represents the proportion of non-punctual ships, and the limitation of ship appointment adjustment rate (i.e., α) is set to 0.3. In addition, we further construct new instances based on the group of instances with 210 ships, where the limitation of the ship rescheduling rate for each period (i.e., β) varies from 0.1, 0.2, …, 0.5. **Fig. 10** shows the objective value and computational time with different levels of ship rescheduling rate.

As can be seen, as the ship rescheduling rate for each period increases, the objective value is slightly decreased, and the computational time of the PSO-SA algorithm is relatively stable. If it is necessary to reduce the waiting time of ships around the dam, we can set an appropriate rescheduling rate to improve the transportation efficiency of unpunctual ships. Such sensitivity analysis can help dam operators to formulate rescheduling rules for unpunctual arrival ships, so as to reduce the waiting time of ships and improve the navigation efficiency.

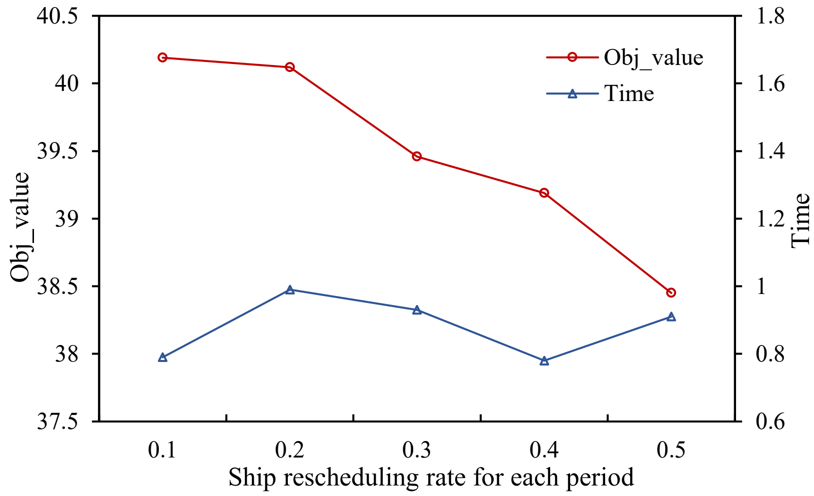


Fig. 10 Sensitivity analysis of the ship rescheduling rate for each period.

6. Conclusions and future research

This study presented a new mathematical model for addressing the ship appointment scheduling problem for lockage operations of waterway transport, where the queuing of ships, the non-punctual arrival of appointment ships, the appointment adjustment level of ships, and the ship rescheduling rate factors are comprehensively considered. The $M/M/C$ queueing method was applied to calculate the waiting time of ships around the dam, and a straightforward yet effective PSO-SA algorithm was designed to solve the ship appointment scheduling optimization problem. The proposed model and method are verified with some numerical experiments based on a real case study at the TGD. The results show that the waiting time and carbon emission of ships can be significantly reduced by shifting or adjusting a small number of ships from peak to off-peak periods of the day. The proposed ship appointment scheduling system aims to improve the matching between ship arrivals and lockage capacity by managing the ship arrival pattern at different appointment periods, which can also level the arrival peak and alleviate the waterway traffic congestion. In addition, the difference in arrival scenarios (i.e., the on-time arrival scenarios and non-punctual arrival scenarios) has a significant impact on the performance of the proposed ship appointment scheduling system.

Several important points can be summarized as follows: (i) The proposed hybrid PSO-SA algorithm outperforms the traditional SA and PSO algorithm in solving this problem, which can jump out of a locally optimal solution and satisfy the real-world ship appointment requirement. (ii) By implementing the ship appointment scheduling system, the ship arrival pattern can be flattened when more even quotas are allocated for different appointment periods, which will be helpful for ships to better match the service capacity of the lockage facilities. As a result, the model can be applied to determine the optimal arrival scheme of ships and matching relationship between the number of ship arrivals and the service capacity of the lockage facilities. (iii) The implementation effect of the ship appointment scheduling system is different in two arrival scenarios (i.e., on-time arrival scenarios and non-punctual arrival scenarios). Specifically, In the on-time arrival scenarios, the ship arrival pattern can be better flattened and managed, which can help to better match the service capacity of the lockage facilities, and reduce the waiting time and carbon emission of ships. This point can help to improve the environmental pollution around the dam. However, in the non-punctual arrival scenarios, it is very necessary to further consider the rescheduling strategy of unpunctual ships, which can reduce the interference effects of unpunctual ships, but the waiting time can be longer than before. (iv) The proportion of unpunctual ships, the ship appointment adjustment rate, and the ship rescheduling rate can be optimized, those factors have an important impact on the implementation performance of ship appointment scheduling system, which can provide an important reference for ship arrival pattern management and rescheduling rule making. Thus, the above results can provide theoretical support for enhancing transportation efficiency and reducing the negative impact of unpunctual ships.

Although this study developed an effective heuristic algorithm and established a new mathematical model for the ship appointment scheduling problem, some innovative extensions can also be made for further study. First, the appointment scheduling of ships is related to the lockage operation of waterway transport (i.e., lock scheduling). Therefore, an innovative extension is to incorporate the scheduling of locks into the model presented in this paper (Liu et al., 2024). Second, other important routes are not included in the ship appointment scheduling system, such as the water-land transshipment mode. Thus, another innovative and valuable research direction is to formulate a ship appointment scheduling optimization model under the framework of multimodal transport (Zhang et al., 2024). Third, under the space limitation of the lock chamber, the different specifications of the ships may have an important impact on the lockage capacity and the appointment quota in each period, so future research is anticipated to model and investigate this impact. Finally, more real-world case data is needed to verify the proposed ship appointment scheduling system to obtain reliable results and applications.

CRediT authorship contribution statement

Shun Liu: Conceptualization, Methodology, Software, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Yu Zhang**: Conceptualization, Resources, Supervision, Funding acquisition, Writing – review & editing. **Wenjing Guo**: Methodology, Investigation, Supervision, Writing – review & editing. **Weifeng Wang**: Resources, Investigation. **Qianqian Zheng**: Methodology, Investigation. **Hao Yu:** Supervision, Methodology.

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

Data will be made available on request.

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