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APPLYING BI-RANDOM MODM MODEL TO NAVIGATION COORDINATED SCHEDULING: A CASE STUDY OF THREE GORGES PROJECT

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Abstract. The aim of this paper is to deal with the optimal navigation coordinated scheduling (NCS) problem in ship transportation of the Three Gorges Project in China, i.e. the Three Gorges Dam and the Gezhouba Dam. The NCS includes operational scheduling for two five-step locks in Three Gorges Dam and three single-step locks in Gezhouba Dam. A birandom multiple objective decision-making model is first proposed for the NCS problem to cope with hybrid uncertain environment where twofold randomness exists in practice. Then, particle swarm optimization is applied to search for the optimal solution. Based on real execution data, the results generated by a computer validate effectiveness of the proposed model and algorithm in solving large-scale practical problems is presented.

Keywords: scheduling; navigation; navigation coordinated scheduling; bi-random variable; Three Gorges Project; large-scale; multiple objective; PSO.

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Introduction

Recently, as a means of forming global networks and improving operation efficiency, coordinated scheduling has attracted ever-growing attention both from the fields of science and practice, especially in transportation. The setting of a good coordinated schedule of transportation can not only enhance operating performance of timetable, but can also be a useful reference for the whole decision-making process, such as cost control, effective utilization of the resource, etc. For example, in air industry, a suitable coordinated scheduling could assist the allied airlines to find the most satisfactory fleet routes and timetables and help the participating carriers more efficiently use resources on alliance routes, thereby reducing their operating cost. Meanwhile, passengers could also save the waiting time and cost. Because of its important practical significance, coordinated scheduling has been addressed by a number of researchers in many areas, such as supply chain management (Bonfill *et al*. 2008; Sawik 2009), production and delivery (Garcia *et al*. 2004; Li *et al*. 2008; Tang, Gong 2009; Lee, Yoon 2010; Delavar *et al*. 2010; Tang *et al*. 2010), transportation (Shrivastava, O'Mahony 2006; Yan, Chen 2007; Yan *et al*. 2008; Zegordi, Nia 2009; Chen *et al*. 2010), customer orders system (Liu 2010), etc.

As a very important part of the transportation coordinated scheduling, navigation coordinated scheduling (NCS) of a ship transportation has received more widespread concern owing to the application of RTK technology and laser solutions in navigation system, especially in the Inland waterways (Taylor *et al*. 2005; Konings *et al*. 2006; Januszewski 2011). Naturally, as the largest water conservancy and hydropower construction project in the world, navigation scheduling of the Three Gorges Project (including the Three Gorges Dam and the Gezhouba Dam) in China has been addressed by a number of researchers – Lu *et al*. (2000), Liu and Qi (2002a, b), Lai and Qi (2002), Du and Yu (2003), etc. The studies above all focus on a single-lock chamber. Furthermore, researchers have started to explore the issue of NCS for the two dams of the Three Gorges Project. In Qi *et al*. (2007), the researchers applied Progressive Optimality Algorithm to obtain the optimal scheduling of NCS. Besides, Zhang *et al*. (2010) presented a rolling horizon procedure (RHP) to deal with the large-scale NP-hard problem on cooperative lockage-timetables and service policies of the five locks in the Three Gorges

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Project. In this study, motivated by the applications in ship transportation of the Three Gorges Project, we first propose a birandom multiple objective decision-making (MODM) model to resolve the NCS problem for two locks in the Three Gorges Dam (TGD) and three locks in the Gezhouba Dam (GD).

In practice, however, uncertainty always exists in NCS because of the complex navigation environment, the randomness of arrival time, etc. (Fowler, Sørgård 2000). The uncertainty is traditionally assumed to be random, but random variables are sometimes not able to cope with the complicated situation in NCS to attain more suitable scheduling. For instance, the arrival anchor time is a random variable at the first place, but it may change because of treacherous weather in the navigation period. To deal with this change, the mean of the arrival anchor time is also a random variable, which means that the arrival anchor time is a random variable taking a random parameter. In this case, a birandom variable, proposed by Peng and Liu (2006, 2007), can be a useful tool for this hybrid uncertainty. So far no attempt has been made in considering the arrival anchor time and the penalty coefficients as birandom variables. Hence, there is a strong motivation and justification for the study of NCS under birandom phenomena.

The remainder of the paper is organized as follows. The problem statement of NCS in the Three Gorges Project is presented in Section 1. Subsequently, a presentation of birandom MODM model for NCS is proposed in Section 2, including the explanation of motivation and justification for employing birandom variables in the practical NCS model and equivalent crisp model. In Section 3, we propose particle swarm optimization (PSO) to resolve NCS problems. The effectiveness of the proposed model and algorithm is proven by the practical application in Section 4. Concluding remarks are made in next section, along with a discussion about further research.

1. Problem statement

The Three Gorges Project includes the Three Gorges Dam upriver and the Gezhouba Dam downriver. Three Gorges reach, as the Golden Channel's of the Yangtze River, is 59 km from MiaoHe to ZhongShui-Men. It locates the hinge of the Three Gorges Dam and the Gezhouba Dam. The distance between the two dams is less than 40 km, and a ship will spend 2÷4 hours in the navigation. Therefore, the Three Gorges Dam and the Gezhouba Dam could be disposed as a whole system. In order to improve the navigation capacity of the Three Gorges Project, it is necessary to design NCS for five locks in two dams. The navigation system between the Three Gorges Dam and the Gezhouba Dam involves Upper Yangtze River, The Three Gorges Dam (two five-step locks: North Lock and South Lock), the Reach between two dams, the Gezhouba Dam (three single-step locks: Lock No. 1, Lock No. 2, and Lock No. 3), Lower Yangtze River, and the Reach of HuangBai River (Fig. 1). North Lock and South Lock of the Three Gorges Dam are the largest ship locks in the world, and both of them are one-way locks. Usually, upward ship passes the North Lock, while downward ship passes the South Lock. Three single-step locks of the Gezhouba Dam are bidirectional lock, and Lock No. 1, Lock No. 2, and Lock No. 3 take turns from the west to the east. The ship not only could navigate by the main channel but also enter or leave the main channel by the reach of HuangBai River.

Unlike generating scheduling for hydroelectric systems – such as the research in Lian and Jiang (2005), Paulauskas (2010) – the NCS between the Three Gorges Dam and the Gezhouba Dam involves lock-

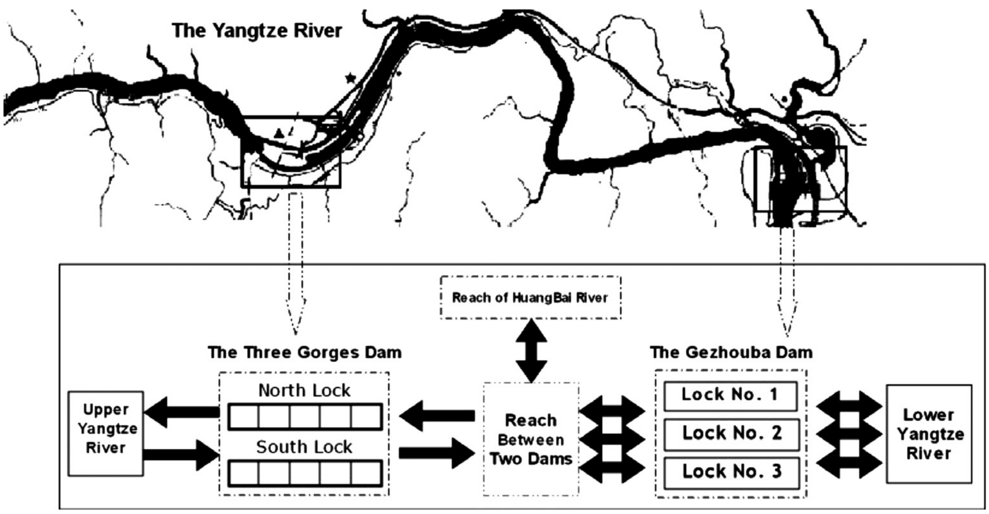

Fig. 1. Navigation system between the Three Gorges Dam and the Gezhouba Dam

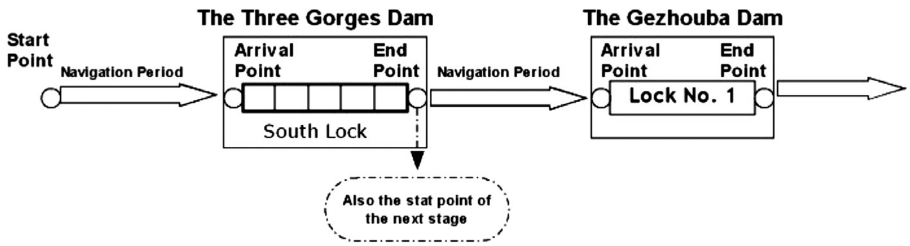

Fig. 2. An example of the navigation route (a ship from upriver)

operation scheduling and ship-dispatch scheduling (due to complexity of NCS in the Three Gorges Project, in practice, the Navigation Department will give some ship-dispatch scheduling data first by the application information of ships). Lock-operation scheduling is the operation timetable for each lock (including chamber arrangement), and ship-dispatch scheduling is the passing timetable for each ship (including ship arrangement in the chamber). In accordance with the application time and priority order of the ships, NCS generates the corresponding service timetable to make sure the five locks transfer ships collaboratively (Fig. 2). In this process, the application time and priority order of the ships are all known before scheduling (Lin 1987, 1998). In order to represent the details of NCS in the Three Gorges Project, there are some descriptions that should be explained first.

Since the ship may pass the two dams on its navigation in the Yangtze River Channel, we separate its navigation into multiple corresponding stages (Fig. 4). The process of the ship passing the dam is defined as – the lock gate opens, the ship enters the lock chamber, and then the ship is transferred through the dam (Lu *et al.* 2000; Liu, Qi 2002a; Zhang *et al.* 2010). Four important points of this process are stated as follows:

- *Lock service point*: Lock's gate opens;
- *Service direction*: The direction of the ships that is transferred by the lock;
- *Transfer time*: Lock transfers the ship in a chamber through the dam. Transfer time is shorter in TGD than in GD because the five-step locks are running as a pipe and single-step locks are running as an elevator;
- *Service interval*: Time interval between the lock service points to two consecutive lock services.

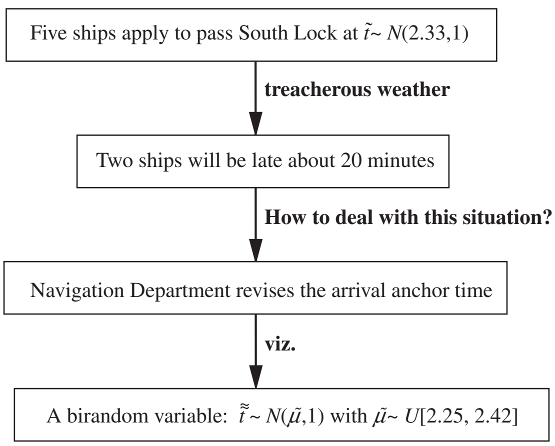

Fig. 3. Flowchart of why the arrival anchor time is a birandom variable

2. Mathematical model

In this section, before presenting the mathematical formulation model for NCS in the Three Gorges Project, first, we explain the motivation and justification for employing birandom variables in a practical NCS model. Subsequently, the equivalent crisp model is obtained from the expected value of birandom variables.

2.1. Motivation and justification for employing birandom variables in the practical NCS model

To cope with the hybrid uncertainty in NCS, we employ bi-random variables in this study. Actually, the bi-random variable has been successfully applied in many areas, such as a flow shop scheduling problem (Xu, Zhou 2009), portfolio selection (Yan 2009a, b), vendor selection (Xu, Ding 2011), etc. These studies show the efficiency of bi-random variables in dealing with a hybrid uncertain environment where twofold randomness exists.

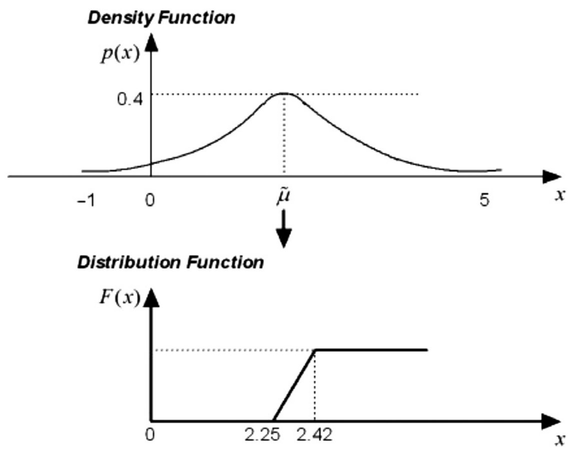

Fig. 4. Employing a birandom variable to express the arrival anchor time

In this study, we also employ the birandom variable because it is hard to describe random parameters as crisp ones. For instance, five ships apply to pass the Three Gorges Dam (*Jiangyun 803*, *Xinshun 898*, *Hangshun 778*, *Hangli 908*, *Zhongdao 9*). They will reach the South Lock at about 2:10–2:30 pm, and the arrival anchor time is denoted as $\tilde{t}\{N(2.33, 1)$ (2.33 corresponds to 2:20 pm) according to the application time. However, due to treacherous weather in the navigation period, *Hangshun 778* and *Zhongdao 9* cannot reach the South Lock within the original schedule (*Hangshun 778* and *Zhongdao 9* are both small general cargo ships). The information given to the Navigation Department is that *Hangshun 778* and *Zhongdao 9* will arrive about 20 min behind the schedule. In this situation, the Navigation Department will revise the arrival anchor time. Let the mean of the arrival anchor time be a random variable $\tilde{\mu} \sim U[2.25, 2.42]$. Now, the arrival anchor time is a random variable taking a random parameter, thus it is a birandom variable viz. $\tilde{\tilde{t}} \sim N(\tilde{\mu}, 1)$ with $\tilde{\mu} \sim U[2.25, 2.42]$ (2.25 represent the time is 2:15 pm and 2.42 represent 2:25 pm, respectively, see Figs 3 and 4). Similarly, the penalty coefficient of the waiting time for the other three ships (*Jiangyun 803*, *Xinshun 898*, *Hangli 908*) is no longer $\tilde{c} \sim N(20, 2)$ but $\tilde{\tilde{c}} \sim N(\tilde{\mu}, 2)$ with $\tilde{\mu} \sim U[20.2, 20.7]$.

In fact, there are additional uncertainties in NCS besides treacherous weather, such as the complexity of navigation environment, the quantity of ship, equipment failure of the lock, etc. Therefore, the Navigation Department would like to employ birandom variable to cope with the hybrid uncertainty and obtain more feasible scheduling in the ship transportation.

2.2. Notations and parameters

The following notations and parameters will be used in NCS model of the Three Gorges Project:

i (or p) – ship index, $i = \{1, 2, \ldots, I\}$;

j (or q) – stage index, $j = \{1, 2, \ldots, J\}$;

(i, j) or (p, q) – scheduling units denote ship i at stage j, or ship p at stage q;

U – scheduling units set, where $U = \{(i, j) | i \in I, 0 \le j < J\}$;

k (or l) – lock index;

K – lock index set, $K = \{1, 2, 3, 4, 5\}$, where:

$$k = \begin{cases} 1, \text{ No. 1 Lock in GD;} \\ 2, \text{ No. 2 Lock in GD;} \\ 3, \text{ No. 3 Lock in GD;} \\ 4, \text{ South Lock in TGD;} \\ 5, \text{ North Lock in TGD;} \end{cases}$$

$K(i, j)$ – the set of available locks for ship i at stage j for translating, $K(i, j) \in K$;

n – sequence number of lock service;

(k, n) – the nth lock service of lock k;

$N(k)$ – the maximum lock services of lock k;

S – lock services set, where $S = \{(k, n) | k \in K, 0 \le n < N(k)\}$;

o_{kn} – lock service operates index, where:

$$o_{kn} = \begin{cases} 1, \text{ lock service } (k, n) \text{ is operational;} \\ 0, \text{ otherwise;} \end{cases}$$

t_b^k, t_e^k – the earliest and latest lock k service time in a certain period;

t_s^k – service interval of lock k;

d_{ij} – navigation direction of ship i at stage j, where: 0 denotes upriver and 1 denotes downriver, respectively;

d_{kn} – service direction of the lock (k, n), where 0 denotes upriver and 1 denotes downriver, respectively;

b_k – optimal workload balance rate of lock k, where: $b_1 + b_2 + b_3 = 1$, $b_4 = b_5 = 0$;

l_i, w_i – length and width of ship i;

l_k, w_k – available length and width of lock k, where: $l_1 = l_2 = l_4 = l_5 = 266$ m, $l_3 = 118$ m, $w_1 = w_2 = w_4 = w_5 = 32.8$ m, $w_3 = 17.2$ m;

$\tilde{\tilde{t}}_{ik}$ – the arrival anchor time of ship i to lock k;

t_{kn} – the service time lock k;

$\tilde{\tilde{c}}_i$ – penalty coefficient of waiting time for ship i;

$$z_{ijkn} - z_{ijkn} = \begin{cases} 1, \text{ if ship } i \text{ is transferred by} \\ \text{lock service } (k, n) \text{at its stage } j; \\ 0, \text{ otherwise;} \end{cases}$$

x_{ij} – x-coordinate of ship i placed in the lock chamber at the stage j, and $x_{ij} \in R^+ \cup 0$;

y_{ij} – y-coordinate of ship i placed in the lock chamber at the stage j, and $y_{ij} \in R^+ \cup 0$;

$\mu(x)$ – step function, i.e. $\mu(x) = \begin{cases} 1, \text{ if } x > 0, \\ 0, \text{ otherwise.} \end{cases}$

2.3. Modeling

In this subsection, we will propose a birandom MODM model to solve NCS in the ship transportation as follows:

Objective functions. As a MODM model under birandom phenomena for NCS, the first objective is to minimize the total weighted tardiness of the ships. The tardiness of a ship is an increasing function of its waiting time. The waiting time equals to the service time lock k minus the arrival anchor time (in order to maintain the unity of units, we choose $t_e^k - t_b^k$ as the denominator), i.e. $t_{kn} - \tilde{\tilde{t}}_{ik}/t_e^k - t_b^k$. Additionally, the weight equals the penalty coefficients of the waiting time multiplies the importance of the ship (the occupied area in the chamber). Similarly, we choose $l_k w_k$ as the denominator, i.e. $\tilde{\tilde{c}}_i(l_i w_i)/(l_k w_k)c$.

Therefore, the total weighted tardiness of ships can be described as follows:

$$\min T \cong \sum_{(i,j) \in U} \tilde{\tilde{c}}_i \frac{l_i w_i}{l_k w_k} \frac{t_{kn} - \tilde{\tilde{t}}_{ik}}{t_e^k - t_b^k}. \quad (1)$$

Furthermore, the second objective is to minimize unbalanced workload. A more reasonable balance of the workload of a lock means its actual rate is closer to the optimal value. Each lock in the Three Gorges Project has a predefined optimal workload balance rate b_k, where $b_1+b_2+b_3=1$, $b_4=b_5=0$. In this study, the workload is measured by the sum of all lock services. Thus, we develop mathematical formulation of the second objective as follows:

$$\min B = \sum_{k=1}^{3} \left| \frac{\sum_{n=1}^{N(k)} o_{kn}}{\sum_{l=1}^{3} \sum_{n=1}^{N(l)} o_{ln}} - b_k \right|. \tag{2}$$

Navigation constraints. Apparently, for each ship, the lock service time should be in the earliest and latest service time interval, and the arrival anchor time $\tilde{\tilde{t}}_{ik}$ is no later than the lock service time t_{kn}, i.e.

$$t_b^k \le t_{kn} < t_e^k; \tag{3}$$

$$\tilde{\tilde{t}}_{ik} \le t_{kn}. \tag{4}$$

In order to ensure the pass of a scheduling unit (i, j) through one lock only, we have:

$$\sum_{k \in K(i,j)} \sum_{n=1}^{N(k)} z_{ijkn} = 1 \text{ and } \sum_{k \in K-K(i,j)} \sum_{n=1}^{N(k)} z_{ijkn} = 0. \tag{5}$$

The navigation direction of ship is the same as the lock service, hence:

$$d_{kn} = d_{ij}. \tag{6}$$

Besides, to ensure that the ship will sail in accordance with the established order, we use the constraint:

$$\sum_{(k,n) \in S} z_{ijkn} \le \sum_{(k,n) \in S} z_{i(j-1)kn}. \tag{7}$$

Lock services sequencing constraints. To ensure that all lock services are in the same lock, they are listed in the ascending time order, and we have:

$$o_{kn} \le o_{kn-1};\ t_{kn-1} + t_k^s \le t_{kn};\ 1 \le n < N(k). \tag{8}$$

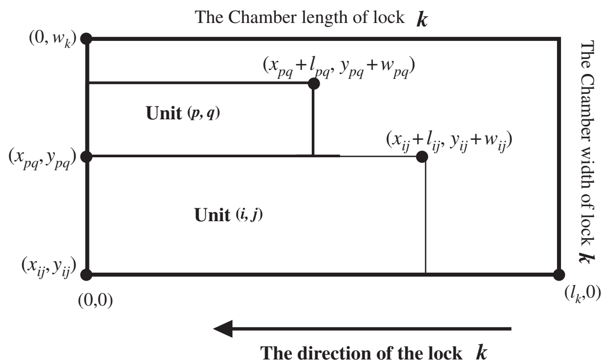

Fig. 5. An example of a ship's arrangement in a lock chamber

Packing constraints. Ship arrangement in a lock chamber (as shown in Fig. 5) is based on the two-dimensional strip-packing model (Lu *et al.* 2000; Liu, Qi 2002a, b). For ensuring the location of parking, it cannot exceed the effective area boundary of chamber and the constraints:

$$0 \le x_{ij} \le l_k - l_i;\ 0 \le y_{ij} \le w_k - w_i \tag{9}$$

can be employed. Also, the ships in the same lock chamber cannot overlap, thus,

$$\mu\left(x_{ij} + l_i - x_{pq}\right)\mu\left(y_{ij} + w_i - y_{pq}\right) \times$$
$$\mu\left(x_{pq} + l_p - x_{ij}\right)\mu\left(y_{pq} + w_p - y_{ij}\right) = 0. \tag{10}$$

From the discussions above, by integrating Eqns (1)–(10), the mathematical model of the NCS in the ship transportation for the Three Gorges Project under birandom phenomena can be stated as (*M*1). In order to solve the model under birandom phenomena, we discuss the equivalent crisp model of a birandom programing model in the next subsection.

2.4. Equivalent crisp model

To understand better the following text, the basic properties of birandom variables are reviewed first.

Definition 1 (Peng, Liu 2007). A birandom variable $\tilde{\tilde{\xi}}$ is a mapping from a probability space (Ω, A, Pr) to a collection of random variables S such that for any Borel subset B of the real line R, the induced function $\Pr\left\{\tilde{\tilde{\xi}}(\omega) \in B\right\}$ is a measurable function with respect to ω (Fig. 6).

Model M1:

$$\min T \cong \sum_{(i,j) \in U} \tilde{\tilde{c}}_i \frac{l_i w_i}{l_k w_k} \frac{t_{kn} - \tilde{\tilde{t}}_{ik}}{t_e^k - t_b^k};$$

$$\min B = \sum_{k=1}^{3} \left| \frac{\sum_{n=1}^{N(k)} o_{kn}}{\sum_{l=1}^{3} \sum_{n=1}^{N(l)} o_{ln}} - b_k \right|;$$

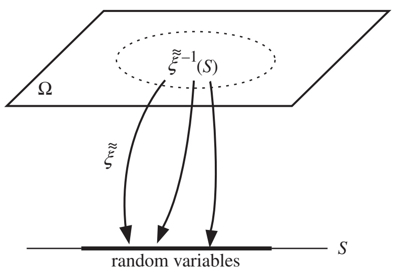

Fig. 6. Birandom variable

$$
\begin{cases}
t_b^k \le t_{kn} < t_e^k; \\
\tilde{\tilde{t}}_{ik} \le t_{kn}; \\
\sum\limits_{k \in K(i,j)} \sum\limits_{n=1}^{N(k)} z_{ijkn} = 1; \\
\sum\limits_{k \in K-K(i,j)} \sum\limits_{n=1}^{N(k)} z_{ijkn} = 0; \\
d_{kn} = d_{ij}; \\
\sum\limits_{(k,n) \in S} z_{ijkn} \le \sum\limits_{(k,n) \in S} z_{i(j-1)kn}; \\
o_{kn} \le o_{kn-1}; \\
t_{kn-1} + t_k^s \le t_{kn}; \\
1 \le n < N(k); \\
0 \le x_{ij} \le l_k - l_i; \\
0 \le y_{ij} \le w_k - w_i; \\
\mu\left(x_{ij} + l_i - x_{pq}\right) \mu\left(y_{ij} + w_i - y_{pq}\right) \mu\left(x_{pq} + l_p - x_{ij}\right) \times \\
\mu\left(y_{pq} + w_p - y_{ij}\right) = 0; \\
\sum_{k=1}^{3} b_k = 1; \\
i \in I; \\
0 \le j < J; \\
k \in K; \\
1 \le n < N(k).
\end{cases}
\tag{11}
$$

Definition 1 suggests that a birandom variable is a measurable function from a probability space to a collection of random variables. Roughly speaking, a birandom variable is a random variable taking random values. In exceptional circumstance, if Ω consists of a single element or S is a collection of real numbers, the birandom variable degenerates to a random variable.

Example 1

Let $\Omega = \{\omega_1, \omega_2, \ldots, \omega_n\}$, and

$$\Pr\{\omega_1\} = \Pr\{\omega_2\} = \cdots = \Pr\{\omega_n\} = 1/n.$$

Assume that $\tilde{\tilde{\xi}}$ is a function on (Ω, A, Pr) as follows:

$$
\tilde{\tilde{\xi}}(\omega) = \begin{cases}
\tilde{\xi}_1, \text{ if } \omega{=}\omega_1; \\
\tilde{\xi}_2, \text{ if } \omega{=}\omega_2; \\
\quad \vdots \\
\tilde{\xi}_n, \text{ if } \omega{=}\omega_n,
\end{cases}
$$

where: $\tilde{\xi}_1$ is a random variable uniformly distributed on [0,1]; $\tilde{\xi}_2$ is a normally distributed random variable with mean 1 and standard variance 0.5; $\tilde{\xi}_3, \cdots, \tilde{\xi}_n$ are standard normally distributed random variables with mean 0 and standard variance 1, i.e. $\tilde{\xi}_1 \sim U[0,1]$, $\tilde{\xi}_2 \sim N(1, 0.5)$, and $\tilde{\xi}_3, \cdots, \tilde{\xi}_n \sim N(0,1)$.

According to Definition 1, $\tilde{\tilde{\xi}}$ is clearly a birandom variable (see Fig. 7).

Definition 2 (Liu 2002). Let $\tilde{\tilde{\xi}}_i$ be a birandom variable defined in (Ω_i, A_i, $\Pr_i$), $i = 1, 2, \ldots, n$, respectively, and then $\tilde{\tilde{\xi}} = \left(\tilde{\tilde{\xi}}_1, \tilde{\tilde{\xi}}_2, \cdots, \tilde{\tilde{\xi}}_n\right)$ is a birandom vector.

Lemma 1 (Liu 2002). Let $\tilde{\tilde{\xi}}_i$ be a birandom vector, and f be a Borel measurable function from R^n to R. Then $f\left(\tilde{\tilde{\xi}}_i\right)$ is a birandom variable.

Due to the existence of random parameters, we usually cannot find a precise decision for complicated real-life problems. However, we can usually employ the expected value operator to obtain the deterministic expected value model. The expected value operator of a birandom variable is defined as follows.

Definition 3 (Peng, Liu 2007). Let $\tilde{\tilde{\xi}}$ be a birandom variable defined on the probability space (Ω, A, Pr).

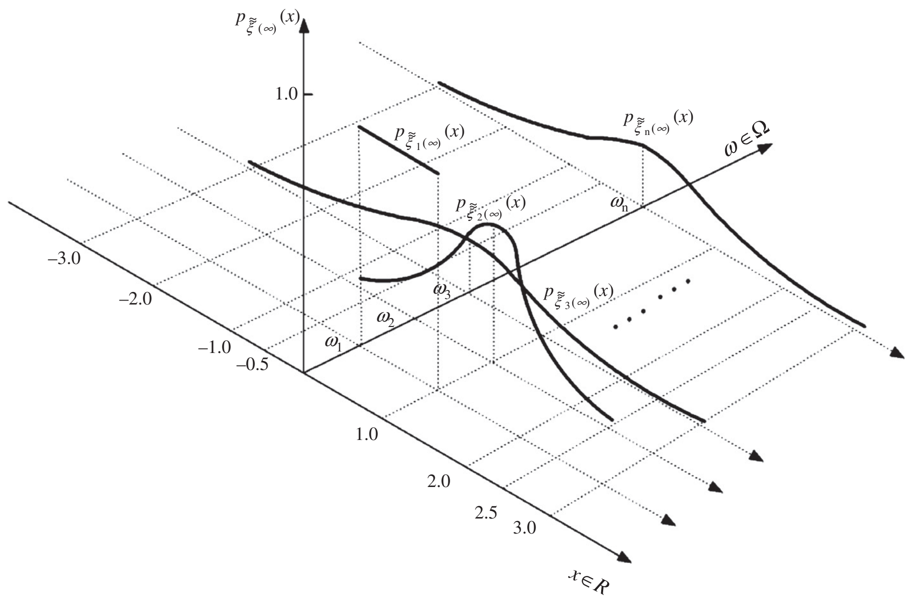

Fig. 7. Representation of a birandom variable in Example 1

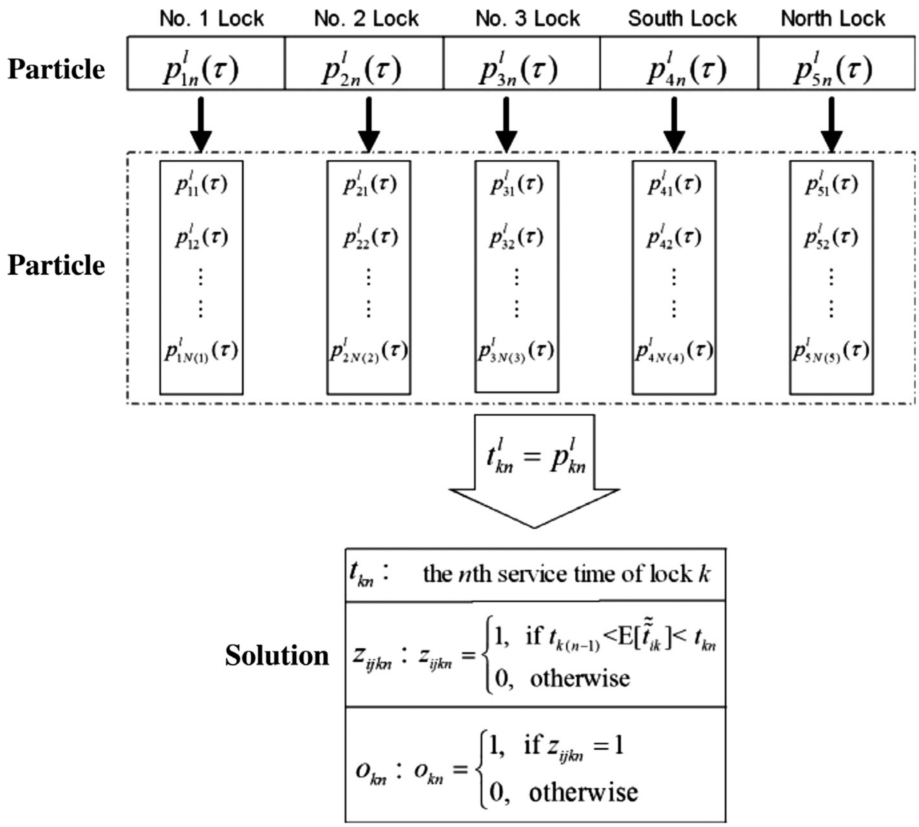

Fig. 8. Decoding method and mapping between PSO particles and solutions

Then the expected value of birandom variable $\tilde{\tilde{\xi}}$ is defined as follows:

$$E\left[\tilde{\tilde{\xi}}\right] = \int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \geq t\right\}dt - \int_{-\infty}^{0} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \leq t\right\}dt.$$

Provided that at least one of the above two integrals is finite.

Lemma 2 Assume that $\tilde{\tilde{\xi}}$ and $\tilde{\tilde{\eta}}$ are birandom variables with finite expected values. Then, for any real numbers a and b, we have:

$$E\left[a\tilde{\tilde{\xi}} + b\tilde{\tilde{\eta}}\right] = aE\left[\tilde{\tilde{\xi}}\right] + bE\left[\tilde{\tilde{\eta}}\right].$$

Proof. In order to prove Lemma 2, the following two equations need to be verified:

$$E\left[\tilde{\tilde{\xi}} + \tilde{\tilde{\eta}}\right] = E\left[\tilde{\tilde{\xi}}\right] + E\left[\tilde{\tilde{\eta}}\right] \text{ and } E\left[a\tilde{\tilde{\xi}}\right] = aE\left[\tilde{\tilde{\xi}}\right].$$

(i)

$$E\left[\tilde{\tilde{\xi}} + \tilde{\tilde{\eta}}\right] = \int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\left(\tilde{\tilde{\xi}} + \tilde{\tilde{\eta}}\right)\omega\right] \geq t\right\}dt - \int_{-\infty}^{0} \Pr\left\{\omega \in \Omega | \left[\left(\tilde{\tilde{\xi}} + \tilde{\tilde{\eta}}\right)\omega\right] \leq t\right\}dt =$$

$$\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \geq t\right\}dt + \int_0^{+\infty} \Pr\{\omega \in \Omega | E[\tilde{\eta}(\omega)] \geq t\}dt - \int_{-\infty}^{0} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \leq t\right\}dt - \int_{-\infty}^{0} \Pr\{\omega \in \Omega | E[\tilde{\eta}(\omega)] \leq t\}dt =$$

$$\left(\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \geq t\right\}dt - \int_{-\infty}^{0} \Pr\left\{\omega \in \Omega | E\left[\tilde{\xi}(\omega)\right] \leq t\right\}dt\right) + \left(\int_0^{+\infty} \Pr\{\omega \in \Omega | E[\tilde{\eta}(\omega)] \geq t\}dt - \int_{-\infty}^{0} \Pr\{\omega \in \Omega | E[\tilde{\eta}(\omega)] \leq t\}dt\right) =$$

$$= E\left[\tilde{\tilde{\xi}}\right] + E\left[\tilde{\tilde{\eta}}\right].$$

(ii)

(1) If a = 0, then the equation $E\left[a\tilde{\tilde{\xi}}\right] = aE\left[\tilde{\tilde{\xi}}\right]$ holds trivially.

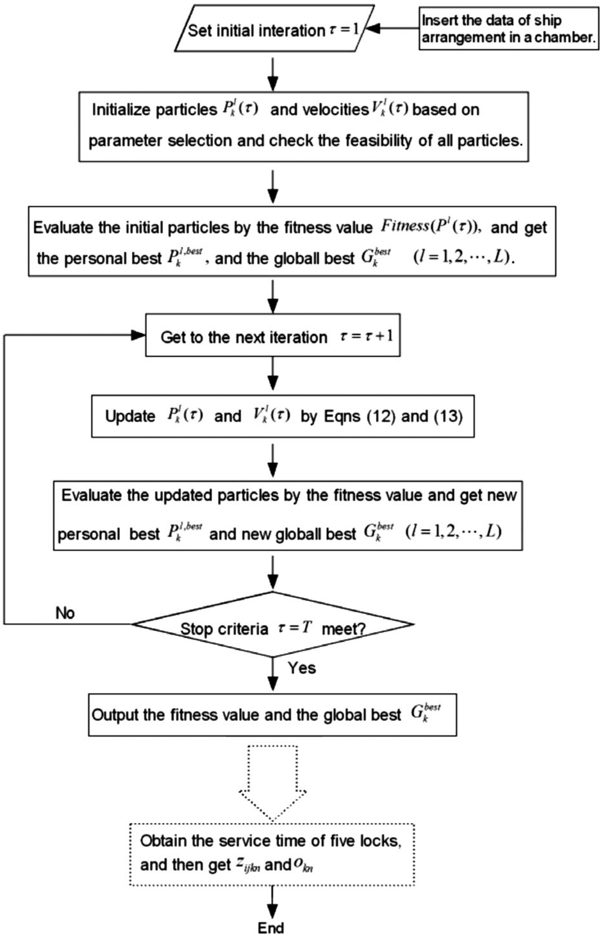

Fig. 9. Procedure of the PSO framework

(2) If $a > 0$, $t/a = r$, then:

$$E\left[a\tilde{\tilde{\xi}}\right] = \int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[a\tilde{\tilde{\xi}}(\omega)\right] \ge t\right\} dt -$$

$$\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[a\tilde{\tilde{\xi}}(\omega)\right] \le t\right\} dt =$$

$$\int_0^{+\infty} \Pr\left\{\omega \in \Omega | aE\left[\tilde{\tilde{\xi}}(\omega)\right] \ge t\right\} dt -$$

$$\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | aE\left[\tilde{\tilde{\xi}}(\omega)\right] \le t\right\} dt =$$

$$a\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge \frac{t}{a}\right\} dt -$$

$$a\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le \frac{t}{a}\right\} dt =$$

$$a\left(\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge r\right\} dr -\right.$$

$$\left.\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le r\right\} dr\right) =$$

$$aE\left[\tilde{\tilde{\xi}}\right].$$

(3) If $a < 0$, $t/a = r$, then:

$$E\left[a\tilde{\tilde{\xi}}\right] = \int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[a\tilde{\tilde{\xi}}(\omega)\right] \ge t\right\} dt -$$

$$\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[a\tilde{\tilde{\xi}}(\omega)\right] \le t\right\} dt =$$

$$a\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le \frac{t}{a}\right\} dt -$$

$$a\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge \frac{t}{a}\right\} dt =$$

$$(-a)\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le r\right\} dr -$$

$$(-a)\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge r\right\} dr =$$

$$a\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge r\right\} dr -$$

$$a\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le r\right\} dr =$$

$$a\left(\int_0^{+\infty} \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \ge r\right\} dr -\right.$$

$$\left.\int_{-\infty}^0 \Pr\left\{\omega \in \Omega | E\left[\tilde{\tilde{\xi}}(\omega)\right] \le r\right\} dr\right) =$$

$$aE\left[\tilde{\tilde{\xi}}\right].$$

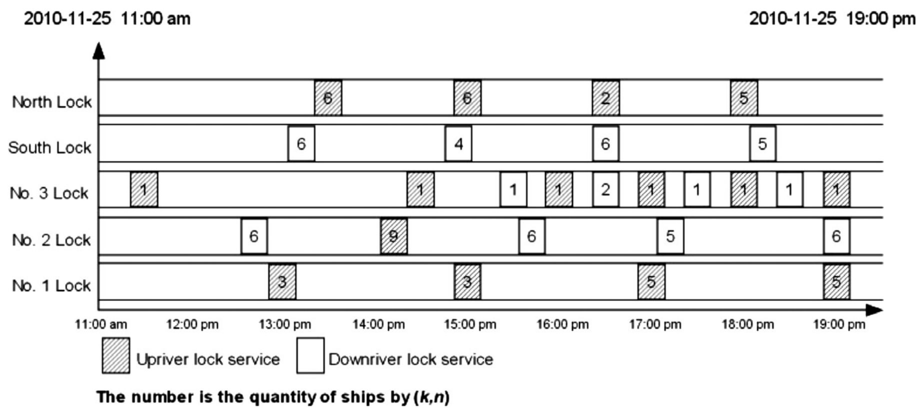

Fig. 10. The optimal lock operation plan

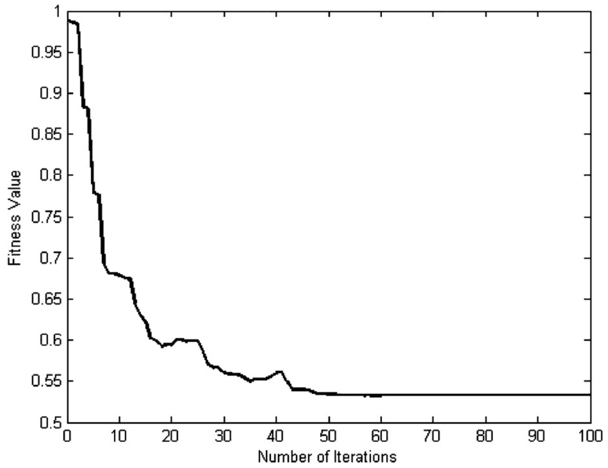

Fig. 11. PSO search process of the optimal solution

Combining (i) with (ii), Lemma 2 is proved.

Based on Lemma 2, the expected value of the first objective function Eqn (1) and navigation constraint Eqn (4) can be transformed into the following:

$$E[T] = E\left[\sum_{(i,j)\in U} \tilde{\tilde{c}}_i \frac{l_i w_i}{l_k w_k} \frac{t_{kn} - \tilde{\tilde{t}}_{ik}}{t_e^k - t_b^k}\right] =$$

$$\sum_{(i,j)\in U} E\left[\tilde{\tilde{c}}_i\right] \frac{l_i w_i}{l_k w_k} \frac{t_{kn} - E\left[\tilde{\tilde{t}}_{ik}\right]}{t_e^k - t_b^k};$$

$$E\left[\tilde{\tilde{t}}_{ik}\right] \le t_{kn}.$$

Lemma 3 (Xu, Zhou 2009). Let $\tilde{\tilde{\xi}}$ be a birandom variable which is subjected to the normal distribution $\tilde{\tilde{\xi}} \sim N(\tilde{\mu}, \sigma^2)$ with $\tilde{\mu} \sim U[a, b]$. Then,

$$E\left[\tilde{\tilde{\xi}}\right] = \frac{a+b}{2}.$$

Now, suppose that birandom variables $\tilde{\tilde{c}}_i$ and $\tilde{\tilde{t}}_{ik}$ are defined as $\tilde{\tilde{c}}_i \sim N(\tilde{\mu}_c, \sigma_c^2)$ with $\tilde{\mu}_c \sim [a_c, b_c]$ and $\tilde{\tilde{t}}_{ik} \sim N(\tilde{\mu}_t, \sigma_t^2)$ with $\tilde{\mu}_t \sim [a_t, b_t]$. By Lemma 3, we have the following:

$$E[T] = E\left[\sum_{(i,j)\in U} \tilde{\tilde{c}}_i \frac{l_i w_i}{l_k w_k} \frac{t_{kn} - \tilde{\tilde{t}}_{ik}}{t_e^k - t_b^k}\right] =$$

$$\frac{1}{4} \sum_{(i,j)\in U} (a_c + b_c) \frac{l_i w_i}{l_k w_k} \frac{2t_{kn} - (a_t + b_t)}{t_e^k - t_b^k};$$

$$\frac{a_t + b_t}{2} \le t_{kn}.$$

Thus, we transform the model (*M1*) into a deterministic one using the expected value operator. In addition, the weighted value λ_T and λ_B, which reflect the importance of the overall NCS considering the two objective functions based on experiential value, are given by the decision manager of the Navigation Department in the preliminary design report. Now, we get the model as follows:

Module M2:

$$\min F(U, S) =$$

$$\frac{1}{4}\lambda_T \sum_{(i,j)\in U} (a_c + b_c) \frac{l_i w_i}{l_k w_k} \frac{2t_{kn} - (a_t + b_t)}{t_e^k - t_b^k} +$$

$$\lambda_B \sum_{k=1}^{3} \left| \frac{\sum_{n=1}^{N(k)} o_{kn}}{\sum_{l=1}^{3} \sum_{n=1}^{N(l)} o_{ln}} - b_k \right|;$$

$$\begin{cases} t_b^k \le t_{kn} < t_e^k; \\ \frac{a_t + b_t}{2} \le t_{kn}; \\ \sum\limits_{k\in K(i,j)} \sum\limits_{n=1}^{N(k)} z_{ijkn} = 1; \\ \sum\limits_{k\in K-K(i,j)} \sum\limits_{n=1}^{N(k)} z_{ijkn} = 0; \\ d_{kn} = d_{ij}; \\ \sum\limits_{(k,n)\in S} z_{ijkn} \le \sum\limits_{(k,n)\in S} z_{i(j-1)kn}; \\ o_{kn} \le o_{kn-1}; \\ t_{kn-1} + t_k^s \le t_{kn}; \\ 1 \le n < N(k); \\ 0 \le x_{ij} \le l_k - l_i; \\ 0 \le y_{ij} \le w_k - w_i; \\ \mu\left(x_{ij} + l_i - x_{pq}\right)\mu\left(y_{ij} + w_i - y_{pq}\right)\mu\left(x_{pq} + l_p - x_{ij}\right)\times \\ \mu\left(y_{pq} + w_p - y_{ij}\right) = 0; \\ \sum_{k=1}^{3} b_k = 1; \\ i \in I; \\ 0 \le j < J; \\ k \in K; \\ 1 \le n < N(k). \end{cases}$$

Then putting the certainty parameters into PSO, the equivalent crisp model (*M2*) for the practical NCS problem in the ship transportation can be solved by a computer program. Due to the complexity of NCS in the Three Gorges Project, in practice, the Navigation Department will propose some ship-dispatch scheduling data first, including x_{ij} and y_{ij} based on the application information of the ships.

3. Particle swarm optimization (PSO) for NCS

In NCS, locks in the Three Gorges Project transfer a batch of ships simultaneously; therefore, NCS is a large-scale and NP-hard problem (Zhang *et al*. 2010). Thus, traditional exact scheduling methods, such as Progressive Optimality Algorithm (POA) and Critical Path Method (CPM), are not suitable for obtaining scheduling anymore due to the difficulty and complexity. In this case, heuristic solution procedures are advisable. In this study, we apply particle swarm optimization (PSO) to resolve NSC in ship transportation. The reason for choosing PSO is that compared with other heuristic algorithms, PSO is computationally tractable, easy-to-implement, and does not require any gradient information of an objective function but its value.

PSO is first proposed by Kennedy and Eberhart (1995) and has become one of the most important swarm intelligence algorithms. As an evolutionary algorithm, PSO has superior search performance for numerous difficult optimization problems with faster and more stable convergence rates compared to other population-based stochastic optimization methods. In PSO, an n-dimensional position of a particle (called solution) that is initialized with a random position in a multidimensional search space represents a solution to the problem and resembles the chromosome of a genetic algorithm (Robinson *et al*. 2002). The particles which are characterized by their positions and velocities (see Cervantes *et al*. 2009; Kennedy, Eberhart 1995, 2001) fly through the problem space by following the current optimum particles. Unlike other population-based algorithms, the velocity and position of each particle are dynamically adjusted according to the flying experiences or discoveries of its own and those of its companions. Meanwhile, the updating mechanism of the particle could be implemented easily.

Due to its facility and effectiveness, PSO has been applied in solving the practical optimization problems widely in recent years such as Sha and Hsu (2006), Ling *et al*. (2008), Kashan and Karimi (2009), Pan *et al*. (2008), etc. In PSO, the following formulas (Kennedy, Eberhart 1995) are applied to update the position and velocity of each particle:

$$v_d^l(\tau+1) = w(\tau)v_d^l(\tau) + c_p r_1\left[p_d^{l,best}(\tau) - p_d^l(\tau)\right] +$$
$$c_g r_2\left[g_d^{l,best}(\tau) - p_d^l(\tau)\right]; \tag{12}$$

$$p_d^l(\tau+1) = p_d^l(\tau) + v_d^l(\tau+1), \tag{13}$$

where: $v_d^l(\tau)$ is the velocity of l-th particle at the dth dimension in the τth iteration; $w(\tau)$ is the inertia weight; $p_d^l(\tau)$ is the position of l-th particle at the dth dimension; r_1 and r_2 are random numbers in the range [0,1]; c_p and c_g are the best personal and global position acceleration constant respectively; $p_d^{l,best}(\tau)$ is the best personal position of l-th particle at the d-th dimension and $g_d^{l,best}(\tau)$ is the best global position at the dth dimension.

3.1. Notations

The following notations are used in PSO for NCS:

τ – iteration index, $\tau = 1, 2, \ldots, T$;

l – particle index, $l = 1, 2, \ldots, L$;

k – index of lock, $k = 1, 2, 3, 4, 5$;

n – index of sequence number of lock service, $n = 1, 2, \ldots, N(k)$;

d – dimension index, $d = kn$;

r_1, r_2 – uniform distributed random number within [0, 1];

$w(\tau)$ – inertia weight in the τ iteration;

$v_{kn}^l(\tau+1)$ – velocity of the l-th particle at the kn-th dimension in the τ-th iteration;

$p_{kn}^l(\tau)$ – position of the l-th particle at the kn-th dimension in the τ-th iteration;

$p_{kn}^{l,best}(\tau)$ – personal best position of the l-th particle at the kn-th dimension in the τ-th iteration;

$g_{kn}^{best}(\tau)$ – the best global position at the kn-th dimension;

c_p – the best personal position acceleration constant;

c_g – the best global position acceleration constant;

$V_k^l(\tau)$ – vector velocity of the l-th particle for lock k in the τ-th iteration, $V_k^l(\tau) = [v_{k1}^l(\tau), v_{k2}^l(\tau), \cdots, v_{kN(k)}^l(\tau)]$;

$P_k^l(\tau)$ – vector position of the l-th particle for lock k in the τ-th iteration, $P_k^l(\tau) = [p_{k1}^l(\tau), p_{k2}^l(\tau), \cdots, p_{kN(k)}^l(\tau)]$;

$P_k^{l,best}$ – vector personal best position of the l-th particle for lock k, $P_k^{l,best} = \left[p_{k1}^{l,best}(\tau), p_{k2}^{l,best}(\tau), \cdots, p_{kN(k)}^{l,best}(\tau)\right]$;

$G_k^{l,best}$ – vector global best position for lock k, $G_k^{l,best} = \left[g_{k1}^{l,best}(\tau), g_{k2}^{l,best}(\tau), \cdots, g_{kN(k)}^{l,best}(\tau)\right]$;

S^l – the l-th set of solution;

Fitness $P^l(\tau)$ – fitness value of $P^l(\tau)$.

3.2. Framework of PSO for NCS

Parameter selection. Since more particles require more evaluation runs and lead to more optimization costs (Trelea 2003), we select 50 particles as the population size and 100 as the iteration number in our case study. We also employ the inertia weight to control the impact of the previous velocities on the current velocity (Shi, Eberhart 1998, 1999).

$$w(\tau) = w(T) + \frac{\tau - T}{1 - T}[w(1) - w(T)].$$

Insert data and initialize. At first, we insert the data of the ship arrangement in the chamber (provided by the Navigation Department), including x_{ij} and y_{ij} based on the application information of the ships.

Set iteration $\tau = 1$. For $l = 1, 2, \ldots, L$, generate the position of the l-th particle with integer random position (every particle consists of $5\sum_{n=1}^{N(k)} n$ dimensions in this study). Therefore, for all the five locks, we have:

$$P_k^l(1) = \left[p_{k1}^l(1), p_{k2}^l(1), \cdots, p_{kN(k)}^l(1)\right],\ k = 1,\ 2,\ \cdots,\ 5.$$

In addition,

$$V_k^l(1) = \left[v_{k1}^l(1), v_{k2}^l(1), \cdots, v_{kN(k)}^l(1)\right],\ k = 1,\ 2,\ \cdots,\ 5.$$

Table 1. The penalty coefficients of waiting time for ship i

$\tilde{\tilde{c}}_1 \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.45, 0.50]$	$\tilde{\tilde{c}}_2 \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.50, 0.50]$	$\tilde{\tilde{c}}_3 \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.12, 0.19]$
$\tilde{\tilde{c}}_4 \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[0.80, 0.85]$	$\tilde{\tilde{c}}_5 \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.75, 0.75]$	$\tilde{\tilde{c}}_6 \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.25, 0.28]$
$\tilde{\tilde{c}}_7 \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.60, 0.60]$	$\tilde{\tilde{c}}_8 \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.42, 0.55]$	$\tilde{\tilde{c}}_9 \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[0.52, 0.60]$
$\tilde{\tilde{c}}_{10} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.42, 0.57]$	$\tilde{\tilde{c}}_{11} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.35, 0.40]$	$\tilde{\tilde{c}}_{12} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.20, 0.20]$
$\tilde{\tilde{c}}_{13} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.39, 0.39]$	$\tilde{\tilde{c}}_{14} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.57, 0.66]$	$\tilde{\tilde{c}}_{15} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.86, 0.92]$
$\tilde{\tilde{c}}_{16} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.76, 0.82]$	$\tilde{\tilde{c}}_{17} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.43, 0.49]$	$\tilde{\tilde{c}}_{18} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.28, 0.34]$
$\tilde{\tilde{c}}_{19} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.41, 0.45]$	$\tilde{\tilde{c}}_{20} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.59, 0.67]$	$\tilde{\tilde{c}}_{21} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.50, 0.50]$
$\tilde{\tilde{c}}_{22} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.29, 0.35]$	$\tilde{\tilde{c}}_{23} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.43, 0.49]$	$\tilde{\tilde{c}}_{24} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.20, 0.32]$
$\tilde{\tilde{c}}_{25} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[0.75, 0.81]$	$\tilde{\tilde{c}}_{26} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.54, 0.60]$	$\tilde{\tilde{c}}_{27} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[0.44, 0.52]$
$\tilde{\tilde{c}}_{28} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.45, 0.53]$	$\tilde{\tilde{c}}_{29} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.50, 0.50]$	$\tilde{\tilde{c}}_{30} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[0.38, 0.44]$
$\tilde{\tilde{c}}_{31} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.12, 0.16]$	$\tilde{\tilde{c}}_{32} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.31, 0.39]$	$\tilde{\tilde{c}}_{33} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.24, 0.32]$
$\tilde{\tilde{c}}_{34} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.76, 0.82]$	$\tilde{\tilde{c}}_{35} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.62, 0.70]$	$\tilde{\tilde{c}}_{36} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.34, 0.48]$
$\tilde{\tilde{c}}_{37} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.13, 0.17]$	$\tilde{\tilde{c}}_{38} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.24, 0.32]$	$\tilde{\tilde{c}}_{39} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.75, 0.75]$
$\tilde{\tilde{c}}_{40} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.64, 0.70]$	$\tilde{\tilde{c}}_{41} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.35, 0.41]$	$\tilde{\tilde{c}}_{42} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.28, 0.34]$
$\tilde{\tilde{c}}_{43} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.25, 0.25]$	$\tilde{\tilde{c}}_{44} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.59, 0.65]$	$\tilde{\tilde{c}}_{45} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.33, 0.41]$
$\tilde{\tilde{c}}_{46} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[0.67, 0.71]$	$\tilde{\tilde{c}}_{47} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.36, 0.42]$	$\tilde{\tilde{c}}_{48} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.15, 0.21]$
$\tilde{\tilde{c}}_{49} \sim N(\tilde{\mu}, 0.16)$ with $\tilde{\mu} \sim U[0.28, 0.34]$	$\tilde{\tilde{c}}_{50} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.60, 0.68]$	$\tilde{\tilde{c}}_{51} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.75, 0.75]$
$\tilde{\tilde{c}}_{52} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.86, 0.94]$	$\tilde{\tilde{c}}_{53} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.27, 0.35]$	$\tilde{\tilde{c}}_{54} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.48, 0.56]$
$\tilde{\tilde{c}}_{55} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.17, 0.25]$	$\tilde{\tilde{c}}_{56} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.72, 0.80]$	$\tilde{\tilde{c}}_{57} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.55, 0.61]$
$\tilde{\tilde{c}}_{58} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.63, 0.71]$	$\tilde{\tilde{c}}_{59} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.18, 0.26]$	$\tilde{\tilde{c}}_{60} \sim N(\tilde{\mu}, 0.16)$ with $\tilde{\mu} \sim U[0.41, 0.53]$
$\tilde{\tilde{c}}_{61} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.26, 0.34]$	$\tilde{\tilde{c}}_{62} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.68, 0.72]$	$\tilde{\tilde{c}}_{63} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.50, 0.50]$
$\tilde{\tilde{c}}_{64} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.50, 0.58]$	$\tilde{\tilde{c}}_{65} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.36, 0.42]$	$\tilde{\tilde{c}}_{66} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[0.19, 0.25]$
$\tilde{\tilde{c}}_{67} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.60, 0.66]$	$\tilde{\tilde{c}}_{68} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.30, 0.30]$	$\tilde{\tilde{c}}_{69} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.63, 0.71]$
$\tilde{\tilde{c}}_{70} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[0.18, 0.24]$	$\tilde{\tilde{c}}_{71} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[0.36, 0.42]$	$\tilde{\tilde{c}}_{72} \sim N(\tilde{\mu}, 0.16)$ with $\tilde{\mu} \sim U[0.15, 0.23]$
$\tilde{\tilde{c}}_{73} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.35, 0.41]$	$\tilde{\tilde{c}}_{74} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.47, 0.55]$	$\tilde{\tilde{c}}_{75} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.11, 0.19]$
$\tilde{\tilde{c}}_{76} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.18, 0.26]$	$\tilde{\tilde{c}}_{77} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[0.26, 0.34]$	$\tilde{\tilde{c}}_{78} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.64, 0.68]$
$\tilde{\tilde{c}}_{79} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.49, 0.49]$	$\tilde{\tilde{c}}_{80} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.29, 0.35]$	$\tilde{\tilde{c}}_{81} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.25, 0.33]$
$\tilde{\tilde{c}}_{82} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.22, 0.30]$	$\tilde{\tilde{c}}_{83} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[0.51, 0.59]$	$\tilde{\tilde{c}}_{84} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[0.44, 0.52]$
$\tilde{\tilde{c}}_{85} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.70, 0.70]$	$\tilde{\tilde{c}}_{86} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.51, 0.63]$	$\tilde{\tilde{c}}_{87} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[0.26, 0.34]$
$\tilde{\tilde{c}}_{88} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.20, 0.28]$	$\tilde{\tilde{c}}_{89} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[0.38, 0.42]$	$\tilde{\tilde{c}}_{90} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.59, 0.67]$
$\tilde{\tilde{c}}_{91} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.21, 0.29]$	$\tilde{\tilde{c}}_{92} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[0.36, 0.40]$	$\tilde{\tilde{c}}_{93} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[0.58, 0.62]$
$\tilde{\tilde{c}}_{94} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[0.48, 0.56]$	$\tilde{\tilde{c}}_{95} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[0.60, 0.60]$	

Decode particles into solutions. For $l = 1, 2, \ldots, L$ decode $P^l(\tau)$ to a solution as follows:

$$p^l_{kn}(\tau) = t^\tau_{kn};$$

$$z_{ijkn} = \begin{cases} 1, & \text{if } \; p^l_{kn-1}(\tau) < E\left[\tilde{\tilde{t}}_{ik}\right] < p^l_{kn}(\tau); \\ 0, & \text{otherwise;} \end{cases}$$

$$o_{kn} = \begin{cases} 1, & \text{if } \; z_{ijkn} = 1; \\ 0, & \text{otherwise.} \end{cases}$$

Remark. We employ $p^l_{kn-1}(\tau) < E\left[\tilde{\tilde{t}}_{ik}\right] < p^l_{kn}(\tau)$ to determine z_{ijkn} because according to the known information (navigation application of ship i to (k, n)), the ship i has arrived and is ready for the nth service of the lock k. Therefore, as long as the arrival anchor time of the ship i to the lock k is in the interval service time of $(n-1)$-th and n-th, we can fix z_{ijkn}. Mapping between one potential solution to NCS and particle representation is shown in Fig. 8.

Check the feasibility. For $l = 1, 2, \ldots, L$, if the feasibility criterion is met by all the particles, i.e. all the particles satisfied the constraints of the model (*M2*). Then, the particles are feasible.

Fitness Value. The fitness value used to evaluate the particle is the value of objective function of (*M2*), i.e.:

$$\text{Fitness } P^l(\tau) =$$

$$\frac{1}{4}\lambda_T \sum_{(i,j)\in U} (a_c + b_c)\frac{l_i w_i}{l_k w_k}\,\frac{2p^l_{kn}(\tau) - (a_t + b_t)}{t^k_e - t^k_b} +$$

$$\lambda_B \sum_{k=1}^{3} \left| \frac{\sum_{n=1}^{N(k)} o_{kn}}{\sum_{l=1}^{3}\sum_{n=1}^{N(l)} o_{ln}} - b_k \right|.$$

Based on the above, we can get the framework of PSO for NCS in Fig. 9.

4. A case study

To test how well the proposed model and algorithm may be applied to the real world, we perform a case study based on the real execution data in the Three Gorges Project. We use *Matlab 7.0* and *Visual C++* language on an *Inter Core I3 M370*, 2.40 GHz, with 2048 MB memory, running *Microsoft Windows 7*. First, we t implement the proposed birandom MODM model and PSO algorithm to obtain the coordinated scheduling of TGD and GD in a certain period by the actual data from the Navigation Department

Table 2. The related data of navigation ship

Ship i	d_{ij}	The lock to be passed	$\tilde{\tilde{t}}_{ik}$	l_i	w_i
1. Lintong 518	0	No. 3 Lock	$\tilde{\tilde{t}}_{13} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[11.00, 11.25]$	100	16
2. E'shi 3158	1	No. 2 Lock	$\tilde{\tilde{t}}_{22} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[12.25, 12.42]$	62	15
3. Tonghai 618LS	1	No. 2 Lock	$\tilde{\tilde{t}}_{32} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[12.18, 12.39]$	55	14
4. Yuanyang 3	1	No. 2 Lock	$\tilde{\tilde{t}}_{42} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[12.31, 12.50]$	87	16
5. Yuanyang 7601	1	No. 2 Lock	$\tilde{\tilde{t}}_{52} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[12.25, 12.25]$	90	16
6. Xinjiangping 1016	1	No. 2 Lock	$\tilde{\tilde{t}}_{62} \sim N(\tilde{\mu}, .36)$ with $\tilde{\mu} \sim U[12.33, 12.47]$	65	15
7. E'yicang 2039	1	No. 2 Lock	$\tilde{\tilde{t}}_{72} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[12.33, 12.42]$	104	20
8. Gangsheng 1012	0	No. 1 Lock	$\tilde{\tilde{t}}_{81} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[12.60, 12.72]$	172	22
9. Gangsheng 810	0	No. 1 Lock	$\tilde{\tilde{t}}_{91} \sim N(\tilde{\mu}, 9.00)$ with $\tilde{\mu} \sim U[12.50, 12.65]$	164	18
10. Xinghang 519	0	No. 1 Lock	$\tilde{\tilde{t}}_{(10)1} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[12.50, 12.50]$	65	14
11. Jinyang 369	1	South Lock	$\tilde{\tilde{t}}_{(11)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[12.83, 12.83]$	65	13
	1	No. 2 Lock	$\tilde{\tilde{t}}_{(11)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[18.67, 18.67]$		
12. Zigui 666	1	South Lock	$\tilde{\tilde{t}}_{(12)4} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[12.75, 12.83]$	97	15
	1	No. 2 Lock	$\tilde{\tilde{t}}_{(12)2} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[18.67, 18.75]$		
13. Heniu 786	1	South Lock	$\tilde{\tilde{t}}_{(13)4} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[12.75, 12.83]$	66	12
	1	No. 2 Lock	$\tilde{\tilde{t}}_{(13)2} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[18.675, 18.75]$		
14. Chuanji 2	1	South Lock	$\tilde{\tilde{t}}_{(14)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[12.75, 12.75]$	51	12
	1	No. 2 Lock	$\tilde{\tilde{t}}_{(14)2} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[18.75, 18.83]$		
15. Longfei	1	South Lock	$\tilde{\tilde{t}}_{(15)4} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[12.83, 12.91]$	100	14
16. Zhongyuan 06	1	South Lock	$\tilde{\tilde{t}}_{(16)4} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[12.75, 12.83]$	105	16
17. sGaizhen	0	North Lock	$\tilde{\tilde{t}}_{(17)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.17, 13.17]$	82	15
18. Yuwanhang 10387	0	North Lock	$\tilde{\tilde{t}}_{(18)5} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[13.15, 13.22]$	66	12
19. Haifeng 699	0	North Lock	$\tilde{\tilde{t}}_{(19)5} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[13.00, 13.25]$	100	20
20. Yichangqixiang 5	0	North Lock	$\tilde{\tilde{t}}_{(20)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.25, 13.33]$	70	13
21. Huihuang 168	0	North Lock	$\tilde{\tilde{t}}_{(21)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.12, 13.25]$	64	12
22. Yuxinyang 1421	0	North Lock	$\tilde{\tilde{t}}_{(22)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.25, 13.25]$	108	21
23. gWanshun 2	0	No. 2 Lock	$\tilde{\tilde{t}}_{(23)2} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[13.75, 13.83]$	57	13
24. gChang'an 118	0	No. 2 Lock	$\tilde{\tilde{t}}_{(24)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.83, 13.83]$	68	14
25. gYuxinyang 0527	0	No. 2 Lock	$\tilde{\tilde{t}}_{(25)2} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[13.75, 13.83]$	86	18
26. gWanxin 618	0	No. 2 Lock	$\tilde{\tilde{t}}_{(26)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.75, 13.75]$	77	14
27. gYunshuang 168	0	No. 2 Lock	$\tilde{\tilde{t}}_{(27)2} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[13.64, 13.75]$	56	13
28. gWuqiao 34	0	No. 2 Lock	$\tilde{\tilde{t}}_{(28)2} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[13.75, 13.83]$	54	12
29. gJinggang 518	0	No. 2 Lock	$\tilde{\tilde{t}}_{(29)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.83, 13.83]$	65	14
30. gE'yichang 67	0	No. 2 Lock	$\tilde{\tilde{t}}_{(30)2} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[13.64, 13.72]$	65	13
31. gHuayun 168	0	No. 2 Lock	$\tilde{\tilde{t}}_{(31)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[13.75, 13.75]$	62	12
32. Changhangjianghao	0	No. 3 Lock	$\tilde{\tilde{t}}_{(32)3} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.50, 14.50]$	86	14
33. Qiaotai 7	1	South Lock	$\tilde{\tilde{t}}_{(33)4} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[14.33, 14.50]$	115	21
34. Gouping 7	1	South Lock	$\tilde{\tilde{t}}_{(34)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.50, 14.50]$	104	19
35. Jangneng 808	1	South Lock	$\tilde{\tilde{t}}_{(35)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.33, 14.42]$	66	13
36. Boxun 929	1	South Lock	$\tilde{\tilde{t}}_{(36)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.33, 14.42]$	100	20
37. Wangang 1030	0	No. 1 Lock	$\tilde{\tilde{t}}_{(37)1} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[14.50, 14.67]$	88	17
38. Yuandong 902	0	No. 1 Lock	$\tilde{\tilde{t}}_{(38)1} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[14.58, 14.75]$	152	21
39. Xianglong 896	0	No. 1 Lock	$\tilde{\tilde{t}}_{(39)1} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.67, 14.67]$	74	15
40. Sitong 3	0	North Lock	$\tilde{\tilde{t}}_{(40)5} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[14.50, 14.63]$	72	13
41. Rongjiang 14023	0	North Lock	$\tilde{\tilde{t}}_{(41)5} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[14.58, 14.67]$	64	12
42. Jinzhou 656	0	North Lock	$\tilde{\tilde{t}}_{(42)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.63, 14.75]$	56	11
43. E'enshi 688	0	North Lock	$\tilde{\tilde{t}}_{(43)5} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[14.54, 14.63]$	104	19
44. Jinyuan 828	0	North Lock	$\tilde{\tilde{t}}_{(44)5} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[14.55, 14.75]$	66	12
45. Ruitai 968	0	North Lock	$\tilde{\tilde{t}}_{(45)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[14.67, 14.67]$	97	18
46. gChangjiangsanxia 1	1	No. 3 Lock	$\tilde{\tilde{t}}_{(46)3} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[15.17, 15.25]$	106	15
47. Yunshuang 138	1	No. 2 Lock	$\tilde{\tilde{t}}_{(47)2} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[15.25, 15.33]$	64	13
48. Yuanlin 998	1	No. 2 Lock	$\tilde{\tilde{t}}_{(48)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[15.33, 15.33]$	60	13
49. Jiangfa 698	1	No. 2 Lock	$\tilde{\tilde{t}}_{(49)2} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[15.25, 15.42]$	72	14
50. Yidu 159LS	1	No. 2 Lock	$\tilde{\tilde{t}}_{(50)2} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[15.33, 15.42]$	70	13
51. Guijie 808	1	No. 2 Lock	$\tilde{\tilde{t}}_{(51)2} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[15.25, 15.33]$	100	21
52. Luhai 689	1	No. 2 Lock	$\tilde{\tilde{t}}_{(52)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[15.33, 15.33]$	62	15

Table 2. (*Continued*)

Ship i	d_{ij}	The lock to be passed	$\tilde{\tilde{t}}_{ik}$	l_i	w_i
53. Fuxun 608	0	No. 3 Lock	$\tilde{\tilde{t}}_{(53)3} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[15.67, 15.75]$	74	16
54. Yuxinyang 0387	1	No. 3 Lock	$\tilde{\tilde{t}}_{(54)3} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[16.17, 16.25]$	62	14
55. Changyuan 29	1	No. 3 Lock	$\tilde{\tilde{t}}_{(55)3} \sim N(\tilde{\mu}, 9.00)$ with $\tilde{\mu} \sim U[16.09, 16.25]$	57	12
56. Xinyu 9	1	South Lock	$\tilde{\tilde{t}}_{(56)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[16.17, 16.17]$	67	13
57. Yunchang 1	1	South Lock	$\tilde{\tilde{t}}_{(57)4} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[16.08, 16.25]$	86	15
58. Dyang 15	1	South Lock	$\tilde{\tilde{t}}_{(58)4} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[16.12, 16.17]$	100	20
59. Yichang-Tiancheng 6	1	South Lock	$\tilde{\tilde{t}}_{(59)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[16.17, 16.17]$	103	21
60. Yuanlin 678	1	South Lock	$\tilde{\tilde{t}}_{(60)4} \sim N(\tilde{\mu}, 9.00)$ with $\tilde{\mu} \sim U[16.00, 16.25]$	66	13
61. Zigui 868	1	South Lock	$\tilde{\tilde{t}}_{(61)4} \sim N(\tilde{\mu}, 0.49)$ with $\tilde{\mu} \sim U[16.07, 16.17]$	59	12
62. Gangsheng 812	0	North Lock	$\tilde{\tilde{t}}_{(62)5} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[16.17, 16.25]$	122	21
63. Rongjiang 3007	0	North Lock	$\tilde{\tilde{t}}_{(63)5} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[16.17, 16.21]$	103	20
64. Yuanlin 111	0	No. 1 Lock	$\tilde{\tilde{t}}_{(64)1} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[16.67, 16.67]$	70	15
65. Hangyuan 922	0	No. 1 Lock	$\tilde{\tilde{t}}_{(65)1} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[16.50, 16.67]$	68	15
66. Juhang 09	0	No. 1 Lock	$\tilde{\tilde{t}}_{(66)1} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[16.46, 16.58]$	114	21
67. Yuxin 0768	0	No. 1 Lock	$\tilde{\tilde{t}}_{(67)1} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[16.50, 16.62]$	102	20
68. Wangang 818	0	No. 1 Lock	$\tilde{\tilde{t}}_{(68)1} \sim N(\tilde{\mu}, 9.00)$ with $\tilde{\mu} \sim U[16.49, 16.64]$	65	15
69. Yifa 6	0	No. 3 Lock	$\tilde{\tilde{t}}_{(69)3} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[16.50, 16.67]$	102	18
70. Xinyi 3	1	No. 2 Lock	$\tilde{\tilde{t}}_{(70)2} \sim N(\tilde{\mu}, 0.25)$ with $\tilde{\mu} \sim U[16.75, 16.83]$	68	15
71. Yuyangxin 0577	1	No. 2 Lock	$\tilde{\tilde{t}}_{(71)2} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[16.58, 16.77]$	106	19
72. Zigui 218	1	No. 2 Lock	$\tilde{\tilde{t}}_{(72)2} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[16.83, 16.83]$	65	14
73. Xianzi 19	1	No. 2 Lock	$\tilde{\tilde{t}}_{(73)2} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[16.50, 16.75]$	53	12
74. Yushu 516	1	No. 2 Lock	$\tilde{\tilde{t}}_{(74)2} \sim N(\tilde{\mu}, 0.64)$ with $\tilde{\mu} \sim U[16.68, 16.83]$	112	21
75. Changyang 806	1	No. 3 Lock	$\tilde{\tilde{t}}_{(75)3} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[17.15, 17.25]$	66	14
76. Changtong	0	No. 3 Lock	$\tilde{\tilde{t}}_{(76)3} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[17.50, 17.67]$	72	15
77. Hongyang 916	0	North Lock	$\tilde{\tilde{t}}_{(77)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[17.67, 17.67]$	96	17
78. Gangsheng 1013	0	North Lock	$\tilde{\tilde{t}}_{(78)5} \sim N(\tilde{\mu}, 0.09)$ with $\tilde{\mu} \sim U[17.57, 17.65]$	65	14
79. Hongda	0	North Lock	$\tilde{\tilde{t}}_{(79)5} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[17.50, 17.62]$	53	12
80. Yichangchupeng 166	0	North Lock	$\tilde{\tilde{t}}_{(80)5} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[17.67, 17.67]$	108	19
81. Xiangpingjiang 0268	0	North Lock	$\tilde{\tilde{t}}_{(81)5} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[17.62, 17.75]$	110	21
82. Luzhou 308	1	South Lock	$\tilde{\tilde{t}}_{(82)4} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[17.75, 17.83]$	105	19
83. Jinchang 959	1	South Lock	$\tilde{\tilde{t}}_{(83)4} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[17.83, 17.92]$	68	12
84. Jishun 98	1	South Lock	$\tilde{\tilde{t}}_{(84)4} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[17.83, 17.83]$	96	18
85. Jiangjiyun 1209	1	South Lock	$\tilde{\tilde{t}}_{(85)4} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[17.67, 17.75]$	100	20
86. sChangjiang 2515	1	South Lock	$\tilde{\tilde{t}}_{(86)4} \sim N(\tilde{\mu}, 4.00)$ with $\tilde{\mu} \sim U[17.75, 17.92]$	58	12
87. Gongrong 19	1	No. 3 Lock	$\tilde{\tilde{t}}_{(87)3} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[17.75, 17.83]$	65	12
88. Gongshao 699	0	No. 3 Lock	$\tilde{\tilde{t}}_{(88)3} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[18.67, 18.67]$	100	16
89. Hanglin 618	0	No. 1 Lock	$\tilde{\tilde{t}}_{(89)1} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[18.50, 18.64]$	67	14
90. Yuzhoujianghe 0188	0	No. 1 Lock	$\tilde{\tilde{t}}_{(90)1} \sim N(\tilde{\mu}, 0.81)$ with $\tilde{\mu} \sim U[18.62, 18.75]$	102	20
91. Xiangpingjiang 0263	0	No. 1 Lock	$\tilde{\tilde{t}}_{(91)1} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[18.59, 18.67]$	105	21
92. Qiaotai 2	0	No. 1 Lock	$\tilde{\tilde{t}}_{(92)1} \sim N(\tilde{\mu}, 1.00)$ with $\tilde{\mu} \sim U[18.67, 18.67]$	100	19
93. Jianghong 898	0	No. 1 Lock	$\tilde{\tilde{t}}_{(93)1} \sim N(\tilde{\mu}, 0.01)$ with $\tilde{\mu} \sim U[18.67, 18.75]$	65	15
94. Minghua 899	0	No. 2 Lock	$\tilde{\tilde{t}}_{(94)2} \sim N(\tilde{\mu}, 0.04)$ with $\tilde{\mu} \sim U[18.65, 18.72]$	96	19
95. Suote 59	0	No. 2 Lock	$\tilde{\tilde{t}}_{(95)2} \sim N(\tilde{\mu}, 0.36)$ with $\tilde{\mu} \sim U[18.50, 18.67]$	103	20

Note: 11.00, 11.25. 2:25 represent that the time is 11:00 am, and 11.25 means 11:15 am, respectively.

(11:00 am–19:00 pm on 25 November 2010). Then, we present the model comparison. Finally, we perform sensitivity analysis on the model.

4.1. Related date and case problem results

At present, 95 ships propose navigation application to the Navigation Department. Since there are four ships (*Jinyang 369*, *Zigui 666*, *Heniu 78*, *Chuanji 2*) among these 95 ships that will pass the South Lock of TGD and the No. 2 Lock of GD in turn, the total number of lock services is 99. The ship navigation application information involves the lock to be passed, the navigation direction, the arrival anchor time, and the length and width of the ship. The penalty coefficient of waiting time for the ship i and related date of navigation application are shown in Tables 1 and 2, respectively. Other parameter values provided by the Navigation Department are shown in Table 3.

In addition, the parameters of PSO are the following: population size $L = 50$; iteration number $T = 100$; acceleration constant $c_p = 2.0$ and $c_g = 2.0$, inertia weight $w(1) = 0.9$ and $w(T) = 0.1$, respectively. After 10 reruns of the PSO computer program, we

Table 3. Parameter values provided by the Navigation Department

The weight of two objectives	$\lambda_T = 0.75$, $\lambda_B = 0.75$
The earliest and latest lock k service time	$t_b^1 = 13.00$, $t_e^1 = 19.00$, $t_b^2 = 12.67$, $t_e^2 = 19.00$, $t_b^3 = 13.50$, $t_e^3 = 19.00$, $t_b^4 = 13.17$, $t_e^4 = 18.17$, $t_b^5 = 13.50$, $t_e^5 = 18.00$
Optimal workload balance rate of lock k	$b_1 = 0.206$, $b_2 = 0.246$, $b_3 = 0.538$,
Service interval of lock k	$t_1^s = 1.50$, $t_2^s = 1.00$, $t_3^s = 0.50$, $t_4^s = 1.83$, $t_5^s = 1.50$

Note: To facilitate the calculation, we convert time to numerical value. For example, $t_b^1 = 13.00$ means that the earliest service time of No. 1 lock in GD is 13:00 pm; $t_1^s = \frac{90\,\text{min}}{60\,\text{min}} = 1.50$ represents service interval of No. 1 lock is 90 min.

obtained the following 8 hours NCS on 25 November 2010 (11:00 am–19:00 pm) and the effective utilization of chamber in Table 4. The optimal lock operation plan is shown in Fig. 10. Search process of PSO for NCS is shown in Fig. 11.

The case problem is solved by the proposed algorithm within 22 minutes on average and the fitness value is 0.532585, $T = 0.527954$, $B = 0.004631$, all of which are satisfactory for the Navigation Department. Compared with historical data, illustrative results show that the total weighted tardiness of ships is reduced and the navigation capability is improved remarkably. Hence, by the practical application in the Three Gorges Project, this birandom MODM model is proved that it is feasible and efficient for NCS in inland waterways optimization under birandom phenomenon.

4.2. Model comparison

In order to test the advantages of birandom variables in hybrid, uncertain environment where twofold randomness exists in practice, we utilize the initial data (i.e. random variables) to NCS model. Then, after 10 reruns, we obtain relevant comparisons below (all parameters of PSO are same, Table 5).

From the results, we can see that the convergence iteration number and average running time are almost the same, but min $F(U, S)$ is improved remarkably

Table 4. 8 hours NCS of the Three Gorges Project on 25 November 2010 (11:00 am–19:00 pm)

Lock	n	t_{kn}	$N(k)$	Ship: Upriver $d_{kn} = d_{ij} = 0$	Ship: Downriver $d_{kn} = d_{ij} = 1$	Effective utilization of the chamber
No. 1 Lock	1	13:00	3	Gangsheng 1012, Gangsheng 810, Xinghang 519	–	87.6%
	2	15:00	3	Wangang 1030, Yuandong 902, Xianglong 896	–	66.5%
	3	17:00	5	Yuanlin 111, Hangyuan 922, Juhang 09, Yuxin 0768, Wangang 818	–	85.7%
	4	19:00	5	Xiangpingjiang 0263, Yuzhoujianghe 0188, Hanglin 618, Qiaotai 2, Jianghong 898	–	92.3%
No. 2 Lock	1	12:40	6	–	E'shi 3158, Tonghai 618LS, Yuanyang 3, Yuanyang 7601, Xinjiangping 1016, E'yicang 2039	86.9%
	2	14:10	9	gWanshun 2, gChang'an 118, gYuxinyang 0527, gWanxin 618, gYunshuang 168, gWuqiao 34, gJinggang 518, gE'yichang 67, gHuayun 168	–	93.9%
	3	15:40	6	–	Yunshuang 138, Yuanlin 998, Jiangfa 698, Yidu 159LS,Guijie 808, Luhai 689	75.2%
	4	17:10	5	–	Xinyi 3, Yuyangxin 0577, Zigui 218 Xianzi 19, Yushu 516	79.5%
	5	19:00	6	–	Heniu 786, Chuanji 2, Zigui 666, Minghua 899, Suote 59, Jinbo 369	75.1%

Table 4. (*Continued*)

Lock	n	t_{kn}	$N(k)$	Ship: Upriver $d_{kn}=d_{ij}=0$	Ship: Downriver $d_{kn}=d_{ij}=1$	Effective utilization of the chamber
No. 3 Lock	1	11:30	1	Lintong 518	–	78.8%
	2	14:30	1	Changhangjianghao	–	59.3%
	3	15:30	1	–	gChangjiangsanxia 1	78.3%
	4	16:00	1	Fuxun 608	–	58.3%
	5	16:30	2	–	Yuxinyang 0387, Changyuan 29	76.4%
	6	17:00	1	Yifa 6	–	90.4%
	7	17:30	1	–	Changyang 806	45.5%
	8	18:00	1	Changtong	–	53.2%
	9	18:30	1	–	Gongrong 19	38.4%
	10	19:00	1	Gongshao 699	–	78.8%
South Lock	1	13:10	6	–	Longfei, Zigui 666, Zhongyuan 06, Heniu 786, Chuanji 2, Jinyang 369	76.3%
	2	14:50	4	–	Qiaotai 7, Gouping 7, Boxun 929, Jangneng 808	83.1%
	3	16:30	6	–	Xinyu 9, Dyang 15, Yichang-Tiancheng 6, Yunchang 1, Yuanlin 678, Zigui 868	90.4%
	4	18:10	5	–	Luzhou 308, Jinchang 959, Jishun 98, Jiangjiyun 1209, sChangjiang 2515	82.9%
North Lock	1	13:30	6	Huihuang 168, Yuwanhang 10387, Haifeng 699, Yichangqixiang 5, sGaizhen, Yuxinyang 1421	–	91.3%
	2	15:00	6	Sitong 3, Rongjiang 14023, Jinzhou 656, E'enshi 688, Jinyuan 828, Ruitai 968	–	78.3%
	3	16:30	2	Gangsheng 812, Rongjiang 3007	–	52.9%
	4	18:00	5	Hongyang 916, Gangsheng 1013, Hongda, Yichangchupeng 166, Xiangpingjiang 0268	–	86.4%

Note: Lock No.1 in GD only transfers ship in one-way because of complex flow conditions.

Table 5. Model comparison

	Initial data (Random variables)	Revised data (Birandom variables)
min $F(U,S)$	0.573233	0.532585
Convergence iteration number	47	52
Average running time	19.42 min	21.16 min

from 0.573233 to 0.532585 (7.09%). Without a doubt, this improvement can bring a considerable economic benefit, especially for large-scale projects, such as the Three Gorges Project.

4.3. Sensitivity analysis

Below we perform a sensitivity analysis of the weighted values λ_T and λ_B, optimal workload balance rate of No. 1 Lock (b_1), No. 2 Lock (b_2), and No. 3 Lock (b_3), all of which are essential inputs into the model. We alter their values and, subsequently, compare the corresponding fitness value results to

Table 6. Sensitivity analysis

	Original value	Test value		
λ_T	0.75	0.95	0.55	0.05
λ_B	0.25	0.05	0.45	0.95
b_1	0.206	0.206	0.206	0.206
b_2	0.256	0.256	0.256	0.256
b_3	0.538	0.538	0.538	0.538
T	0.527954	0.657873	0.721428	0.834632
B	0.004631	0.004631	0.004631	0.004631
min $F(US)$	0.532585	0.662504	0.726059	0.839263

Table 7. Sensitivity analysis

	Original value	Test value		
λ_T λ_B	0.75 0.25	0.75 0.25	0.75 0.25	0.75 0.25
b_1	0.206	0.333	0.100	0.450
b_2	0.256	0.333	0.100	0.450
b_3	0.538	0.333	0.800	0.100
T	0.527954	0.527954	0.527954	0.527954
B	0.004631	0.004631	0.004631	0.004631
min $F(U,S)$	0.532585	0.096407	0.137210	0.224951

analyze the effect of each parameter. This analysis could provide the necessary information about these parameters to the Navigation Department.

At first, we keep $b_1 = 0.206$, $b_2 = 0.256$, $b_3 = 0.538$ as the original value and change λ_T and λ_B as $\lambda_T = 0.95$, $\lambda_B = 0.05$ (T is extremely important) and $\lambda_T = 0.55$, $\lambda_B = 0.45$ (T and B are almost of the same importance), $\lambda_T = 0.05$, $\lambda_B = 0.05$ (B is extremely important), respectively. In these three tests, the biggest change of the total cost min $F(U, S)$ is in the third test (increases from 0.532585 to 0.839263) because the value of $t_{kn} - E\left[\tilde{\tilde{t}}_{ik}\right]$ is increasing significantly. The results mean that the Navigation Department should give larger priority to the waiting time of the ship (all the tests we processed is in 10 reruns of the PSO, Table 6).

Then, we keep $\lambda_T = 0.75$, $\lambda_B = 0.25$ as original values and change $b_i (i = 1, 2, 3)$ as $b_1 = b_2 = b_3 = 0.333$ (workload balance rates are equivalent), $b_1 = 0.100$, $b_2 = 0.100$, $b_3 = 0.800$ (workload balance rate of No. 3 Lock is very high), $b_1 = 0.450$, $b_2 = 0.450$, $b_3 = 0.100$ (workload balance rate of No. 3 Lockis very low), respectively. In these three tests, the biggest change of the total cost min $F(U, S)$ is also in the third test (increases from 0.532585 to 0.752908). Thus, as the smallest lock chamber, No. 3 Lock should be arranged for more ship to transport (all the tests we processed are in 10 re-runs of the PSO, Table 7).

Based on the sensitivity analysis above, we know that the Navigation Department should give greater priority to the waiting time of ship. On this basis, workload balance rate of No. 3 Lock should be higher than No. 1 Lock and No. 2 Lock.

Conclusions

In this paper, we first propose a birandom MODM model for NCS in ship transportation of the Three Gorges Project, and then apply particle swarm optimization (PSO) to resolve this large-scale practical problem. By sensitivity analysis, we provide our suggestion to the Navigation Department for NCS.

In the proposed model, we consider the two objectives: the total weighted tardiness of ships and the unbalanced workload in Gezhouba Dam (GD). The model employs birandom variables to characterize the practical hybrid uncertain environment where twofold randomness exists. This represents the first effort to use birandom variables to practical NCS in ship transportation, and this work is original. For addressing the birandom variables, we employ birandom expected value operator to handle the birandom objective function and constraint. Then, we apply PSO to resolve NCS that is known as an NP-hard problem. Due to the introduction of birandom uncertainty, the proposed model and algorithm could be also suitable for describing other uncertainty problems with multiobjectives in the real world, such as fuzzy random, fuzzy rough, rough random, and so on.

One of the most important follow-up researches should be focused on the software development that is based on the proposed model and algorithm in this study. Besides, navigational safety in the ship transportation should be concerned in the continued research because of its influence on time optimization in NCS. Another area for continued research includes the development of more efficient heuristic methods to solve NP-hard NCS problem, such as a priority rule-based PSO, comprehensive learning PSO, discrete version of PSO, etc. All of three areas are very important and worth of an equal concern.

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