Efficient Online One-way Traffic Scheduling for Restricted Waterways[★]

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ARTICLE INFO

Keywords:
Restricted waterways
ship sequencing and scheduling
traffic uncertainties
sliding window

ABSTRACT

In Yangtze River traffic management, to manage ship sequencing and scheduling effectively and efficiently in restricted waterways has long been a challenging issue. This paper proposes a Sliding Window based Online ship Sequencing and Scheduling algorithm (OSS-SW) to tackle this problem. The OSS algorithm is capable of generating a more efficient ship sequence by introducing the 'position shift' concept which takes advantages of ships' sailing time differences in the restricted waterway. The sliding window mechanism on the other hand is introduced to handle the traffic uncertainties and to reduce the computational complexity. The impact of the restricted waterway congestion on the performance of OSS-SW is also investigated. Further, the parameter settings of the proposed OSS-SW are investigated in detail. Both simulation studies and the real data applications confirm that the proposed OSS-SW algorithm outperforms the existing widely adopted Traffic Signal Revealing System (TSRS) and the Expert System based algorithm (FAHP-ES) in solving the ship sequencing and scheduling problem.

1. Introduction

Restricted waterways are special regions along the Yangtze River in China and many other inland waterways worldwide with twisting turns, rapid waters, and narrow channels Li et al. (2013). Ships need to be scheduled and sequenced to pass through the restricted waterways as only one direction ships are allowed to pass through at one time Liangxiong and Headquarters (2014), i.e., either upstream direction or downstream direction. Ships traveling in opposite directions at the same time in restricted waterways are strictly forbidden to ensure shipping safety. Traffic Signal Revealing System (TSRS), shown in fig. 1, are currently deployed along the Yangtze River and some other waterways to manage the ships passing through the restricted waterways automatically Gan et al. (2016a), and ships have to wait in the waiting areas for the go signal before entering the restricted waterways. A first-come-first-served (FCFS) based method is adopted in the TSRS to calculate the ship sequence and control the passing time. The FCFS based method is a conventional method to ensure traffic safety and has been successfully used in many real applications Rajesh and Mahalakshmi (2015); Montoya et al. (2014); Fang et al. (2015); Lalla-Ruiz et al. (2018); Zhang et al. (2017b); Wang et al. (2018); Zhang et al. (2017a). However, this method does not take into account other useful information which may lead to a more efficient traffic sequence and passing time. With the rapid development of the Yangtze River transportation, the number of ships traveling across the waterway has increased dramatically in recent years. FCFS based TSRS method has difficulties to meet the increased requirement for efficient traffic management, as in current situation, most ships have to wait in a long queue, leading to severe traffic congestion. The consequent economic loss and exhaust gas emission call for more efficient online ship sequencing and scheduling methods, which can significantly reduce the ships' waiting time and enhance the waterway traffic capacity.

Limited work has been reported so far on ship sequencing and scheduling problem for restricted waterways. A numerical method has been presented for estimating delays through a series of queues with inflows and outflows occurring only at end nodes Dai and Schonfeld (1998). A simulation-based scheduling system has been designed to assist in barge dispatching and boat assignment problems for inland waterways Taylor et al. (2005). A rolling-horizon based framework to optimize maritime inventory routing under uncertainty was developed by Dong et al.

[★] This document is the results of the research project funded by the National Natural Science Foundation of China.
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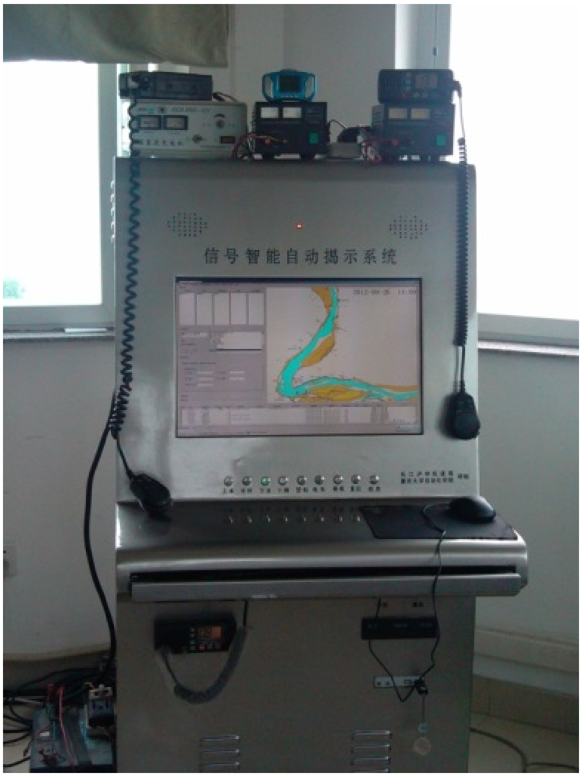


Figure 1: Traffic signal revealing system currently deployed in restricted waterways.

(2018). Other relevant work includes investigation of the ports sequence to be visited by ships. Smith et al. (2011) used a simulation system to demonstrate the benefits to employ an efficient heuristic scheduler to tackle a series of bottlenecks in a transportation system. A mathematical formulation of the ship placement problem in tide river harbours was presented by Verstichel et al. (2014), aiming to assign ships into as few locks as possible while satisfying the practical constraints. An integer programming model to optimize the container liner network on the Yangtze River by minimizing the total transportation cost was built by Yang et al. (2014). The model can determine the shipping routes, calling ports, calling sequences, number, and type of used ships. Ulusçu et al. (2009) presented a mathematical formulation of the scheduling process, which was then validated by comparing its results with scheduling decisions made by the operators. A mixed-integer linear programming mathematical formulation was developed by Lalla-Ruiz et al. (2016), some greedy heuristic methods based on commonly used queue rules as well as a simulated annealing algorithm were also proposed to solve the optimization problem. Liu et al. (2018) presented a novel communication based distributed conflict resolution mechanism to allow a group of connected autonomous vehicles to navigate safely and efficiently across intersections without any traffic manager. Liang et al. (2019) proposed a fuzzy-based algorithm, namely FAHP-ES, to control the ship sequence for passing through the Shenbeizui Restricted waterway in China. Key factors influencing traffic management were identified by questionnaires and their significance was further quantified. Despite the aforementioned work on the traffic sequencing and scheduling problem, it is still challenging to apply these approaches to the restricted waterway traffic management due to the following features:

1. A lot of uncertainties exist in the restricted waterway traffic management. There are a number of ports inside the restricted waterways and ships may enter or leave the ports without advanced notifications. Ships heading to the ports should be cleared from the signalling list while ships leaving the ports should be scheduled and managed immediately as they are already inside the restricted waterway.
2. It is not recommended for the ships to change the speed and trajectory in the restricted waterways due to the complex geographic environment. The incidents of insufficient power and excessive speed may occur to upstream and downstream ships if they increase their speed.

Even though limited research has been reported on the ship sequencing and scheduling in restricted waterways, a similar problem has been addressed for aircraft sequencing and scheduling (ASS) in the aircraft landing management. ASS aims to arrange a series of aircraft to land on the same runway and minimize their total airborne delays. While in the restricted waterway traffic management, ships are sequenced and scheduled with the aim to minimize the total waiting time. A popular concept that has been proposed recently to address the ASS problem is 'position shifting' which changes the landing sequence of the arrival aircraft to minimize the total airborne delay Balakrishnan and Chandran (2006). The latest development in ASS has inspired this research to address the ship sequencing and scheduling problem based on the 'position shifting' concept. The considerable progress in 'position shifting' in ASS suggested that sliding window is a desirable choice as it divides the entire problem into subproblems with smaller search space, leading to reduced computational burden and better quality solutions. A sliding window based ASS algorithm was proposed by Hu and Chen (2005b) and a detailed investigation on the influences of tuning parameters on the performance using Monte Carlo simulations was presented. The sliding window scheme was introduced into generic algorithms to solve the dynamic ASS problem in a busy hub airport Hu and Chen (2005a). A new framework combining the ant colony system algorithm with the sliding window mechanism was proposed to address the ASS problem Zhan et al. (2009). A two-opt exchange heuristic local search was further introduced to enhance the performance Zhan et al. (2010).

However, these methods can not be directly applied to the ship sequencing and scheduling problem due to the following key differences:

1. Ships will pass through the restricted waterway from both the upstream and downstream, while in the ASS problem, only the aircraft landing is considered.
2. For the ASS problem, the landing time of an aircraft is ignored. However, the travelling time of a ship in the restricted waterways varies from 10 to 60 minutes, thus cannot be ignored as it has significant impacts on the scheduling result.
3. In the restricted waterway traffic management, downstream ships have the priority to pass through the restricted waterway. This is a constraint in the ship sequence optimization problem. In ASS problem, all aircraft are equally treated for landing at the airport.

In this paper, an Online Sequencing and Scheduling algorithm (OSS) is proposed to achieve the optimal ship sequence and passing time when ships pass through the restricted waterways. A salient feature of the proposed OSS method is that it takes the ships' predicted arrival time (t_{PAT}) and predicted crossing time (t_{PCT}) into consideration and aims to achieve the least total waiting time (T_{twt}) by changing the ships' passing sequence, while only t_{PAT} is taken into account in current TSRS Gan et al. (2016b,a). The sliding window mechanism is then employed to divide the whole problem into subproblems and solve one subproblem in each step such that the computational burden is reduced and the overall solution quality is improved. It also helps to improve the robustness of the OSS algorithm to uncertain dynamic environment with excellent global search ability as it ignores the information of ships further away from the restricted waterway which might contain a large amount of uncertainties.

The rest of this paper is organized as follows. The formulation of ship sequencing and scheduling problem is given in Section 2, the TSRS method for ship sequencing and scheduling is also introduced. The proposed sliding window based online optimization algorithm OSS-SW is detailed in Section 3. Section 4 presents the Monte Carlo simulation results. The influence of the restricted waterway dynamics and the parameter settings on the performances of the proposed OSS-SW are thoroughly investigated in this section. Further, a real-life application is also presented in this section. Finally, Section 5 concludes this paper and future work is presented.

2. Background and Problem Formulation

The ship sequencing and scheduling problem involves a set of ships passing through a restricted waterway during a period of time, as illustrated in fig. 2. Assume N_u upstream ships and N_d downstream ships arrived at the restricted waterway in T_{range} minutes, each ship has a respective predicted arrival time $t_{PAT}(i)$ and a predicted crossing time $t_{PCT}(i)$, representing the ith ship's estimated arrival and crossing time in the restricted waterway. N_u, N_d, and T_{range} are used to simulate different congestion in the restricted waterway, larger N_u and N_d within smaller T_{range} implies more congestion. To ensure the restricted waterway traffic safety, each ship has to be assigned an allowed travelling time t_{ATT} and an allowed crossing time t_{ACT}. t_{ATT} is the time instance that the ship is allowed to travel into the restricted waterway and t_{ACT} is the assigned time duration that the ship is allowed to pass through the restricted waterway. The current TSRS method generates the FCFS based ship sequence through the following steps.

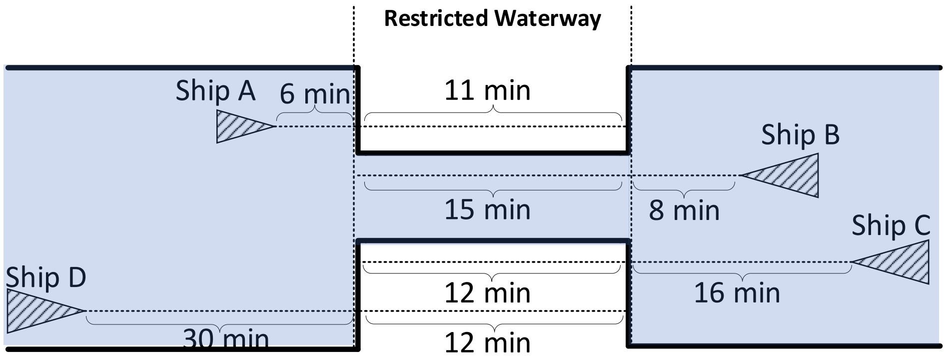


Figure 2: Example of 4 ships passing through the restricted waterway.

Table 1
Experimental result of changing ship sequence.

Original Sequence				Scheduled Sequence By TSRS			The True Optimal Solution		
Ship No.	Ship Direction	t_{PAT} (second)	t_{PCT} (second)	Ship No.	t_{ATT} (second)	Waiting Time (second)	Ship No.	t_{ATT} (second)	Waiting Time (second)
1	Downstream	360	660	1	360	0	1	360	0
2	Upstream	480	900	4	1800	0	3	1020	60
3	Upstream	960	720	2	2520	2040	4	1800	0
4	Downstream	1800	720	3	2520	1560	2	2520	2040
Total Waiting Time (second)				3600			2100		

1. Step 1. Sort the ships by their t_{PAT} in ascending order and export the results to $final\_list$.
2. Step 2. Calculate the allowed travelling time (t_{ATT}) and allowed crossing time (t_{ACT}) for ships in $final\_list$ according to equation 1 if the jth and $j+1$th ships are with the same direction or according to equation 2 if the jth and $j+1$th ships head to different directions. δ is the buffer index which denotes the gaps between ships and helps to enhance the traffic safety. The basic principle is that overtaking is not allowed and the safety interval must be guaranteed for identical direction ships. While for opposite direction ships, they are strictly forbidden to travel in the restricted waterway at the same time.

$$\begin{aligned} t_{ATT}(j+1) &= \max\{t_{ATT}(j)+\delta, t_{PAT}(j+1)\} \\ t_{ACT}(j+1) &= \max\{t_{ATT}(j)+t_{ACT}(j)-t_{ATT}(j+1), t_{PAT}(j+1)\} \end{aligned} \tag{1}$$

$$\begin{aligned} t_{ATT}(j+1) &= \max\{t_{ATT}(j)+t_{ACT}(j)+\delta, t_{PAT}(j+1)\} \\ t_{ACT}(j+1) &= t_{PCT}(j+1) \end{aligned} \tag{2}$$

Suppose an algorithm is implemented to change the ship positions in the $final\_list$. Each ship in the original sequence was given an optimised t_{ATT} and t_{ACT} which indicate its allowed time to travel into the restricted waterway and the passing time in the restricted waterway. Then the objective of the position change is to minimize the total waiting time T_{twt} of the new ship sequence, which is defined as

$$T_{twt} = \sum_{i=1}^{N} [t_{ATT}(i) - t_{PAT}(i) + t_{ACT}(i) - t_{PCT}(i)] \tag{3}$$

The waiting time of a ship includes two parts, the departure delay ($t_{ATT} - t_{PAT}$) and the travelling delay($t_{ACT} - t_{PCT}$). The departure delay is the waiting time for entering the restricted waterway. The travelling delay is to ensure no overtaking in the restricted waterway.

Besides T_{twt}, the length of the new ship sequence len (the completion time for all ships to pass through the restricted waterway) is also adopted to evaluate the optimization performance in some cases.

$$len = \max[t_{ATT}(1), \cdots, t_{ATT}(N)] - \min[t_{ATT}(1), \cdots, t_{ATT}(N)] \tag{4}$$

Even though these two indexes are not precisely equivalent, the minimum T_{twt} is achieved with a minimum len for the same set of ships in most cases. len usually focuses on the traffic capacity of the restricted waterway, while T_{twt} emphasizes the operating cost of the restricted waterway traffic management. Therefore, without loss of generality, T_{twt} is adopted in this paper. Whatever optimization objective is adopted, the ship sequence optimization problem has proven to be NP-hard. As the number of ships waiting to pass through the restricted waterway increases, the computational burden will significantly increase Hu and Chen (2005b).

It is evident that t_{PAT} and t_{PCT} vary significantly under different conditions for each ship. By taking advantage of diversity in t_{PAT} and t_{PCT}, and appropriately changing the positions of ships in the TSRS sequence, it is possible to reduce the total waiting time and to improve the traffic capacity at the restricted waterways. Fig. 2 gives a simple example of 4 ships (Ships A to D) passing through the restricted waterway. Ships A and D are downstream while ships B and C are upstream. For the sake of simplicity, t_{PAT} and t_{PCT} of ships A to D are supposed to be full minutes. $t_{PAT}(i) = \{6, 8, 16, 30 | i = A, B, C, D\}$, $t_{PCT}(i) = \{11, 15, 12, 12 | i = A, B, C, D\}$. As only four ships are used in the test, and the actual optimal ship sequence can be obtained by an exhaustive search. The potential benefits by changing the ship sequence are summarized in Table 1. The total waiting time of these four ships passing through the restricted waterway is significantly reduced by 25 minutes after changing the ship positions compared with the TSRS sequence. Therefore, there is a great potential in reducing the total waiting time in the restricted waterway management in the Yangtze River.

If the ship sequence only needs to be optimized offline, then the computational burden is manageable. This is the case when all ships travel exactly according to their t_{PAT} and t_{PCT}. Unfortunately, many uncertainties exist in real applications, the ship's actual arriving time is likely different from the predicted arriving time. In some worse scenarios, some new ships may 'appear suddenly' due to Automatic Identification System (AIS) signal failure and some ships may dock before entering the restricted waterway. It presents a major challenge for restricted waterway traffic management as accurate ship information is the key to optimize the ship sequence. Therefore, offline optimization often does not meet the reality. For online optimization, the computational complexity and the robustness of the algorithm against uncertainties are the two key considerations.

3. Sliding window based online ship sequencing and scheduling algorithm

The sliding window is an essential stream data processing technique which divides the whole problem into several subproblems Mattingley et al. (2011). Due to smaller search space for subproblems, this technique can achieve a better solution using less computation effort Hu and Chen (2005b). Further, realtime information could be used effectively to achieve a robust performance. With sliding windows, the optimization problem can be solved in real-time by looking ahead several schedule windows, and only the output within the first schedule window is applied to the system Gupta et al. (2016). The result is then checked, and a new decision is made by considering the updated information in the following iterations Hu and Chen (2005b); Zhan et al. (2010). There are two tuning parameters in the sliding window based ship sequencing and scheduling algorithm: 1) the time interval of a scheduling window T_{int} representing the length of each window. 2) the number of scheduling windows N_{sw}, which controls the information to be used in each step. During the optimization process, the realtime information within the whole sliding window will be used to make a scheduling decision, while only the decision for the ships in the first window will be applied Hu and Di Paolo (2008).

When integrated with the sliding window scheme, the ship scheduling problem can be converted into several subproblems. For the kth ($k = 1, 2, 3, \cdots$) subproblem, the realtime ship information from the kth time interval to the $(k + N_{sw} - 1)$ time interval will be used, while the optimization objective is only for the kth subproblem. The optimizing process repeats until the entire problem is solved. The length of the sliding window is much smaller than the whole problem. Thus the computational effort is significantly reduced such that it can be solved in realtime. Further, the optimization problem can be more effectively and efficiently solved due to the search space is much smaller.

Fig. 3 illustrates the 1st and 2nd iterations of the proposed sliding window based algorithm for ship sequencing and scheduling problem. The detailed procedure can be summarized as follows:

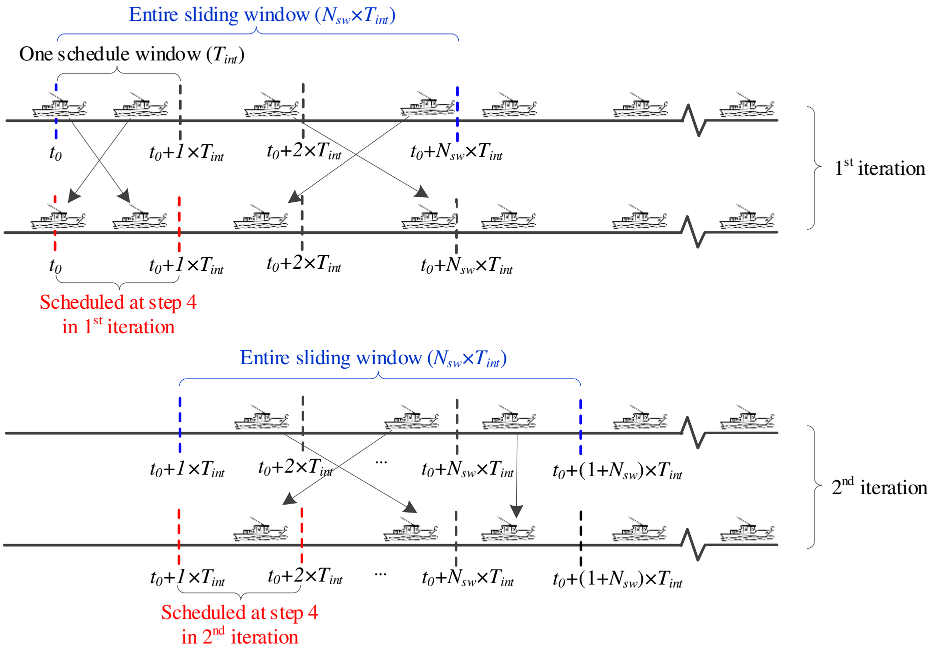


Figure 3: Example of the sliding window process for the ship schedule problem.

1. Step 1: Initialization. Assume that a ship sequence $S = \{a_1, a_2, \cdots, a_n\}$ is available, where $a_i, i = 1...n$ denotes the ships to be scheduled, and they are sorted in order by their t_{PAT} and n is the number of ships to be signalled. Set T_{int} and N_{sw} for the sliding window according to each practical scenario where T_{int} is the length of the schedule window and N_{sw} is the total number of schedule windows. Set the iteration $k = 1$.
2. Step 2: For the kth iteration, identify the ships collection Θ which contains all the ships with t_{PAT} smaller than $t_0 + (k-1) \times T_{int} + N_{sw} \times T_{int}$ and larger than $t_0 + (k-1) \times T_{int}$, t_0 is the start time of the sliding window and is set to the t_{PAT} of the first ship in S. All realtime information of the ships in Θ is needed to search for the optimal ship sequence in kth iteration. For the ships with t_{PAT} larger than $\mathrm{t}_0+(k-1)\times T_{\mathrm{int}}+N_{sw}\times T_{\mathrm{int}}$, their information will be included in the following iterations. And for the ships with t_{PAT} smaller than $\mathrm{t}_0 + (k-1) \times T_{\mathrm{int}}$, they have been scheduled in the previous iterations.
3. Step 3: Solve the following optimization problem

$$\min \sum t_{ATT}(i) - t_{PAT}(i) + t_{ACT}(i) - t_{PCT}(i) \tag{5}$$

subject to the constraint that only ships in one direction are allowed to pass through the restricted waterway at one time.

4. Step 4: An optimized ship sequence was carried out after step 3, only ships with t_{ATT} in $[t_0 + (k-1) \times T_{int}, t_0 + k \times T_{int}]$ are allowed to pass through the restricted waterway in this iteration. Adding up the waiting time of these ships by

$$T_{twt}(\mathrm{k}) = \sum t_{ATT}(i) - t_{PAT}(i) + t_{ACT}(i) - t_{PCT}(i) \tag{6}$$

5. Step 5: Let $k = k + 1$, repeat steps 2 to 5 until all the t_{PAT} of ships are smaller than $t_0 + (k-1) \times T_{int}$, thus all ships in the ship sequence are scheduled and passed through the restricted waterway through this real-time iterations.
6. Step 6: Calculate the total waiting time of the optimized ship sequence as follows

$$T_{twt} = \sum_{\mathrm{k}} T_{twt}(\mathrm{k}) \tag{7}$$

Step 3 is the key step of the algorithm. Although a number of algorithms have been proposed for the ASS problem, none of them has been applied to the ship sequencing and scheduling problem. In this paper, inspired by the online aircraft landing sequence optimization method Bianco et al. (1997), a new optimization method, namely OSS, is developed and described as follows:

1. Let $S_d = \{a_d^1, a_d^2, \cdots, a_d^n\}$ and $S_u = \{a_u^1, a_u^2, \cdots, a_u^n\}$ denote the original downstream and upstream ship sequence respectively, a_d^i and a_u^j are the ith ship in the downstream sequence and jth ship in the upstream sequence. Their t_{PAT} are within the current interest period, thus need to be considered in the subproblem.
2. Sort the downstream ships according to their t_{PAT} in ascending order. Adjust their travelling times t_{ACT} by equation 8 to prevent overtaking in the restricted waterways.

$$t_{ACT}(i) = \max\{t_{ATT}(i-1) + t_{ACT}(i-1) - t_{PAT}(i) + \delta, t_{PCT}(i)\} \tag{8}$$

3. If there exists unoccupied time between downstream ships, which means the previous ship leaves the restricted waterway before the next ship arrives, i.e. $t_{PAT}(i-1) + t_{PCT}(i-1) < t_{PAT}(i)$. Traverse all upstream ships in S_u and find the ships a_u^j which can pass through the restricted waterway during the gap. Insert a_u^j into the gap. The t_{ATT} do not need to be recalculated as a_u^j would not have any impact on the downstream ship sequence.
4. Put the unscheduled upstream ships to the end of the sequence. Arrange the first upstream ship with a proper t_{ATT} by equation 9 to prevent collisions.

$$\begin{aligned} t_{ATT}(i) = \max\{&t_{ATT}(i-1) + t_{ACT}(i-1) \\ &+ \delta, t_{PAT}(i)\} \end{aligned} \tag{9}$$

5. Arrange all the upstream ships at the end of the sequence with adoptable t_{ACT} by equation 8 to prevent overtaking in the restricted waterways.

The sliding window in the above process is a crucial factor in obtaining better performances while using less computation. In the kth iteration, only the ships within the period $[t_0+(k-1)\times T_{int}, t_0+(k-1)\times T_{int}+N_{sw}\times T_{int}]$ are taken into consideration. Generally, this period is much shorter than the entire optimization period, and the solution space is significantly reduced. Therefore the optimization method based on the sliding window technique can obtain a better solution efficiently. Once an optimal sequence is obtained, only the ships within the first window are allowed to pass through the restricted waterway. After that, the optimization process would slide into the future by one window length, and a new set of ships will be scheduled. This mechanism provides the algorithm with strong robustness under a dynamic, uncertain environment. The performance heavily relies on the proper choice of the number of the schedule windows N_{sw} in the sliding window. If N_{sw} is too small, the length of the sliding window is too short, the algorithm will be very shortsighted as very few ships can be included in each optimization operation. If N_{sw} is too large, the length of the sliding window is too long, too far away ships which contain many uncertainties would be taken into account in the algorithm and will result in poor performance and heavy computational burden.

4. Experiments and comparisons

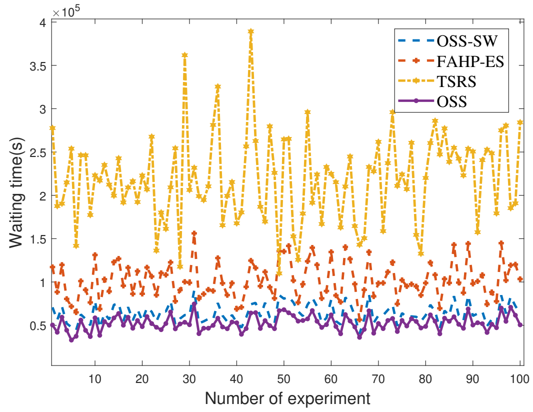
To test the effectiveness, efficiency and robustness of the proposed algorithm, both simulation studies and real-life applications were conducted. All the tests run in Matlab 2019 on an offline Windows 10 x64 computer with a 2.9 GHz Intel i7 CPU and 16 GB RAM. No other software are installed to reduce the disturbances.

The number of ships considered in the experiments is 30. Each ship is randomly allocated with a t_{PAT} and a t_{PCT} in the period of $[0, T_{rangeA}]$ and $[0, T_{rangeC}]$. Another two parameters $p1$ and $p2$ are used to adjust the uncertainties of the restricted waterway. $p1$ represents the percentage of ships that dock outside the restricted waterway and will not pass the restricted waterway. $p2$ is the percentage of ships suddenly appeared outside the restricted waterway. Generally, these are due to the AIS transmission failure, or most likely, they only turn on the AIS device when they approach the restricted waterway in real applications.

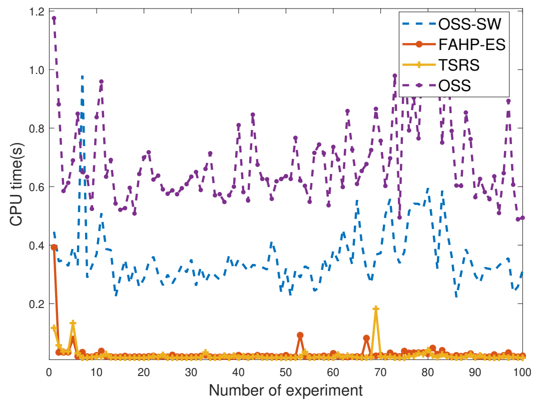
The proposed OSS-SW algorithm is compared with the TSRS method and the FAHP-ES scheduling method. The proposed online optimization method OSS, which is the optimizer in OSS-SW, is also used to validate the contribution of the sliding window scheme. In other words, OSS does not use the sliding window strategy, and all the ships are optimized once.

Table 2
Test cases for the proposed algorithm (T_{rangeC} is set to 30 minutes in all cases).

Case No.	p1	p2	T_{rangeA}	Case No.	p1	p2	T_{rangeA}
1	0	0	60min	7	10%	0	60min
2	0	0	120min	8	10%	0	120min
3	0	0	180min	9	10%	0	180min
4	0	10%	60min	10	10%	10%	60min
5	0	10%	120min	11	10%	10%	120min
6	0	10%	180min	12	10%	10%	180min



(a) The T_{twt} of 100 independent experiments using the 4 methods.



(b) The CPU time of 100 independent experiments using the 4 methods.

Figure 4: The experiment results of 100 independent experiments using the 4 methods.

To examine the performance of the proposed method thoroughly, 12 cases with different settings (table 2) are investigated. There are no uncertainties in cases $1 \sim 3$, i.e., $p1$ and $p2$ are 0. Cases $4 \sim 12$ consider different uncertainties. 100 independent experiments are conducted for each case using Monte Carlo simulations. In each simulation, N_{sw} varies from 1 to 10 and T_{int} is set to 150 seconds.

Table 3 illustrates an example of 30 ships passing through the restricted waterway in case 1, the schedule window length was set to 150 seconds, and the length of the sliding window was set to 4. The sequencing and scheduling results by TSRS, FAHP-ES, OSS and OSS-SW algorithm are summarized and the total waiting times for 30 ships are 121807s, 57384s, 56593s and 52869s respectively. The results indicate that FAHP-ES, OSS and OSS-SW all reached better results than the existing TSRS method. In order to draw a more accurate conclusion of the proposed method, 100 independent experiments under case 1 were conducted, and the results are shown in fig. 4. Fig. 4a shows the T_{twt} of 30 randomly generated ships under Case 1 by the four methods. It is evident that the proposed OSS-SW method achieves the best results.

The CPU time of the 100 independent experiments implemented by the aforementioned methods were compared in fig. 4b. It is evident that OSS-SW method requires less computing time than the OSS only method due to the introduction of the sliding window strategy which divides the whole optimization problem into several subproblems. Since fewer ships were considered in each subproblem, the computational burden is significantly reduced than solving the entire problem without using the sliding window strategy even though a number of subproblems are to be solved. Furthermore, the search space in each subproblem is smaller. Thus the OSS-SW algorithm has a better chance to search the best solution. Generally speaking, for the restricted waterway traffic management, it is unlikely to arrange a very late ship to pass through the restricted waterway very early and vice versa. Thus, the use of the sliding window will not affect the capability of finding the the global optimal solution but it can significantly reduce the computation time

More experiments were conducted to fully investigate the performance of the proposed OSS-SW method under

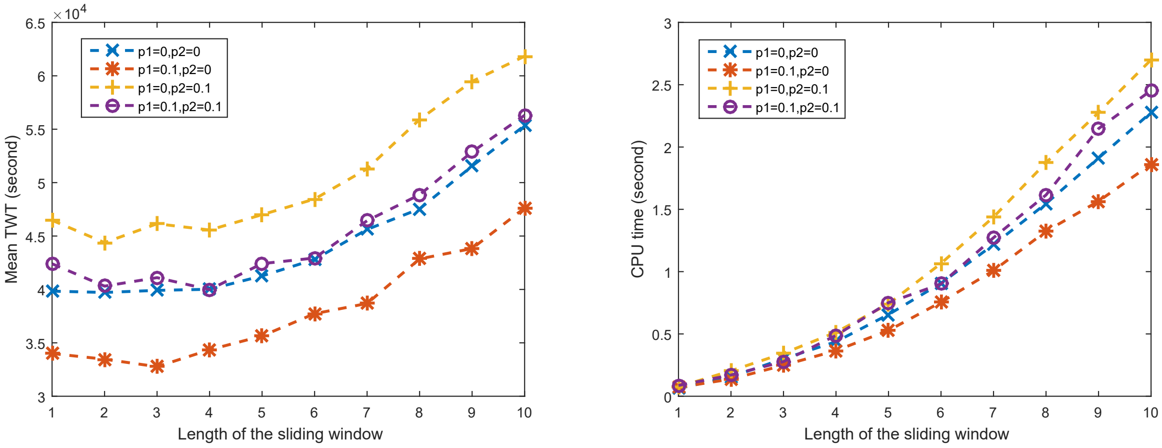
Table 3
Sequenceing and scheduling results (in seconds) of 30 ships under different algorithm.

Original Sequence				TSRS				FAHP-ES				OSS				OSS-SW			
ID	Direction	t_{PAT}	t_{PCT}	ID	t_{ATT}	t_{ACT}	WT	ID	t_{ATT}	t_{ACT}	WT	ID	t_{ATT}	t_{ACT}	WT	ID	t_{ATT}	t_{ACT}	WT
1	downstream	91	1536	1	91	1536	0	1	91	1536	0	1	91	1536	0	1	91	1536	0
2	upstream	319	580	2	1687	580	1368	5	778	1455	1334	5	778	1455	1334	5	778	1455	1334
3	upstream	552	444	3	1747	580	1331	6	863	1430	1297	6	863	1430	1297	6	863	1430	1297
4	upstream	760	431	4	1807	580	1196	7	986	1367	1162	7	986	1367	1162	7	986	1367	1162
5	downstream	778	1455	5	2447	1455	1669	8	1080	1382	229	8	1080	1382	229	8	1080	1382	229
6	downstream	863	1208	6	2507	1455	1891	15	1776	866	571	15	1776	866	571	15	1776	866	571
7	downstream	986	723	7	2567	1455	2313	16	2117	585	993	16	2117	585	993	16	2117	585	993
8	downstream	1080	1382	8	2627	1455	1620	17	2177	602	317	17	2177	585	317	17	2177	602	317
9	upstream	1134	267	9	4142	267	3008	19	2288	1111	1998	19	2288	1111	1998	19	2288	1111	1998
10	upstream	1319	361	10	4202	361	2883	20	2353	1106	1779	20	2353	1106	1779	20	2353	1106	1779
11	upstream	1407	589	11	4262	589	2855	21	2413	1160	1577	21	2413	1106	1577	21	2413	1160	1577
12	upstream	1465	481	12	4322	589	2965	22	2473	1775	2302	22	2473	1775	2302	22	2473	1775	2302
13	upstream	1558	750	13	4382	750	2824	23	2533	1775	2000	23	2533	1775	2000	23	2533	1775	2000
14	upstream	1617	454	14	4442	750	3121	24	2784	1584	2297	24	2784	1584	2297	24	2784	1524	2237
15	downstream	1776	866	15	5252	866	3476	26	2953	1475	1786	26	2953	1475	1786	26	2953	1415	1726
16	downstream	2117	178	16	5312	866	3883	27	3209	1279	2193	27	3209	1279	2193	27	3209	1219	2133
17	downstream	2160	402	17	5372	866	3676	28	3367	1181	1986	28	3367	1181	1986	28	3367	1121	1926
18	upstream	2180	432	18	6298	432	4118	30	3496	1663	2547	30	3496	1663	2547	30	3496	1663	2547
19	downstream	2288	1111	19	6790	1111	4502	2	5219	580	2400	2	5159	580	2400	9	5159	267	2027
20	downstream	2353	88	20	6850	1111	5520	3	5279	580	3418	3	5219	580	3418	10	5219	361	3139
21	downstream	2359	601	21	6910	1111	5061	4	5339	580	2959	4	5279	580	2959	4	5279	431	2750
22	downstream	2461	1775	22	6970	1775	4509	9	5399	580	1743	9	5339	580	1743	18	5339	432	1535
23	downstream	2521	771	23	7030	1775	5513	10	5459	580	2747	10	5399	580	2747	3	5399	444	2551
24	downstream	2784	493	24	7090	1775	5588	11	5519	589	2831	11	5459	589	2831	11	5159	684	2566
25	upstream	2849	1731	25	8925	1731	6076	12	5579	589	1588	12	5519	589	1588	12	5219	684	1323
26	downstream	2953	429	26	10716	429	7763	13	5639	750	3007	13	5579	750	3007	14	5279	684	2581
27	downstream	3209	349	27	10776	429	7647	14	5699	750	2891	14	5639	750	2891	2	5339	684	2465
28	downstream	3367	781	28	10836	781	7469	18	5759	750	2361	18	5699	750	2361	13	5399	750	2001
29	upstream	3443	1487	29	11677	1487	8234	25	5819	1731	2620	25	5759	1731	2620	29	5459	1487	2016
30	downstream	3496	1663	30	13224	1663	9728	29	5879	1731	2451	29	5819	1731	2451	25	5159	1787	1787
				T_{twt}=121807				T_{twt}=57384				T_{twt}=56593				T_{twt}=52869			

different uncertainties in real applications, i.e. ships suddenly docked before entering the restricted waterways or suddenly turned on the AIS device outside the restricted waterways. The influence of sliding window settings on its performance was also studied. As mentioned earlier, $p1$ and $p2$ denote the percentage of docked ships and suddenly appeared ships respectively. In real applications, whether a ship is to be docked or suddenly appeared is unknown until the ship is very close to the restricted waterway. In the following studies, to emulate the real conditions, this information is updated 10 minutes before the ships arrive at the restricted waterway. For example, if the t_{PAT} of a ship is 1000s and the ship is about to dock, this ship can only be removed from the original ship sequence after time 400s. If a ship suddenly appears and its predicted arrival time t_{PAT} is 1500s, this ship's information can only be considered after time 900s. In Monte Carlo simulations, 100 independent experiments were performed, and the mean results are shown in figs. 5 - 7. Each curve stands for the mean results of the T_{twt} and CPU time of 100 independent experiments under different sliding window length N_{sw} which varies from 1 to 10. Figs. 5 - 7 illustrate the results under different congestion level of the restricted waterway, i.e., different setting of t_{rangeA}, ($t_{rangeA} = 3600s, 7200s, 10800s$). Four different line styles are used to distinguish different uncertainties of the ships, i.e., different combinations of $p1$ and $p2$.

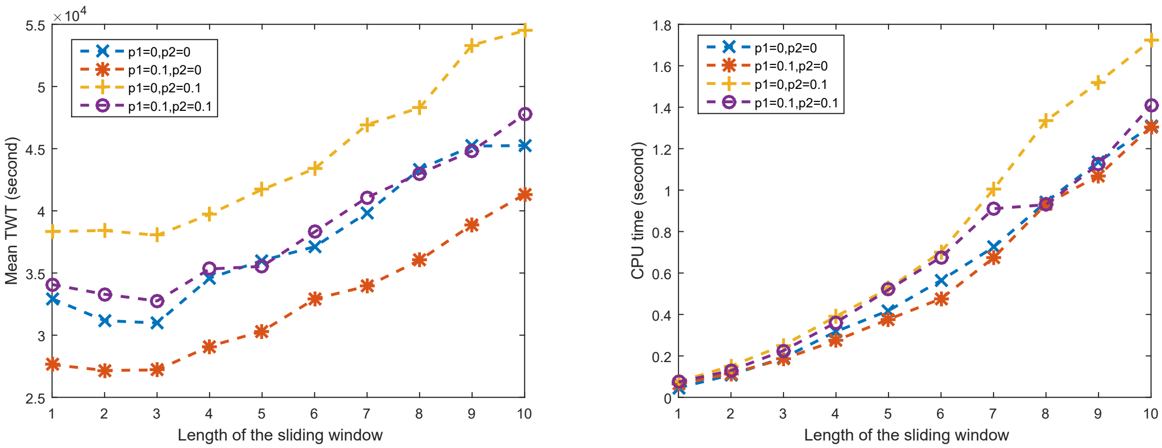
From the Monte Carlo simulation results displayed in figs. 5- 7, the following conclusions can be drawn on the proposed OSS-SW method for the ship sequencing and scheduling problem:

1) It is clear that T_{twt} increases along with the congestion degree in all cases. Fig. 5a shows that T_{twt} of the most congested cases where all 30 ships were randomly allocated t_{PAT} within 3600s, the mean T_{twt} is around 40000s when the length of the sliding window N_{sw} is set to 2 and $p1$ and $p2$ are set to 0. By contrast, fig. 7a shows the mean T_{twt} of the least congested cases where the ships are randomly allocated with t_{PAT} within 10800s. The mean T_{twt} is around



(a) The T_{twt} (in seconds) of the ships. (b) The CPU times (the seconds) of the experiments.

Figure 5: The influence of the length of the sliding window on the performance of the proposed OSS-SW algorithm under different uncertain degree, $T_{rangeA} = 3600s$.

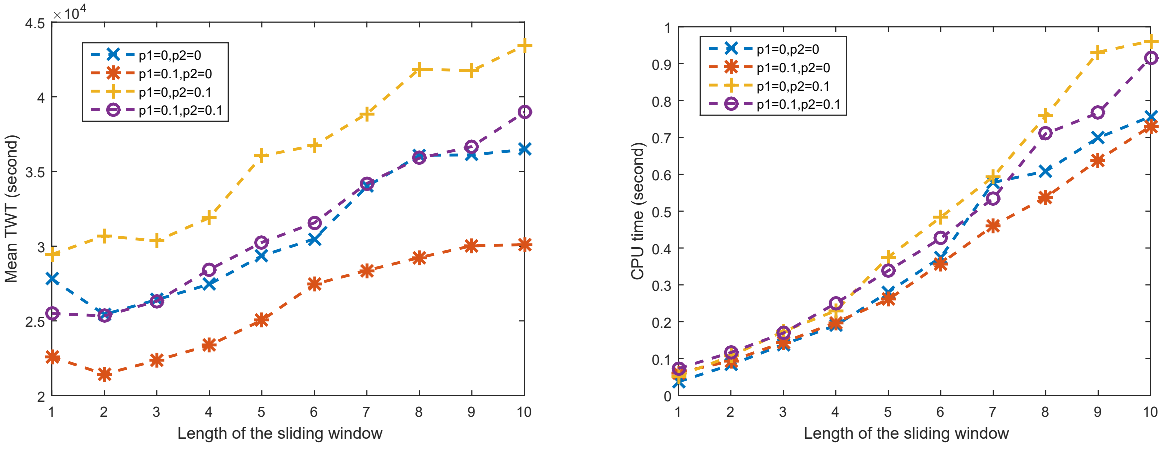


(a) The T_{twt} (in seconds) of the ships. (b) The CPU times (the seconds) of the experiments.

Figure 6: The influence of the length of the sliding window on the performance of the proposed OSS-SW algorithm under different uncertain degree, $T_{rangeA} = 7200s$.

25000s when N_{sw} is 2 and $p1$ and $p2$ are set to 0. This is due to the fact that the traffic capacity of a restricted waterway is limited, a large number of ships cannot pass through the restricted waterway in a short time, thus, more congestion often lead to larger T_{twt}.

2) The proposed OSS-SW algorithm can handle uncertainties better. As shown in fig. 5a to fig. 7a , the cases with $\{p1 = 0, p2 = 0.1\}$ require the longest T_{twt} while cases with $\{p1 = 0.1, p2 = 0\}$ require the least T_{twt} under all congestion conditions. The result does not imply that the proposed OSS-SW cannot deal with the congested situations very well. The underlying reason for different results is that in cases $\{p1 = 0, p2 = 0.1\}$, 33 ships (3 more ships have been added to the sequence) are counted for the T_{twt} while in cases $\{p1 = 0.1, p2 = 0\}$, only 27 ships (3 ships have docked before entering the restricted waterways) are included. While 30 ships are counted for T_{twt} in case $\{p1 = 0, p2 = 0\}$ and $\{p1 = 0.1, p2 = 0.1\}$. Table 4 reveals the average waiting time of a single ship under the four uncertainty scenarios with N_{sw} varies from 1 to 10. It is clear that the mean waiting time of a single ship is almost the same under different uncertainties, i.e., under the same length of the sliding window and same congestion condition. The length of the sliding window has a major impact on the performance of the proposed method for the



(a) The T_{twt} (in seconds) of the ships.

(b) The CPU times (the seconds) of the experiments.

Figure 7: The influence of the length of the sliding window on the performance of the proposed OSS-SW algorithm under different uncertain degree, $T_{rangeA} = 10800s$.

Table 4
The mean waiting time (in seconds) of a single ship in different congestion degrees and different uncertainties under different sliding window length

	N_{sw}	1	2	3	4	5	6	7	8	9	10
$T_{rangeA} = 3600s$	p1=0;p2=0	1328	**1324**	1330	1334	1375	1427	1520	1585	1718	1845
	p1=0.1;p2=0	1260	1240	**1214**	1272	1320	1397	1433	1588	1623	1764
	p1=0;p2=0.1	1408	1345	1398	**1381**	1424	1468	1554	1694	1825	1873
	p1=0.1;p2=0.1	1413	1344	1370	**1333**	1414	1431	1548	1629	1763	1877
$T_{rangeA} = 7200s$	p1=0;p2=0	1098	1039	**1033**	1153	1199	1237	1328	1445	1507	1509
	p1=0.1;p2=0	1023	**1006**	1008	1078	1123	1219	1257	1334	1441	1531
	p1=0;p2=0.1	1162	1164	**1153**	1204	1264	1314	1422	1463	1616	1651
	p1=0.1;p2=0.1	1136	1110	**1092**	1189	1184	1277	1370	1433	1494	1592
$T_{rangeA} = 10800s$	p1=0;p2=0	927	**848**	881	915	978	1016	1133	1202	1204	1216
	p1=0.1;p2=0	836	**794**	828	865	927	1017	1051	1083	1112	1115
	p1=0;p2=0.1	**892**	930	919	967	1092	1113	1178	1268	1265	1316
	p1=0.1;p2=0.1	850	**845**	877	948	1008	1052	1140	1196	1222	1299

*The minimum mean waiting time of a single ship under each case is marked in bold.

ship sequencing and scheduling problem. In summary, if N_{sw} is too small, the algorithm has little information to explore. If N_{sw} is too large, ships far away will be counted, thus bringing many uncertainties into the scheduling. On the other hand, too much information taken into consideration will lead to heavy computational burden. Figs. 5 - 7 confirm that the proposed OSS-SW yields the best performance when sliding window length is 2 or 3 for all scenarios.

3) As expected, the computing time increases along with the number of schedule windows N_{sw} in the sliding window. The reason is that during the optimization process of the proposed OSS-SW, ships with t_{PAT} larger than $t_0+(k-1)\times T_{int}$ and smaller than $t_0+(k-1)\times T_{int}+N_{sw}\times T_{int}$ are included for optimization, larger N_{sw} implies that more ships are analyzed in each step, thus longer computing time is required. However, the schedule window length remains the same, i.e., T_{int} is a constant, and the total number of the optimization steps remains the same. Therefore, the computational burden of the algorithm would increase along with the length of the sliding window. Figs. 5 - 7 also reveal that more computation effort is needed in more congested situations. This is due to the fact that more ships within a sliding window requires more computation time to ensure safety and efficiency. Besides, Figs. 5 - 7 also reveal that the CPU times of the proposed OSS-SW algorithm under different uncertain degrees, i.e., different combinations of $p1$ and $p2$, are almost the same. The reason for the slight difference in CPU time is due to the different number of ships in cases.

Table 5
Real data test in Shenbeizui restricted waterway.

Original Sequence			TSRS			OSS-SW		
ID	t_{PAT}	t_{PCT}	ID	t_{ATT}	t_{ACT}	ID	t_{ATT}	t_{ACT}
1	0	869	1	0	869	1	0	869
2	349	563	2	869	563	3	632	630
3	632	630	3	1432	630	2	1262	563
4	697	1698	4	1432	1698	7	1368	457
5	951	1231	5	1432	1698	6	1825	739
6	1087	739	6	1432	1698	4	1825	1698
7	1368	429	7	3130	429	5	1825	1698
8	1592	483	8	3130	483	9	1825	1698
9	1785	1362	9	3613	1362	8	3523	483
10	1963	1286	10	3613	1362	10	4006	1560
T_{twt}			11161s			8772s		

*Ships 2, 7, 8 are downstream, the others are upstream ships.

A real data test was also conducted for the Shenbeizui restricted waterway on 12th December, 2020. Ten ships were considered in the test. The prediction error was ignored by replacing the t_{PAT} with the true arriving time. The results listed in table 5 also confirmed that the proposed OSS-SW method outperforms the current TSRS method in minimizing the T_{twt}. This confirms the potential of the proposed OSS-SW method in efficiently managing the sequencing and scheduling problem to enhance the Yangtze River traffic capacity.

5. Conclusion

This paper has proposed a novel OSS-SW method for the traffic management of restricted waterways alone the Yangtze River. By incorporating the sliding window scheme, the problem is transformed into several subproblems. Each subproblem is then solved within a sliding window by the proposed OSS method. With the aid of the sliding window scheme, the computational burden was significantly reduced, and a better solution can be achieved under different uncertain scenarios. To validate the effectiveness and efficiency of the proposed method, 100 independent experiments were carried out. The performance of the proposed OSS-SW method and OSS only method were first compared with two other popular ship scheduling methods: TSRS method and FAHP-ES method. The results have confirmed that both the OSS-SW method and the OSS only method achieved similar performance which is better than FAHP-ES method and TSRS method. By analysing the resultant ship sequences, it is clear that OSS-SW method and OSS only method could obtain an optimal sequence for both upstream and downstream ships. Moreover, the proposed OSS-SW algorithm dramatically reduced the computational burden compared with the OSS method. Secondly, the Monte Carlo simulation was conducted to thoroughly examine the performance of the proposed OSS-SW method under different scenarios and different parameter settings. The results have confirmed that the proposed OSS-SW could handle well with the ship sequencing and scheduling problem under different uncertainties, and the sliding window with 2 to 4 schedule windows was sufficient for the restricted waterway traffic management. Additionally, larger T_{twt} values were observed in more congested situations.

Since the ship sequencing and scheduling problem is NP-hard, and hundreds of thousands of ships move along the Yangtze River every day, it is difficult to obtain the global best solution. However, due to the smaller computational cost of the sliding window scheme, it is possible to develop a more effective online optimisation method in the future for the ship sequencing and scheduling problem, and thus improve the capacity of inland waterways such as Yangtze River.

6. Acknowledgements

The authors would like to acknowledge financial support from the National Science Foundation of China (Grant No. 62003011).

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