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Key influencing factors on improving the waterway through capacity of coastal ports

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A R T I C L E I N F O

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A B S T R A C T

This paper aims at solving the problems of how to improve the waterway through capacity and how much each influencing factor can improve the capacity quantitatively. The problems are figured out by building a simulation model of the ships' navigation operation system. First of all, the definition of waterway through capacity and the elements of the ships' navigation operation system are discussed comprehensively. Then, a complicated simulation model, which considers the influencing factors, such as rules of ships entering and leaving port, navigation rules and inner anchorage scales, is constructed. After that, the simulation model is verified to ensure its reliability and effectiveness. Finally, various simulation experiments are designed according to a real bulk cargo port area in China and how much each influencing factor can improve the waterway through capacity is obtained, which provides a theoretical foundation for waterway construction and port management.

1. Introduction

The waterway, which is the way for ships' entering and leaving a port, is one of the most important part of the port. With the continuous increase of ship traffic volumes, the waterway is becoming the bottleneck of port development. For example, Yangshan Port expands the waterway to a two-way traffic waterway in 2013, since the waterway restricts the development of the port with the increment of the throughput (about 14.15 million TEUs) and the number of ships (about 100 international liner ships per week). However, due to the high cost of construction and dredging for the waterway, it's mostly uneconomical or even impractical to build a new waterway or expand an existing waterway to a two-way traffic waterway. Therefore, it has generated considerable attention on how to improve the waterway through capacity in respect of management without expanding the waterway these years, which is the problem we concern in this paper.

For improving seaport waterway through capacity, Ning et al. (2008) proposed the tentative construction standard of the two-way traffic channel and tried to see if it can improve the waterway capacity. Later, my group did a lot of work on how to improve the waterway capacity. For example, Guo et al. (2010) and Wang et al. (2015) gave the definition of seaport waterway through capacity and analysed the influence of port service level or safety level on waterway through capacity, respectively; Wang et al. (2012) studied the impact of three types of ship traffic rules on port service level in Y-type waterway intersection water, which included First Come First Serve Rule, Larger Ship Priority Rule and Ship Leaving Port Priority Rule; Wang et al. (2013a) and Wang et al. (2013b) studied the influence of anchorage number or operation days on waterway capacity in coastal bulk cargo port area, respectively; Tang et al. (2014a) chose the annual average turnaround time, average waiting time, and average waiting time/average service time ratio as the performance measures of port service to explore the feasibility of building a ships-passing anchorage and its dimensions; Tang et al. (2014b) discussed the optimal channel dimensions problem with limited dredging budget constraints in an integrated way; Tang et al. (2016) explored the relationship between entrance channel dimension and berth occupancy of container terminals. Besides, Lin et al. (2014) developed a mathematical model to minimize the weight of ship's waiting time for the channel and applied Genetic Algorithm to solve the model; Zhang et al. (2016) aimed at improving the efficiency of vessel transportation scheduling by coordinating channels and berths, and used the simulated annealing and multiple population genetic algorithm to solve the proposed model; Liu et al. (2016) proposed dynamic ship domain model that take into consideration navigation waterway condition, ship behaviors, ship types and sizes and operators' skill, to estimate the capacity of restricted water channels.

The above literatures involve various aspects of the research on promotion measures of waterway through capacity, which provide a strong foundation for further studies. However, the research mostly considers one aspect of the promotion measure of waterway through

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capacity. Some of them only discuss the problem from qualitative analysis angle and lack the quantitative study on promotion measures of waterway through capacity, which are not suitable for being used to solve the proposed problems in this paper directly.

Besides, due to the complexity and randomness of the seaport operation system, there are so many random factors, which include arriving time of ships, inclement weather conditions, unload time of ships and so on, having impact on system working, numerical methods fail to obtain analytical solutions (Clausen and Kaffka, 2016). And because of the advantages on dealing with such complex systems, simulation technology has been generally applied in port design and management these years (Longo et al., 2013).

Sun et al. (2012) introduced a general simulation platform, named MicroPort, which aimed to provide an integrated and flexible modeling system for evaluating the operational capability and efficiency of different designs of seaport container terminals; Longo et al. (2013) developed a simulation model to recreate the complexity of a medium-sized Mediterranean seaport and analyse the performance evolution of such system with particular reference to the ship turnaround time; Kavakeb et al. (2015) studied the impact of using a new intelligent vehicle technology on the performance and total cost of a European port compared with existing vehicle systems by simulation technology; Petering (2015) analysed how the overall productivity of an RTG-based seaport container terminal depended on the system used for automatically selecting storage locations for export containers in real time as they enter the terminal by a fully-integrated discrete event simulation model; Zhao et al. (2015) proposed a simulation-based optimization method for the storage allocation problem of outbound containers in automated container terminals; (Clausen and Kaffka, 2016) used simulation method to optimize the operations in an overall system with all its stochastic influence and interactions, which may create an experimental model and identify the best recommended course of action; Ngoc et al. (2016) developed a method to optimize the time slot assignment for individual trucks by discrete event simulation, aiming at minimizing total emissions from trucks and cranes at import yards; Peng et al. (2016) modeled the energy replacement problem with the purpose of minimizing the carbon emissions by combining an allocation resource mathematical model and a simulation model of the whole transportation network together, to solve the problem of allocating limited resources for yard cranes; Zhou et al. (2016) proposed a simulation-based optimization framework to obtain a cost-effective and reliable design solution to the physical layout and equipment deployment strategy of the yard at a mega container terminal.

The above research shows the superiority of simulation method in analyzing complex systems design, management and monitoring, which also provides important references for the problem proposed in this paper.

Based on the analysis of the elements of ships' navigation operation system comprehensively, this paper studies the influencing factors on improving the waterway through capacity in respect of management without expanding the waterway, which can provide theoretical basis for port plan and management. Therefore, in the rest of the paper, we first describe some terms including seaport waterway through capacity and its several influencing factors in Section 2. After that, a simulation model of the ships' navigation operation system is constructed and verified in Section 3. Numerous simulation experiments and analysis are carried out in Section 4 to study the influences of rules of ships entering and leaving port, navigation rules and inner anchorage scales on waterway through capacity, respectively. Finally we conclude the paper in Section 5.

2. Term explanations

In this section, we first introduce the definition of the seaport waterway through capacity, and then the key influencing factors are discussed in detail in Section 2.2.

2.1. Seaport waterway through capacity

Since seaport waterway through capacity is affected not only by the natural conditions, waterway dimensions, navigation rules, etc., but also by handling operations and port management, which is not easy to define. Thus, although many researchers have proposed kinds of different definitions of seaport through capacity, none of them has become standardization. Refer to *Design Code of General Layout for Sea Port,* the definition of seaport waterway through capacity we choose in this paper is relatively accepted, which defines seaport waterway capacity for a given waterway of a certain seaport under normal operating status as the total annual tonnage of ships going through it at a specified port service level (Guo et al., 2010).

Waterway through capacity, which is a characterization of ultimate carrying capacity of waterway, should reflect the service quality of the waterway for ships. According to *Port Development: a Hand Book for Planners in Developing Countries* (United Nations, 1985), we introduce *AWT/AST* as the evaluation indicator of port service level in this paper. *AWT* refers to ships' average waiting time including the time waiting for both waterway and berth, and *AST* is the average service time of ships at berth. The smaller the value of *AWT/AST* is, the higher the port service level is.

2.2. Key influencing factors of waterway through capacity

There are plenty of factors affecting the waterway through capacity, we mainly analyse three key aspects in the field of port management, which are rules of ships entering and leaving port, navigation rules of ships going through waterway and the scale of inner anchorage.

2.2.1. Rules of ships entering and leaving port

Rules of ships entering and leaving port refer to that arrival ships should report ships' status to Vessel Movement Center (*VMC*) at a specific time and place based on the requirements of a port, so that *VMC* can determine the sequence and organization of ships before the ships are going to pass the waterway according to certain rules, in which the certain rules are called the rules of ships entering and leaving port.

On the one hand, when the quantity of arrival ships is relatively large, ships need to wait for berth or waterway in queue, which may lead to congestion and bring great economic losses. One the other hand, it can make ships pass the waterway more efficiently and safely when the ships obey proper rules entering and leaving port, which may improve waterway through capacity at the same time. Therefore, it's vital to choose rational rules of ships entering and leaving port.

According to the investigation of the rules of ships entering and leaving port used in main port areas, the rules considered in this paper are expressed as follows.

a) First Come, First Service (*FCFS*) Rule

   Ships enter the waterway based on the sequence of the ships' arriving time at the port area.

   FCFS rule reflects the equity of different ships and treats all ships without difference. Since *FCFS* rule is one of the most common rules and easy to realize, it's treated as the basic rule of ships entering and leaving port in this paper.

b) Large-ton-Ship First Service (*LSFS*) Rule

   The priorities of ships with large tonnage are higher than smaller ones. When ships with different tonnage arrive the port area simultaneously, large ships enter the waterway prior to small ships. Ships with same tonnage still obey *FCFS* rule.

   In actual situation, the costs caused by waiting for berth or waterway of large ships are more than those of small ships, thus many ports adopt *LSFS* rule because of the similar quantities of large ships and small ships arriving the port area.

c) Ships Entering and Leaving port in Cluster (*SELC*) Rule

During a ship waits for entering the waterway, if there are other ships arriving the port area after that, these ships can make up as a group based on the sequence of arriving the port area to enter the waterway in cluster. Otherwise, the ship may enter the waterway alone.

SELC rule is usually used in inland waterway. The major advantages of *SELC* rule are large freight volumes and low transport prices per ship. Refer to the formation form of ships in inland waterway, we introduce *SELC* rule to seaport waterway, aiming at improving the waterway through capacity.

d) Riding-tide-Ship First Service (*RSFS*) Rule

The ships which need to go through the waterway with the tide (For a large ship, whose depth of water is not enough) have higher priorities. When these ships and those don't need to take the tide satisfy the navigation requirements at the same time, the former enters the waterway prior to the latter. Besides, ships with same priority still obey *FCFS* rule.

The ships which need to take the tide have rigid requirements on tidal level and navigation duration per tidal period. Therefore, once these ships miss the best moment of taking the tide, they have to wait for another tidal period to satisfy the tidal level, which will greatly increase ships' waiting time and reduce port service level. To decrease the probability of such problems' occurrence, the port can adopt *RSFS* rule for ships.

e) Unloaded Ship Navigation Faster (*USNF*) Rule

In general, the navigation speed of unloaded ships is increased by 25%, so the unloaded ships can pass the waterway faster.

The ships usually enter ports full and leave empty in import port area while on the contrary in export port area. Therefore, the port can increase the navigation speed of unloaded ships to reduce ships' leaving time in import port area and ships' entering time in export port area. In that case, the port can adopt *USNF* rule.

2.2.2. Navigation rules of ships going through waterway

Navigation rules of ships going through waterway are the rules which mainly focus on the navigation of ships in opposite directions, including *one-way navigation* rule, *two-way navigation* rule and *partial two-way navigation* rule.

a) *One-way navigation* Rule

It refers to that all the ships in opposite directions are not allowed to sail in the waterway at the same time. For *one-way navigation* rule, it is easy to implement with highly security, and it is the most common navigation rule in port area.

b) *Two-way navigation* Rule

While under *two-way navigation* rule, since the waterway is wide enough, two largest arrival ships in opposite directions can sail in the waterway simultaneously and they won't bother each other. However, *two-way navigation* rule requires sufficient width of the waterway, the port may need to expand the waterway to meet the requirement, which does not serve the scope of discussion in this paper. In the paper, we only focus on the field of port management without expanding the waterway to improve the waterway through capacity.

c) *Partial two-way navigation* Rule

Partial two-way navigation rule is the synthesis of the two above rules. For given waterway, if two ships in opposite directions can meet the navigation requirements, they adopt *two-way navigation* rule. Otherwise, *one-way navigation* rule is used. Comparing with *one-way navigation* rule, *partial two-way navigation* rule can reduce small ships' waiting time obviously. Therefore, *partial two-way navigation* rule has superiority in the port area with a large number of small ships arriving.

2.2.3. The scale of inner anchorage

The anchorage provides anchor area and the handling operation place for arrival ships. It is the site where ships wait for operation, transit and transfer, as well as ships' marshalling and disassembly. The anchorage can be divided into inner anchorage and roadstead, which are seated in and out of breakwater, respectively.

The function of inner anchorage is used for anchoring ships when there's no correspondingly spare berth but the waterway is unoccupied. Ships can choose to wait for berth in inner anchorage, so that the utilization ratios of the waterway and berth can be increased, and ships' waiting time in the port can be reduced correspondingly. In this paper, the impact of water depth and capacity of the inner anchorage on waterway through capacity are analysed.

To sum up, we conclude the key influencing factors of waterway through capacity in Table 1 to make it clearer.

Table 1
The summary of influencing factors of waterway through capacity.

Influencing factors	Inclusions	Terms
Rules of ships entering and leaving port	*First-Come, First-Service* rule	*FCFS* rule
	Large-ton-Ship First Service rule	*LSFS* rule
	Ships Entering and Leaving port in Cluster rule	*SELC* rule
	Riding-tide-Ship First Service rule	*RSFS* rule
	Unloaded Ship Navigation Faster rule	*USNF* rule
Navigation rules of ships going through waterway	*One-way navigation* rule	–
	Two-way navigation rule	–
	Partial two-way navigation rule	–
The scale of inner anchorage	Water depth	–
	Inner anchorage capacity	–

3. Simulation model

3.1. Model assumptions

Considering the factors such as the ships, the natural conditions, the berth conditions, the channel dimensions and the inner anchorage scales, this paper constructs the simulation model for ships' navigation operation system based on the following assumptions: a) The port area is under normal operation status and the resources are taken full use of; b) The number of anchorage berths in the port area are enough, which can well provide service for ships waiting for the waterway and berths; c) Ships maintain good technical conditions and keep a safe distance between each other, the running of which is noninterference.

3.2. Model establishment

According to the whole process of the ships' sailing, we first propose the logic model of the ships' navigation operation system, as shown in Fig. 1.

This logic model corresponds to the basic situation, which refers to the situation with the *FCFS* rule of ships entering and leaving port, with *one-way navigation* rule and without building inner anchorages. As for the differences between situations under other rules and the basic one, it will be explained in detail below.

Once the logic model is determined, the simulation model can be constructed, which includes four parts: *waiting for berth at roadstead* sub-process, *entering the port area* sub-process, *handling operation* sub-process and *departing the port area* sub-process.

3.2.1. Waiting for berth at roadstead sub-process

This sub-process begins with ships arriving the port area and ends up with ships being allocated an idle berth. All these processes are completed at the roadstead. In the simulation model, it is achieved by

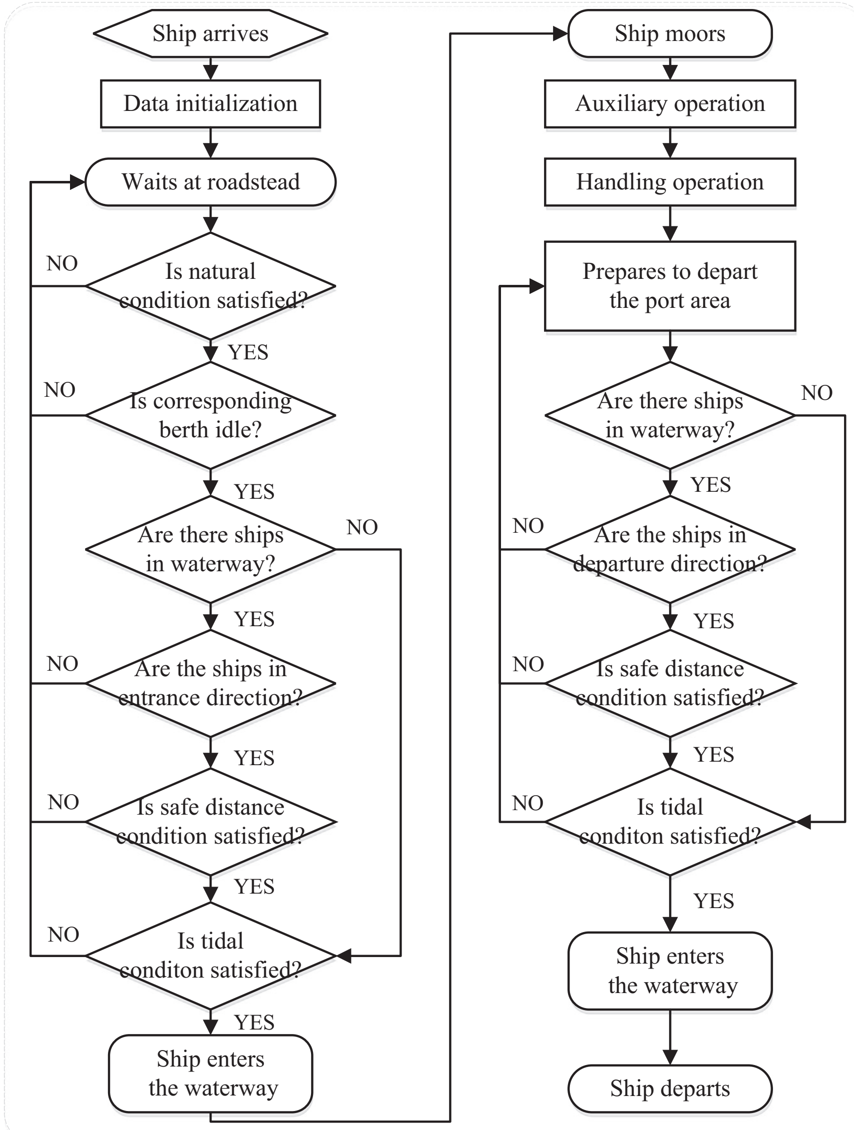

Fig. 1. The logic model of the ships' navigation operation system.

Create sub-model and *Choose berth* sub-model. The interfaces of the two sub-models are shown in Figs. 2 and 3, respectively.

a) *Create* Sub-model
Firstly, the ship entities are created by *Create* modules with a certain interval. Then, *Assign* modules are used for the ships' property assignment, including tonnage, handling operation time and arrival time of ships. Next, a *Decide* module determines whether the weather conditions meet the requirement for entering the port of ships. If the weather conditions are unsatisfactory, some ships will disappear through a *Dispose* module which means these ships will abandon docking and leave the port, while other ships will wait in a *Hold* module. Once the weather conditions are satisfied, the ships move into a *VBA* module to record the number of arrival ships. Finally, ships enter the *Choose berth* sub-model to refer berths.

b) *Choose berth* Sub-model
A *Decide* module is used to determine the tonnage of ships at first. For ships with different tonnage, the requirements of berth resources as well as water depths of inner anchorage are not same. When the corresponding berths are free, ships use *Seize* modules to refer berths. However, if all the corresponding berths are occupied, ships will judge whether there are available inner anchorage resources. If so, a *Seize* module will be used to occupy inner anchorage resources, which won't be released until the ships finish referring berths. Besides, if corresponding berth resources and inner anchorage resources are all occupied, the ships will wait in the roadstead until one of the resources is free. An *Assign* module is used to record ships' waiting time for berths and the time to start occupying berths in the end.

3.2.2. *Entering the port area Sub-process*

Entering the port area sub-process includes the processes of deciding whether the tidal condition, navigation condition and safe-time distance condition are satisfied and ships entering the waterway, which is achieved by *In_waterway* sub-models in simulation model, as shown in Fig. 4. In *Entering the port area* sub-process, rules of ships entering and leaving port are decided, so that ships can enter the *In_waterway* sub-models corresponding to the rules, which will be described in detail as follows.

a) *FCFS* Rule: *FCFS in_waterway* sub-model is shown in Fig. 5. Firstly, an *Assign* module is used to calculate the navigation duration per tidal period. Then, the tide-bound water level of the

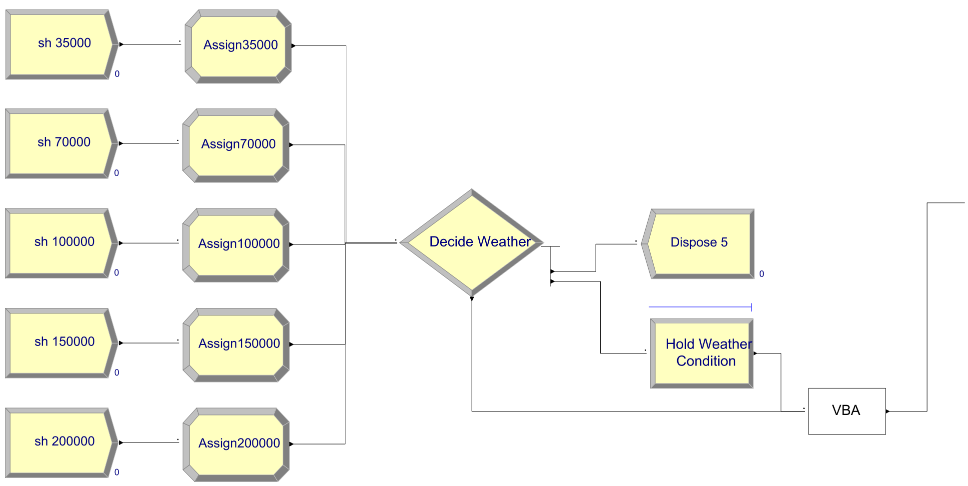

Fig. 2. Interface of *Create* sub-model.

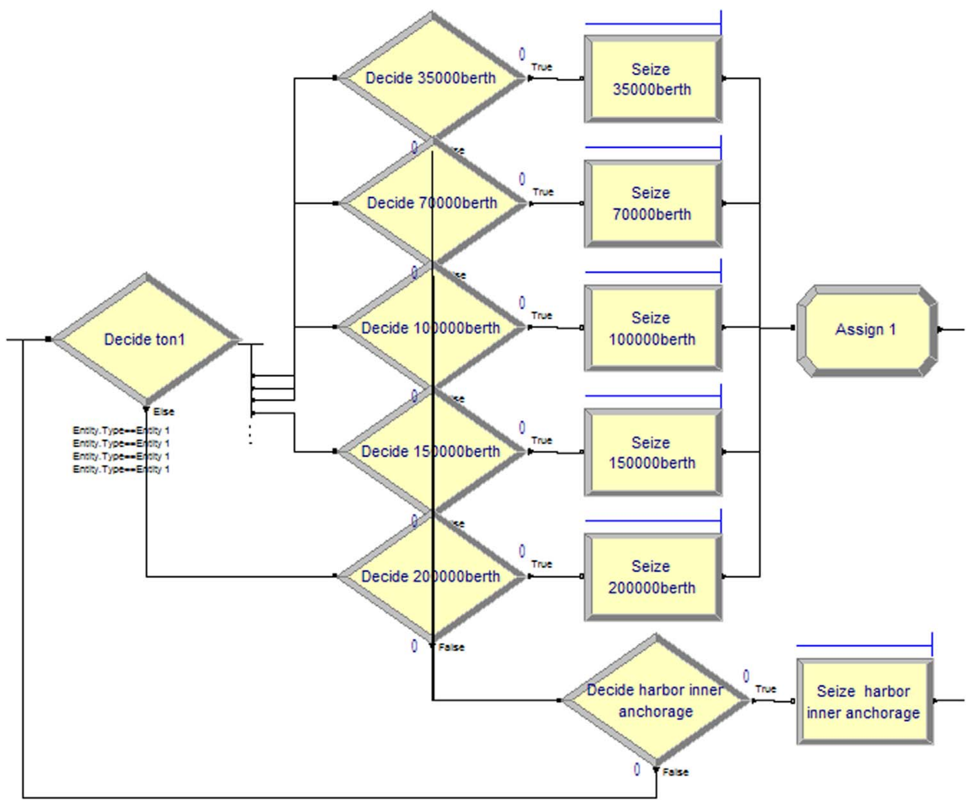

Fig. 3. Interface of *Choose berth* sub-model.

ships with largest tonnage can be determined according to the cumulative time of high tide level. Combining with draft of different ships, not only the tide-bound water level of all ships, but also the time t_1(or t_2) when the tidal level over (or below) the tide-bound water level of ship every flood tide (or ebb tide) can be calculated. Next, a *VBA* module is used to assign different priorities to the ships which need to take the tide or not. After that, whether the navigation conditions meet the requirement are determined by a series of *Decide* modules and *Hold* modules, including which kind of navigation rules are used, whether there are ships leaving the port, whether the number of ships waiting for departing exceed a certain range and whether the tidal level are satisfied for ships that need to take the tide. Once the navigation conditions are met, the waterway can be seized by using a *Seize* module. However, the trailing time intervals between ships in the waterway could also be limited into a safe range. Finally, an *Assign* module is used to record the current time, ships' waiting time for waterway and the total number of ships passing the waterway in entrance direction. A *Release* module and a *Route* module are used to release the roadstead resources and enter the waterway.

b) *LSFS* Rule: The interface of *LSFS* in_*waterway* sub-model is the same as that of FCFS in_waterway sub-model, which is shown in Fig. 5. The difference between the two sub-model is that the order of all ships waiting in queues are based on the tonnage of ships in *LSFS* in_*waterway* sub-model, ships with large tonnage prior to the smaller ones.

c) *SELC* (2, 3, 4) Rules: During a ship waits for entering the waterway, if there isn't other ships arriving the port area after that, the ship enters the waterway alone. Otherwise, these ships can make up as a group based on the sequence of arriving the port area to enter the

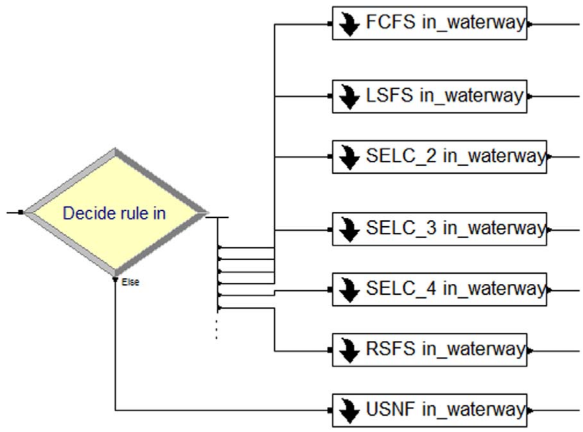

Fig. 4. Interface of *In_waterway* sub-model.

waterway in cluster by using a *Batch* module, the group represents as a temporary entity which has all the attributes of the largest ship in the group. Considering the number of ships in cluster may vary in different port areas and affect waterway through capacity, this paper simulates the situation under *SELC* rules with two ships, three ships or four ships in cluster.

d) *RSFS* Rule: The interface of *RSFS in_waterway* sub-model is the same as that of *FCFS in_waterway* sub-model, which is shown in Fig. 5. The distinction of the *RSFS in_waterway* sub-model is that after deciding the navigation conditions, the queuing order of the *Seize storage* in module should be set that large ships prior to small ships in the simulation model, considering the situation that navigation conditions are satisfied for ships which need to take the tide and don't simultaneously. So that the ships which need to take the tide can enter the waterway preferentially.

e) *USNF* Rule: The *USNF in_waterway* sub-model has no difference with *FCFS in_waterway* sub-model, as shown in Fig. 5.

3.2.3. Handling operation Sub-process

Handling operation sub-process begins with ships leaving the waterway and ends up with ships finishing handling operation and leaving the berths, which is accomplished by *handling operation* sub-models in simulation model, as shown in Fig. 6.

a) *FCFS* Rule: Except the *SELC handling operation* sub-model, all the sub-models under other rules of ships entering and leaving port are the same, as shown in Fig. 7. Take *FCFS handling operation* sub-model for example. Firstly, an *Assign* module is used to record the number of ships sailing in the waterway. Then, two *Delay* modules are used to represent the process of turning around and handling operation. After that, another *Assign* module is used to record current time. A combination of a *Decide* module and several *Release* modules is used to release berth resources to make them available for other ships next. Finally, ships come into the queue waiting for leaving the port area.

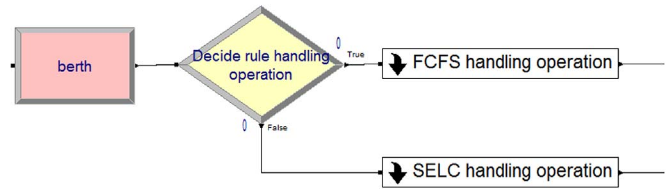

Fig. 6. Interface of *Handling operation* sub-model.

a) *SELC* Rule: Under *SELC* rule, several ships are batched into a temporary entity to pass the waterway. When it comes to *SELC handling operation* sub-model, the temporary entity becomes several individual entities by a *Separate* module again and finishes handling operation respectively.

3.2.4. Departing the Port Area **Sub-process**

Departing the port area sub-process begins with ships releasing the berth resources and ends up with ships leaving the port area, which is accomplished by *Out_waterway* sub-model and *Exit* sub-model.

a) *Out_waterway* sub-model

As shown in Fig. 8, a *Decide* module is first used to determine the rules of ships entering and leaving port, ships then go into corresponding *Out_waterway* sub-model. Since the processes of entering port and leaving port are similar, *Out_waterway* sub-models are basically the same as *In_waterway* sub-models under different rules, as shown in Fig. 9. The distinctions of *Out_waterway* sub-models contain two aspects. One is that ships enter port full and leave empty in import port area, so that ships don't need to take the tide when leaving the port, which means there isn't deciding process of tidal conditions in *Out_waterway* sub-model. The other is that the navigation speed of unloaded ships is higher than that of full-load ships under *UNSF* rule. It means navigation duration of these ships are shorter, which is set as 0.8* navigation duration of ships in the waterway.

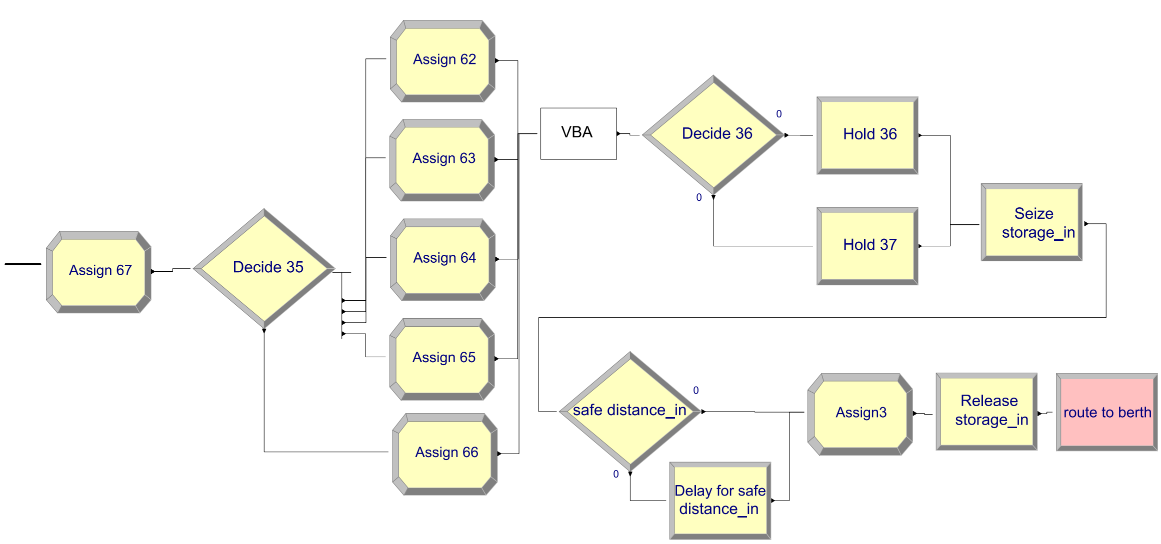

Fig. 5. Interface of *FCFS in_waterway* sub-model.

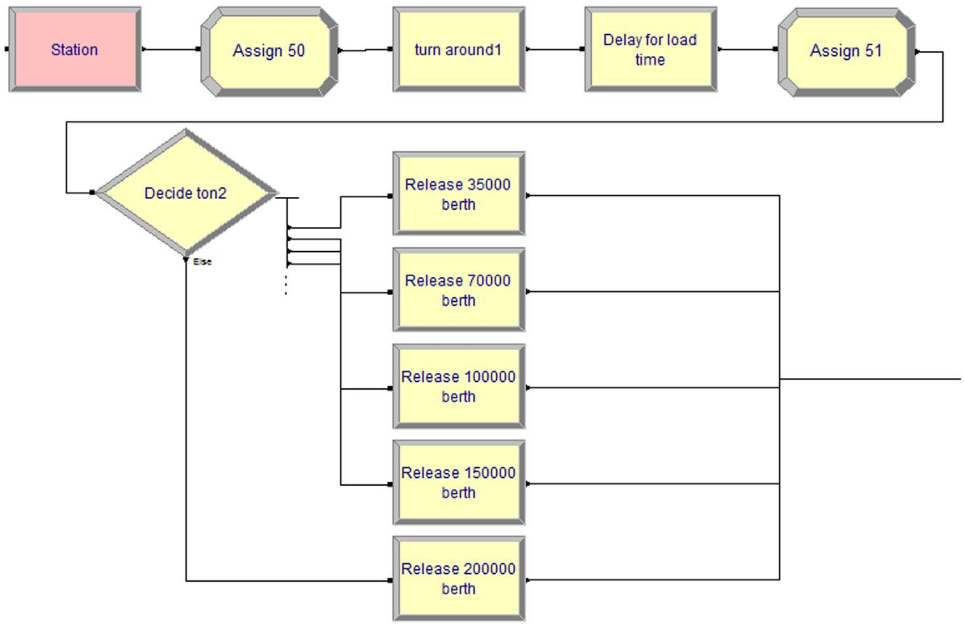

Fig. 7. Interface of *FCFS unload* sub-model.

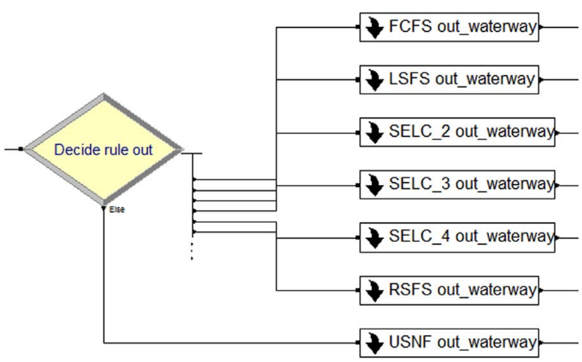

Fig. 8. Interface of *Out_waterway* sub-model.

b) *Exit* sub-model

Ships leave the waterway through a *Station* module. After determining rules of ships entering and leaving port, ships go into the *Exit* sub-model to leave the port, as shown in Fig. 10. Except the *SELC exit* sub-model, all the *Exit* sub-models under other rules are the same, as shown in Fig. 11. Take *FCFS exit* sub-model for example, an *Assign* module is first used to calculate the total time in port of ships and change the number of ships sailing in the waterway. Then, a *VBA* module is used to compute all the time parameters of ship entities, such as waiting time for berths, waiting time for the waterway, handling operation time, etc., so that the value of *AWT/AST* can be obtained. Finally, ships leave the system by a *Dispose* module.

As for *SELC exit* sub-model, after passing the waterway in the form of a temporary entity, ships become several individual entities again and leave the port.

3.3. Model input parameters

3.3.1. Ships

a) Ships' Arrival Distributions

The ships' arrival distributions are generally subject to Poisson distribution, the Irish second-order distribution or Normal distribution according to the research results and analysis of ships' arrival distribution of the coastal port by the researchers.

b) Type Combination of Ships

Type combination of arrival ships, which refers to tonnages and quantities of ships, has a great impact on the operations of the ships' navigation operation system in seaport. The matching degree between the ships' type distribution and the berths affect ships' waiting time for berths directly.

c) Rules of Ships Entering and Leaving Port

Rules of ships entering and leaving port determine the sequence

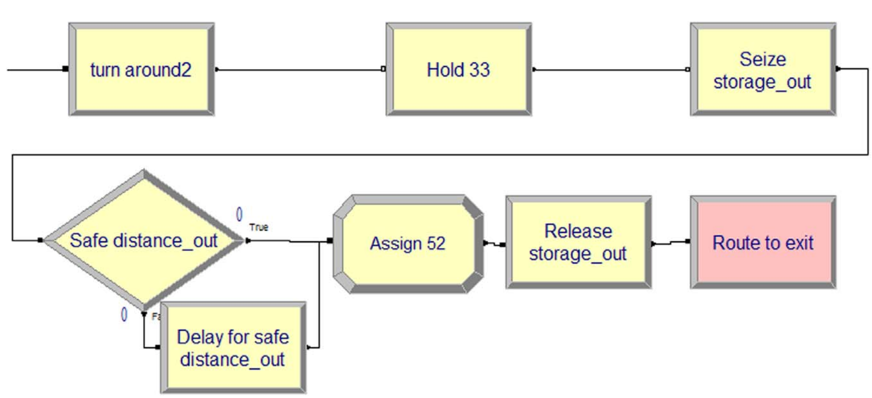

Fig. 9. Interface of *FCFS Out_waterway* sub-model.

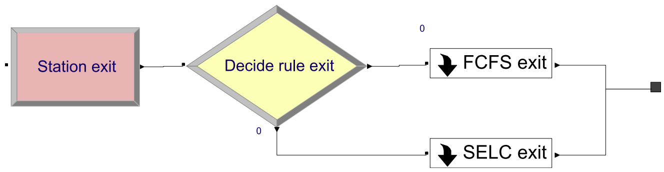

Fig. 10. Interface of *Exit* Sub-model.

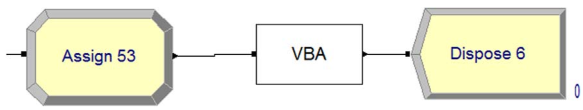

Fig. 11. Interface of *FCFS exit* sub-model.

and organization way of ships when passing the waterway, which include *FCFS* rule, *LSFS* rule, *SELC* rule, *RSFS* rule, *USNF* rule, etc.

3.3.2. Natural conditions

a) Inactivity Days
   The safety of ship navigation requires favorable weather and hydrological conditions. Besides, the adverse weather conditions also affect the normal handling operations on the terminal.
b) Tidal Parameters
   In general, large ships enter the port area by taking the tide because of natural conditions or reducing the cost of channel dredging. Thus, the tide is an important factor for ships sailing in the channel.

3.3.3. Berths

Berth resources are quite important and affect ships' waiting time for berths directly.

3.3.4. Waterway parameters

a) Waterway dimensions
   Waterway dimensions include the length, navigation depth and navigable width of the waterway.
   Taking into account the length of the waterway and the navigation speed of ships simultaneously, the concept of navigation duration is introduced. It means the total time spending in the waterway when ships enter or leave the port.
   The navigation depth refers to the depth that ensures the ships' safely navigation in the waterway, and it is one of the important factors for ships taking the tide.
   The navigable width refers to the width between bottom borderlines of the section in the certain place which has the navigation depth of the waterway. And this parameter determines ships' types and tonnages that can sail in opposite directions simultaneously under *partial two-way navigation* rule. It also affects the ships' waiting time for waterway indirectly.
b) Safety distance
   To ensure the safety of ships' navigation, two ships in the same direction should maintain a certain length of safety distance, so that those ships won't collide with each other due to an emergency brake while passing the waterway. In this paper, we control the safety distance by limiting the trailing time when ships enter the waterway, which is called safe-time distance.
c) Navigation rules of ships
   Navigation Rules of ships focus on the navigation of ships in opposite directions, which include *one-way navigation* rule, *two-way navigation* rule and *partial two-way navigation* rule.

3.3.5. Anchorage parameters

According to geographical location, the anchorage is divided into

Table 2
The numbers of the berths of the first-stage project in the port area.

Tonnages of the berths (T)	Numbers of the berths
10,000	2
25,000	1
30,000	2
50,000	2

inner anchorage and roadstead. The location and capacity of the roadstead as well as the construction and scale of the inner anchorage both have influences on the ships' navigation operation system, where the latter is one of the focuses of this paper.

3.4. Model verification

For model verification, we have run some simulation experiments based on real data from the operators of a container port area in Dalian. The numbers of the berths of the first-stage project in the port area are shown in Table 2.

The total number of ships arriving the port area is counted, which reaches 223. The inter-arrival time of these ships is proved to follow negative exponential distributions.

Once the arrival distribution and actual operation status are input into the simulation model, we run it and obtained the results listed in Table 3. Compared with the real statistics, the maximum relative error is below 10%, which indicates that the model is reliable and can well reflect the actual operation status of the seaport system.

4. Simulation results and analysis

4.1. Parameter settings

In order to study the influences of rules of ships entering and leaving port, navigation rules and inner anchorage scales on waterway through capacity, and to quantify the degree of promotion, a bulk cargo port area in China is used as a simulation case in this paper. The parameter settings of the case are as follows.

4.1.1. Ships

a) Ships' arrival distribution
   The ships' arrival distribution of the bulk cargo port area in case study is proved to follow Poisson distribution, which means the inter-arrival time of arrival ships follows negative exponential distributions
b) Type combination of ships
   The type combination of ships at the bulk cargo port area, which mainly refers to types and proportion of the ships, is shown in Table 4.
c) Rules of Ships Entering and Leaving Port
   Five types of rules of ships entering and leaving port are discussed in this paper, including *FCFS* rule, *LSFS* rule, *SELC* rule, *RSFS* rule and *USNF* rule. For *SELC* rule, two ships, three ships and four ships entering and leaving port in cluster are considered.

Table 3
Simulation results of model verification.

Item	Quantity of arrival ships	*AWT* (h)	*AST* (h)	Average berth occupancy rate (%)
Simulation results	226	2.83	9.34	50.13
Actual data	223	2.99	10.04	51.85
Relative errors	1.35%	5.35%	6.97%	3.32%

Table 4
Type combination of ships at the Bulk Cargo Port area.

Tonnage of ships *DWT* (t)	≤35,000	70,000	100,000	150,000	≥200,000
Proportion (%)	28.91	37.85	22.02	2.28	8.94
Cumulative frequency (%)	28.91	66.76	88.78	91.06	100.00

4.1.2. Natural conditions

a) Inactivity Days
   Due to bad weather, the bulk cargo port area operates only on 325 days randomly distributed in a period of one year.
b) Tidal Parameters
   The tide of waters around the port area belongs to irregular semidiurnal tides, whose mean range of tides is 2 m.

4.1.3. Berth parameters

In order to make the simulation experiments more universal but not too complicated, the proportion of the berths are set as constant when the number of berths increases, which is based on the plan of the bulk cargo port area. The relevant berth parameters of the port area are shown in Table 5.

4.1.4. Waterway parameters

a) Waterway Dimensions
   The object of study in this paper is 200,000 t single-lane waterway. According to the relationship between length of the waterway and ships' speed, the navigation duration is set as 2 h. The navigation depth can meet the demand of ships with the tonnage of 200,000 passing the waterway by taking the tide. The navigable width of the 200,000 t single-lane waterway is 250 m, it can satisfy the ships with not more than 200,000 t sailing in the waterway under *one-way navigation* rule, as well as the ships with not more than 20,000 t passing the waterway under *partial two-way navigation rule*.
b) Safety Distance
   The safety distance is expressed as safe-time distance, which is set as 10 min in the simulation model.
c) Navigation Rule of Ships
   One-way navigation rule and *partial two-way navigation* rule are considered in this paper.

4.1.5. Anchorage parameters

The water depth of inner anchorage are set as 14.95 m, 16.10 m and 16.68 m, which can meet the anchoring demand of bulk cargo ships with the tonnage of 50,000 t, 70,000 t and 100,000 t, respectively. Under the rules of single anchor mooring, the maximum area of mooring water and inner anchorage ton combination are shown in Tables 6–8.

Table 5
Berth parameters of the Bulk Cargo Port area.

Tonnage of berth *DWT* (t)	Handling quantity per ship (t)	Handling efficiency (t/h)		Handling time (h)	
		Loading	Unloading	Export	Import
35,000	22,000	3000	3000	7.33	7.33
70,000	43,000	6000	4000	7.17	10.75
100,000	73,000	7000	5000	10.43	14.60
150,000	139,000	8000	5500	17.38	25.27
200,000	178,000	9000	6000	19.78	29.67

Table 6
The maximum area of mooring water and inner anchorage ton combination (depth of mooring water is 14.95 m).

Number of inner anchorage	Maximum area of mooring water (thousand m^2)	Inner anchorage ton combination				
		5000 t	10,000 t	20,000 t	30,000 t	50,000 t
1	567.2	0	0	0	0	1
2	1134.3	0	0	0	0	2
3	1701.5	0	0	0	0	3
4	2268.7	0	0	0	0	4
5	2835.8	0	0	0	0	5
6	3403.2	0	0	0	0	6
7	3970.1	0	0	0	0	7
8	4537.3	0	0	0	0	8
9	4641.0	0	1	0	1	7
10	4747.8	0	1	0	0	8
11	5149.1	0	0	2	4	5
12	5857.5	0	0	2	4	6

4.2. Results and analysis

4.2.1. Influences of rules of ships entering and leaving port

FCFS rule is treated as the basic rule of ships entering and leaving port in this paper. Based on *FCFS* rule, a serious of simulation experiments are designed, quantities of ships are increased with the number of berth in proportion, and waterway through capacity under *FCFS* rule corresponding to different values of *AWT/AST* can be obtained, as shown in Table 9.

Similarly, waterway through capacity under other rules of ships entering and leaving port corresponding to different values of *AWT/AST* are simulated, which is shown as the block diagram in Fig. 12. Then, comparing with the one under *FCFS* rule, the promotion of waterway through capacity by using different kinds of rules can be calculated, which is shown as line chart in Fig. 12. Besides, since some rules of ships entering and leaving port fail to reach particularly small value of *AWT/AST*, we take the waterway through capacity under different rules and its promotion when the value of *AWT/AST* reaches 0.4–0.9 for example in this paper.

From the Fig. 12, we can see that: (1) Compared with basic rule, the promotion of waterway through capacity of *LSFS* rule is mostly in the range of ± 5%, which reveals that the impact of *LSFS* rule on waterway through capacity is indistinctive. (2) When the quantity of arrival ships and the value of *AWT/AST* is relatively small, such as the value of *AWT/AST* is 0.4, *SELC* rules with three ships and four ships fail to take their advantage, which are even inferior to the basic rule. Moreover, the larger the number of ships passing the waterway in cluster is, the more disadvantage of *SELC* rule shows. As the value of *AWT/AST* increases, *SELC* rule can improve the waterway through capacity obviously, whose promotion is between 15% and 60%. The larger the number of ships in cluster is, the more obvious of the promotion is. (3) *RSFS* rule and *USNF* rule can improve the waterway through capacity comparing with the basic rule, the promotion of the two rules have no significant difference, which are in the range of 10–25%.

4.2.2. Influence of navigation rules

To analyse the impact of the navigation rules on waterway through capacity, several simulation experiments are designed. The number of arrival ships is increased with the number of berth in proportion, so the waterway through capacity under *one-way navigation* rule and *partial two-way navigation* rule corresponding to different values of *AWT/AST* are obtained, which is shown as the block diagrams in Fig. 13. Besides, the promotions of waterway through capacity under *partial two-way navigation* rule comparing with *one-way navigation* rule can also be calculated, which is shown as the line chart in Fig. 13.

Table 7
The maximum area of mooring water and inner anchorage ton combination (depth of mooring water is 16.10 m).

Number of inner anchorage	Maximum area of mooring water (thousand m^2)	Inner anchorage ton combination					
		5000 t	10,000 t	20,000 t	30,000 t	50,000 t	70,000 t
1	594.2	0	0	0	0	0	1
2	1188.3	0	0	0	0	0	2
3	1782.5	0	0	0	0	0	3
4	2376.7	0	0	0	0	0	4
5	2970.8	0	0	0	0	0	5
6	3511.0	0	0	0	0	2	4
7	3859.8	0	0	0	1	5	1
8	4262.7	0	0	0	2	6	0
9	5158.5	0	0	0	0	7	2
10	5603.2	0	0	0	2	2	6
11	5716.6	0	0	0	4	6	1
12	6126.2	0	0	0	2	3	6

Table 8
The maximum area of mooring water and inner anchorage ton combination (depth of mooring water is 16.68 m).

Number of inner anchorage	Maximum area of mooring water (thousand m^2)	Inner anchorage ton combination						
		5000 t	10,000 t	20,000 t	30,000 t	50,000 t	70,000 t	100,000 t
1	731.0	0	0	0	0	0	0	1
2	1462.0	0	0	0	0	0	0	2
3	2193.0	0	0	0	0	0	0	3
4	2924.0	0	0	0	0	0	0	4
5	3518.2	0	0	0	0	0	1	4
6	4112.4	0	0	0	0	0	2	4
7	4296.0	0	0	0	0	0	6	1
8	4671.0	0	0	0	3	0	2	3
9	4972.6	0	0	0	1	1	3	3
10	6269.8	0	0	0	3	0	1	6
11	6316.6	0	0	0	3	0	6	2
12	6805.3	0	0	1	1	0	9	1

Table 9
Waterway through capacity under *FCFS* Rule corresponding to different *AWT/AST*.

AWT/AST	0.4	0.5	0.6	0.7	0.8	0.9
Waterway through capacity (billion tons per year)	0.281	0.420	0.534	0.625	0.699	0.759

It can be seen from the block diagrams that waterway through capacity under *partial two-way navigation* rule is larger than those under *one-way navigation* rule when *AWT/AST* reaches different value. As for the promotion of waterway through capacity, it is relatively stable and in the range of 20–30%.

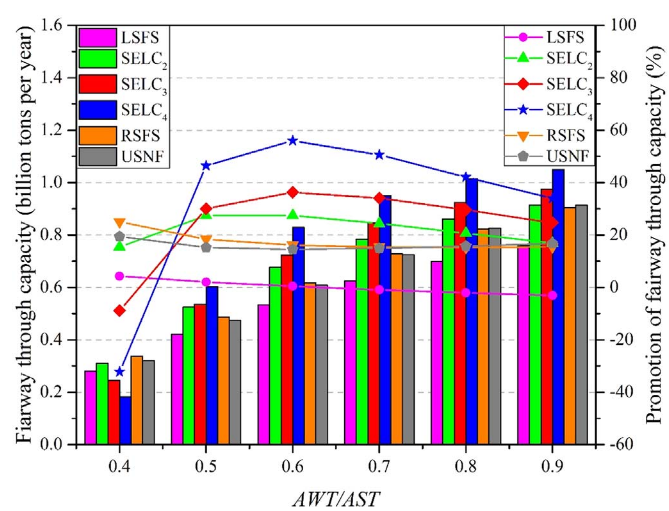

Fig. 12. Waterway through capacity under different rules of ship entering and leaving port and the promotion compared with *FCFS* rule.

4.2.3. Influence of inner anchorage scales

In this paper, in order to analyse the impact of inner anchorage on waterway through capacity, we defined basic situation as the one conform to following conditions: (1) There isn't inner anchorage in port area; (2) *FCFS* rule is chosen as the rule of ships entering and leaving port; (3) *One-way navigation* rule are considered; (4) The value of *AWT/AST* reaches 0.5. Then, the waterway through capacity of basic situation can be obtained, which is 0.420 billion tons per year. On the basis of basic situation, the waterway through capacity under different inner anchorage scales (inner anchorage capacities and water depths) are simulate, as shown as block diagrams in Fig. 14. Finally, the promotion of waterway through capacity under different inner anchorage scales can be calculated compared with the basic situation, which is shown as the line chart in Fig. 14.

It can be seen from Fig. 14 that under three types of water depths, the waterway through capacities rise as the inner anchorage capacity increasing when the inner anchorage capacities are below 12. When the inner anchorage capacity is greater than 12, the waterway through capacities stay the same and the main limitation of waterway through capacity becomes the scale of the waterway. Thus, 12 is the ultimate inner anchorage capacity in this situation.

When the scale is less than the ultimate inner anchorage capacity, waterway through capacity can be improved by 6–88% by constructing inner anchorage corresponding to the water depth is 14.95 m. And the

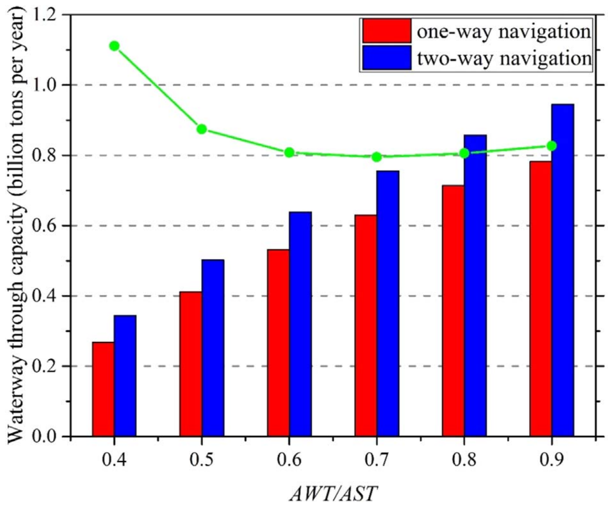

Fig. 13. Waterway through capacity under different navigation rules and the promotion compared with *One-way Navigation* rule.

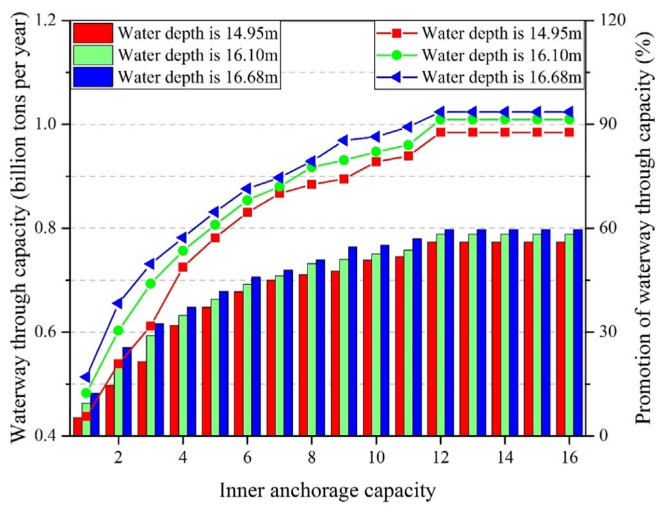

Fig. 14. Waterway through capacity under different inner anchorage capacities and its promotion compared with the basic situation.

promotions are 12–91% and 17–93% when the water depths are 16.10 m and 16.68 m, respectively. In summary, the promotion effect is more and more obvious as the inner anchorage scales increase.

5. Conclusions and discussions

In this paper, we analyse the impact of three kind of key influencing factors, including various rules of ships entering and leaving port, multiple navigation rules of ships going through waterway and different scales of inner anchorages, on improving the waterway through capacity of ports, and how much each kind of influencing factors can improve the capacity quantitatively are also obtained. On the basis of analyzing elements of the ships' navigation operation system comprehensively, *AWT/AST* is introduced as the evaluation indicator of port service level, and a complicated simulation model considering various random factors is constructed. After verifying the reliability and effectiveness of the simulation model, a serious of simulation experiments based on a real bulk cargo port area in China are designed. Under the certain parameter settings, simulation results show that:

(1) Compared with *FCFS* rule, the promotion of waterway through capacity of *LSFS* rule is mostly in the range of ± 5%, which reveals that the impact of *LSFS* rule on waterway through capacity is indistinctive.
(2) When the value of *AWT/AST* is relatively small, *SELC* rules fail to take their advantages, the larger the number of ships passing the waterway in cluster is, the more disadvantage of *SELC* rules shows. However, as the value of *AWT/AST* increases, *SELC* rules can improve the waterway through capacity obviously, whose promotion is between 15% and 60%. The larger the number of ships in cluster is, the more obvious of the promotion is.
(3) *RSFS* rule and *USNF* rule can improve the waterway through capacity comparing with *FCFS* rule, the promotion of the two rules have no significant difference, which are in the range of 10–25%.
(4) Compared with *one-way navigation* rule, *partial two-way navigation* rule can improve waterway through capacity efficiently, whose promotion is in the range of 20–30%.
(5) When the water depths are 14.95 m, 16.10 m and 16.68 m, it can improve waterway through capacity by 6–88%, 12–91% and 17–93% by constructing inner anchorage, respectively. The larger the inner anchorage scale is, which means deeper water depths and more inner anchorage capacity, the larger the promotion of waterway through capacity is. However, the ultimate value of inner anchorage capacity exists, which is 12 in the case study. When reaching the ultimate value, the waterway through capacity stays the same as the inner anchorage capacity increasing, the main limitation of waterway through capacity becomes the scales of the waterway.

The results obtained in this paper can provide a theoretical foundation for waterway construction and management. The proposed methodology can serve as a pattern to solve similar problems. However, in this paper, we only focus on how each single influencing factor improves the waterway through capacity. In the future, we are going to discuss how two or more influencing factors improve the capacity jointly and the impact of expanding the waterway to a two-way waterway on waterway through capacity.

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