SIMULATION RESEARCH ON SEAPORT FAIRWAY CAPACITY AND ITS PROMOTION MEASURE: A CASE STUDY OF JINGTANG PORT AREA IN CHINA

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ABSTRACT
This paper aims at solving the problem of how to improve the fairway through capacity for Jingtang port area in China. The problem is figured out by building a simulation model of the ships' navigation operation system. First of all, the model is constructed based on the Rockwell Arena software to simulate how the port is operated with the increasing number of arrival ships. Then, the total annual tonnages of ships when the fairway reaches the through capacity can be obtained. After that, we use a method of changing navigation rules (from one-way to two-way) for the ships with a tonnage of not more than 50,000 tons to see whether the fairway through capacity can be improved. Finally, the results show that the fairway through capacity can be promoted by changing the navigation rules by 13.7%, which provides a theoretical foundation for fairway construction and management of Jingtang port area.

Keywords: Jingtang port area, fairway through capacity, navigation rules, simulation

1. INTRODUCTION

Jingtang port area is one of the important regional port areas in coastal areas in China. The overall plan of Jingtang port area is shown in Figure 1 (Website of coal in Qinhuangdao 2009). As the development of throughput capacity of the port area together with the continuous increase of scale of berths, there will be ore bulk carriers with a tonnage of 250,000 tons arriving the port area. However, the exiting 200,000 tons fairway fails to meet the demand of these ships. Therefore, Jingtang port area is currently planning on expanding the fairway to 250,000 tons. Then, the operators of the port area want to know how much the through capacity of the 250,000 tons fairway is and how to improve the fairway through capacity, which are the problems that need to be solved in this paper.

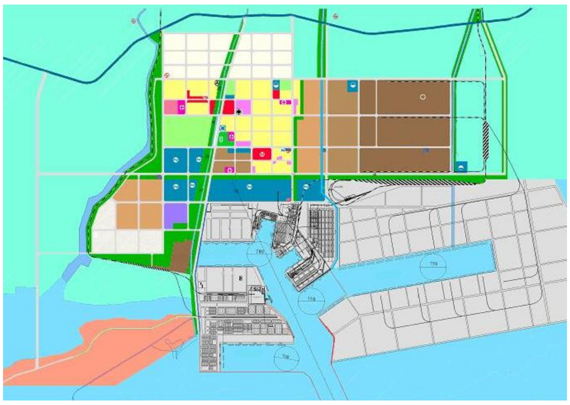

Figure 1: Overall Plan of Jingtang Port Area

As the vigorous development of the shipping industry together with the continuous increase of shipping traffic flow, the fairway is becoming the restriction of port development. Therefore, it has generated considerable research interests on fairway through capacity these years. Early research on the fairway through capacity mostly focused on fairway through capacity of the inland waterway. Researchers devoted special attentions to propose empirical formulas, such as the Western Germany formula, Yangtze Estuary Deepwater Channel formula (Changjiang Waterway Bureau 2005a) and Chuan River Channel formula (Changjiang Waterway Bureau 2005b).

Compared with the inland waterway capacity, research on the seaport fairway through capacity started relatively late. However, the methods has become rather mature with the efforts by researchers. Due to the complexity of the seaport operation system, the simulation method has been generally applied in port design and management. Angeloudis et al. (2011) provided an overview of the domain of container terminal simulation. Lin et al. (2013) addressed an investment planning problem for a container terminal in Humen Port using simulation with Arena software. Longo et al. (2013) developed a simulation model to recreate the complexity of a medium-sized

Mediterranean seaport and analysed the performance evolution of such system with particular reference to the ship turnaround time. 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. Sun et al. (2013) proposed an integrated simulation framework to facilitate the design and evaluation of mega container terminal configurations with integrated multiple berths and yards.

Further more, the simulation method is also widely used to obtain the seaport fairway through capacity. Guo et al. (2010) and Wang et al. (2015) gave the definition of seaport fairway through capacity and analysed the influence of port service level or safety level on fairway through capacity, respectively. Shang (2005) constructed a simulation model for Huanghua Port and studied the relationship between fairway through capacity and port capacity. Song et al. (2010) used simulation methods to find out the relationship between shipping navigation duration and fairway through capacity of single-channel. Tang et al. (2014a) chose the annual average turn around 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 to determine its dimensions. Tang et al. (2014b) discussed the optimal channel dimensions problem with limited dredging budget constraints in an integrated way. Zhang (2009) and Wang et al. (2012) studied the influence of ship traffic rules in bulk cargo port or Y-type fairway intersection water on port service level, respectively.

In conclusion, the above literatures involve various aspects of the research on fairway through capacity, which provide a strong foundation for further studies. However, most of them only focus on constructing universal models instead of modeling for practical engineering projects. Besides, few consider various types of arrival ships combining with the rule of two-way navigation for small ships. There are only a few literatures about the promotion measures of the fairway through capacity, however they are not suitable for being used to solve the proposed problem in this paper directly.

Combining with the actual operation status of Jingtang port area, this paper simulates ships' navigation operation system, obtains the fairway through capacity of the 250,000 tons fairway as measured by port service level, and tries to see whether changing navigation rules can improve the fairway through capacity. The remainder of this paper is organized as follows. The problem is presented in Section 2. The simulation model is given in detail in Section 3, followed by verification and validation in Section 4. The simulation experiments and results analysis are listed in Section 5. Finally, the main conclusions and future works are drawn in Section 6.

2. PROBLEM DESCRIPTION

The 250,000 tons ore berths are of vital importance in Jingtang port area. In order to satisfy the requirements of the big ships berthing at the 250,000 tons berths, the port operators decide to expand the exiting 200,000 tons fairway to 250,000 tons. Then, there comes two issues: one is what the fairway through capacity of the 250,000 tons fairway is based on the current berth state and other information, such as future ship traffic, natural conditions, allocation and scheduling rules of ships, navigation rules of ships and performance indicators, which is described in Section 2.1 to 2.5 separately; the other is how to improve the fairway through capacity.

2.1. Ships

There are totally six types of arrival ships: ore bulk carriers, coal bulk carriers, chemical carriers, LPG carriers, general cargo ships and container ships. The tonnage of the ships is from 7,000 to 250,000 tons. The detailed description of the type and tonnage of the arrival ships is shown in Table 1.

Table 1: Type and Tonnage of Arrival Ships

Type	Tonnage (Tons)
Ore bulk carriers	250,000
Ore bulk carriers	200,000
Ore bulk carriers	70,000
Ore bulk carriers	50,000
Ore bulk carriers	35,000
Coal bulk carriers	200,000
Coal bulk carriers	100,000
Coal bulk carriers	70,000
Coal bulk carriers	50,000
Coal bulk carriers	35,000
Chemical carriers	40,000
Chemical carriers	7,000
LNG carriers	30,000
General cargo ships	30,000
General cargo ships	20,000
Container ships	100,000
Container ships	70,000
Container ships	30,000

For container ships, the distribution of inter-arrival time is taken as constant when they are liner ships. However, the arrival pattern of other types of ships are quite random, we analyse one month's actual data of ships' arrival time intervals in Jingtang port area, as shown in Figure 2, and find out that the inter-arrival time of these ships follows negative exponential distributions. Thus we take the arrival pattern of these ships as a Poisson process.

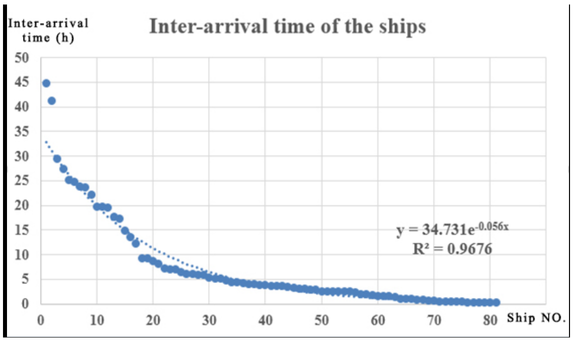

Figure 2: Inter-arrival Time of the Ships

2.2. Natural conditions

Considering the influences of air temperature, rainfall, winds, fogs, storms and tidal conditions on ships' navigation comprehensively, the number of navigable days is 350 days per year.

The tide of waters around Jingtang port area belongs to irregular semidiurnal tides. The tidal data is described as follows: the mean high tide level is 1.69 meters, the mean low tide level is 0.82 meters, the mean sea level is 1.27 meters and the mean range of tides is 0.88 meters.

2.3. Allocation and scheduling rules of ships

Ships can be served at idle berths with the same type and tonnage. When ships are allocated, the priority of container ships is higher than the other types of ships, and big ships are prior to small ships as well. Other allocation and scheduling rules obey first-come-first-service basis.

2.4. Navigation rules of ships

The rules of one-way navigation and two-way navigation for the ships with a tonnage of not more than 50,000 tons are considered in this paper. Under the one-way navigation rule, all the ships in opposite directions are not allowed sailing in the fairway at the same time. While under the two-way navigation rule, for the ships with a tonnage of not more than 50,000 tons, two ships with a tonnage of not more than 50,000 tons in opposite directions can sail in the fairway simultaneously.

2.5. Performance indicators

The fairway through capacity for a given fairway of a certain seaport under normal operation status is defined as the total annual tonnage of ships going through the fairway at a specified port service level (Guo et al. 2010). In this paper, we choose *AWT*/*AST* as the performance indicator (United Nations, 1985). *AWT* refers to ships' average waiting time including the time waiting for both fairway 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. When *AWT*/*AST* reaches 0.5 for the first time, the total annual tonnage of ships going through the fairway at the time is taken as the fairway through capacity.

2.6. Simulation scenarios

The simulation scenarios include the arrival process, service process and departure process of ships in the port area. The simulation scenario under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons can be depicted through Figure 3.

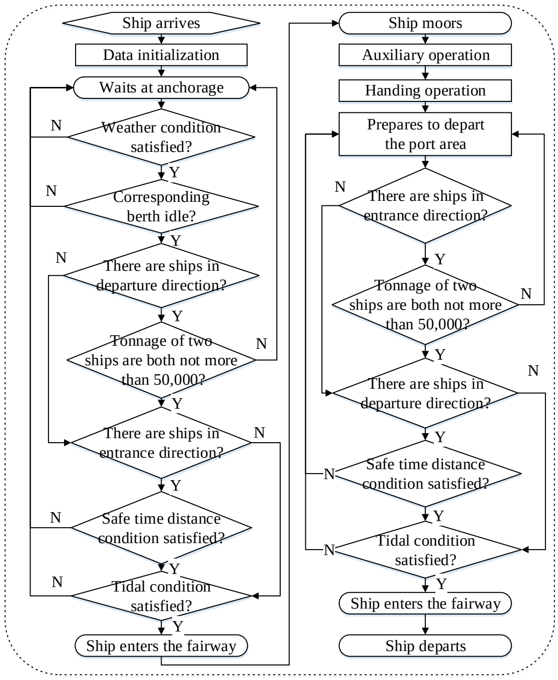

Figure 3: Simulation Scenarios of the Port Operation System under the Rule of Two-way Navigation for the Ships with a Tonnage of not more than 50,000 Tons

At first, a ship is created and enters the system. Then, data initialization should be done to make every ship unique. For example, each ship should be given the ship type, tonnage, arrival time, priority and so on. After initialization, the ship will wait for idle berths at the anchorage until the weather condition is satisfied. Next, after berth allocation, it should be checked whether the tidal condition, navigation condition and safe time distance condition are satisfied. Only if all the three conditions are satisfied, the ship is allowed to move into the fairway. After mooring in the arranged berth, the ship starts auxiliary operation and handing operation. Finally, after handing operation, it moves into the fairway and departs the port area when the above three conditions are satisfied as well.

The difference between the simulation scenario under the rule of one-way navigation and two-way navigation for the ships with a tonnage of not more than 50,000 tons is how to check the navigation conditions. Under the rule of one-way navigation, only if there has been none ship in opposite direction, the navigation condition can be satisfied.

3. SIMULATION MODEL

This paper constructs a complicated and valuable simulation model to obtain the fairway through capacity for Jingtang port area, which is based on the following assumptions:

1. The port area is under normal operation status and the resources are taken full use of.
2. The number of anchorage berths in the port area are enough, which can well provide service for ships waiting for the fairway and berths.
3. Ships maintain good technical conditions and keep a safe distance between each other. The average speed of ships is 7 knots and running is noninterference.

The whole simulation model is composed of four systems: Ships waiting for berths at anchorage system, ships entering the port area system, ships handing operation system and ships departing the port area system. We use the Arena software to implement the modeling work.

3.1. Ships waiting for berth at anchorage system

This system begins with ships arriving the port area and ends up with ships being allocated an idle berth. All these processes are completed at the anchorage. The system is shown in Figure 4.

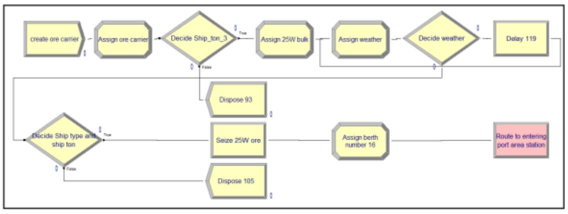

Figure 4: Ships Waiting for Berth at Anchorage System

3.2. Ships entering the port area system

This system includes the processes of deciding whether the tidal condition, navigation condition and safe time distance condition are satisfied and ships entering the fairway. The system is shown in Figure 5.

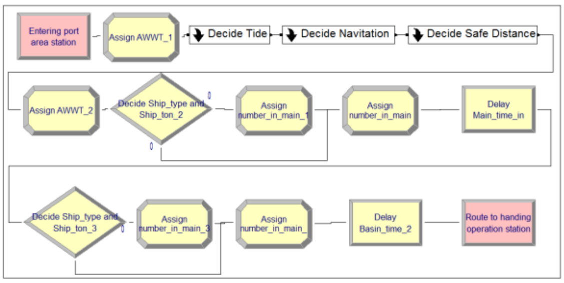

Figure 5: Ships Entering the Port Area System

3.3. Ships handing operation system

This system begins with ships mooring at the berth and ends up with ships finishing handing operation. Ships handing operation system is shown in Figure 6.

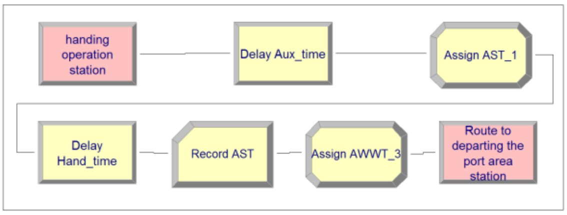

Figure 6: Ships Handing Operation System

3.4. Ships departing the port area system

This system is quite similar to the ships entering the port area system, so it won't be repeated here. Figure 7 shows the ships departing the port area system.

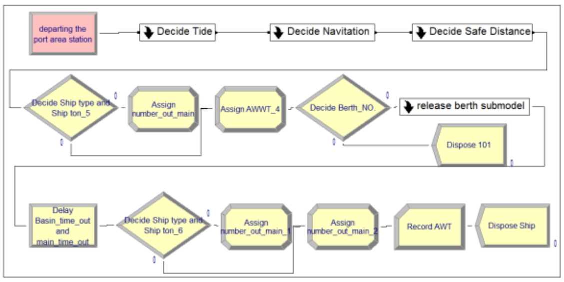

Figure 7: Ships Departing the Port Area System

4. VERIFICATION AND VALIDATION

Our model has to be checked to see if it is working in the way it is planned. For example, we take good advantages of the tracing approach, which is quite convenient and effective in Arena software. Besides, animation is also an effective way to verify our simulation model logically. Finally, we output the important moments of the ships in the whole life cycle, so that we can verify whether the model is correct.

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

Table 2: The number of the Berths of the First-stage Project in the Port Area

Tonnages of the Berths (Tons)	Number of the Berths
10000	2
25000	1
30000	2
50000	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.

Table 3: Simulation Results of Model Validation

Item	Number of Arrival Ships	*AWT* (h)	*AST* (h)	Average Berth Occupancy Rate (%)
Simulation Results	225	2.73	9.13	49.34
Real Statistics	223	2.99	10.04	51.85
Relative Errors (%)	0.90	8.70	9.06	5.09

5. SIMULATION EXPERIMENTS AND RESULTS ANALYSIS

Since the model has been constructed and validated, it can be used to obtain the fairway through capacity of the fairway and analyse the systems under different navigation rules by designing the simulation experiments. The total annual number of arrival ships increases from 4,962 to 6,947.

We design two simulation experiments: one is under the rule of one-way navigation, and the other is under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons. Each experiment runs 50 replications. The replication length is set to be 365 days. The simulation results under the rules of one-way navigation and two-way navigation for the ships with a tonnage of not more than 50,000 tons are shown in Table 4 and Table 5, respectively.

Table 4: Simulation Results under the Rule of One-way Navigation

Number of Arrival Ships	4962	5160	5359	5557	5756	5954
AWT	5.29	5.71	6.22	6.40	6.81	7.33
AST	13.6	13.5	13.5	13.6	13.5	13.5
AWT /AST	0.39	0.42	0.46	0.47	0.50	0.54

Table 5: Simulation Results under the Rule of Two-way Navigation for the Ships with a Tonnage of not more than 50,000 Tons

Number of Arrival Ships	5954	6153	6351	6550	6748	6947
AWT	5.62	6.00	6.43	6.77	7.33	7.63
AST	13.5	13.5	13.6	13.6	13.6	13.5
AWT /AST	0.42	0.44	0.47	0.50	0.54	0.57

From the tables, we can see that *AWT/AST* relies on linear growth basically with the increment of the number of arrival ships. Under the rule of one-way navigation, *AWT/AST* reaches 0.5 when the number of arrival ships is 5756, and the corresponding berth occupancy rate is about 29%. While under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons, *AWT/AST* reaches 0.5 when the number of arrival ships is 6550, and the corresponding berth occupancy rate is about 33%.

The variation of total annual tonnage of ships along with *AWT/AST* under two navigation rules is shown in Figure 8. The increases of the total annual tonnage of ships under the rule of two-way navigation compared with the one under one-way navigation are shown in Table 6.

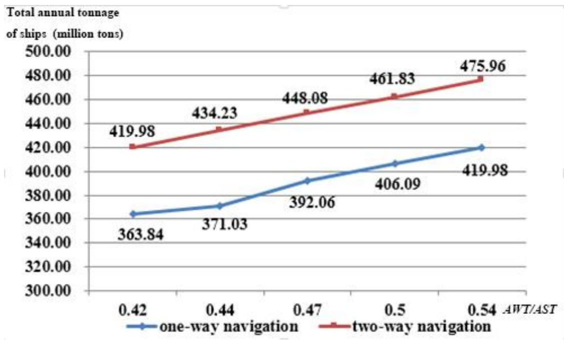

Figure 8: Variation of Total Annual Tonnage of Ships along with *AWT/AST*

Table 6: The Increases of the Total Annual Tonnage of Ships under Different Navigation Rules

AWT /AST	0.42	0.44	0.47	0.50	0.54
Tonnage under One-way Navigation (Million tons)	363.8	371.0	392.1	406.1	420.0
Tonnage under Two-way Navigation (Million tons)	420.0	434.2	448.1	461.8	476.0
Increases (%)	15.4	17.0	14.3	13.7	13.3

It can be seen from Figure 8 that under the rule of one-way navigation, the total annual tonnage of ships is 406.09 million tons when *AWT/AST* reaches 0.5. While under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons, the value is 461.83 million tons when *AWT/AST* reaches 0.5. In other words, the fairway through capacity of the 250,000 tons fairway in Jingtang port area is 406.09 million tons annually and 461.83 million tons annually under the rules of one-way navigation and two-way navigation for the ships with a tonnage of not more than 50,000 tons, respectively. The rule of two-way navigation for the ships with a tonnage of not more than

50,000 tons promotes fairway through capacity by 13.7% compared with the rule of one-way navigation.

Besides, it can be seen from Table 6 that the total annual tonnage under two-way navigation for the ships with a tonnage of not more than 50,000 tons are greater than the one under one-way navigation when *AWT/AST* reaches different values. The increases are from 13% to 17%, which are relatively stable.

6. CONCLUSIONS AND FUTURE WORKS

This paper focuses on solving the problem of how to improve the fairway through capacity for Jingtang port area in China and aims at determining the fairway through capacity of the fairway under different navigation rules. To better simulate and analyse the real system, we consider various types of ships, real natural conditions, flexible allocation and scheduling rules and complicated navigation rules. A simulation model is then proposed based on Arena software. Real data of a container port area in Dalian is used to validate the model.

In the paper, we undertake two simulation experiments to see whether the fairway through capacity can be improved. One is under the rule of one-way navigation, and the other is under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons. The simulation results show that:

1. *AWT/AST* relies on linear growth with the increment of the number of arrival ships.
2. Under the rule of one-way navigation, the fairway through capacity for Jingtang port area is 406.09 million tons annually.
3. Under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons, the fairway through capacity for Jingtang port area is 461.83 million tons annually.
4. It can promote fairway through capacity by 13.7% under the rule of two-way navigation for the ships with a tonnage of not more than 50,000 tons compared with one-way navigation.

The results obtained in this paper can provide a theoretical foundation for fairway construction and management. The proposed methodology can serve as a pattern to solve similar problems.

However, our work still has some limits. If ships overtaking is considered, the speed of ships cannot be set as constant, which may need to build ships-passing anchorages to solve the problem.

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