Simulation Modeling for Ship Traffic Flow in Entrance Channel

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Abstract

The design of coastal entrance channel is a complex challenge, considering the stochastic environment and time-consuming calculation works. Therefore, we implement a process-interaction-based simulation model for ship operation (PI-SMSO) using Java language to help the designers to determine the dimensions of entrance channels. The PI-SMSO component simulates ships in and out through a one- or two-way traffic channel, or a one-way channel with a ship-passing anchorage, and ships discharging/loading at berths. Finally, we apply the PI-SMSO to a Chinese coal-import terminal, to explore its possible bottlenecks by evaluating the performance of entrance channel system, and determine the available improvement strategies according to the simulated port performance. The case study proves that the proposed PI-SMSO effectively simulates the ship traffic flow in entrance channel and provides a decision support for evaluating entrance channel system.

Keywords: entrance channel, stochastics, process-interaction-based simulation, ship traffic flow

1. Introduction

A coastal entrance channel linking the berths of a port and the open sea is required to provide safe and convenient navigation for ships calling at ports. Recently, the rapid increase in the number and size of ships leads to further pressures on the entrance channels [1, 2]. For example, the Senate Appropriations Committee appropriated $33.5 million to deepen and widen the Houston Ship Channel, which deepened the channel from 12.2 to 13.7 m and widened it from 122 to 162 m [3–5]; Guangzhou Port will invest $484 million to expand its 66.6 km entrance channel into two-way traffic for container ships of 100,000 deadweight tons (DWT) [6]. Considering the high costs to expand entrance channels, a tool or model is needed to help the designers to evaluate the capacity of entrance channel and then to determine when to expand the channel and to select the dimensions of the expanded channel.

An entrance channel system can only be schematized as a complex system as it integrates with different ship types, the layout of water areas, and berths. In consideration of the stochastic characteristics of a port system, to explore the performance of integrated system, queuing theory is not applicable, and a simulation technique has to be used by simulating ship operations in and out of a port via entrance channels, e.g., a one- or two-way channel, especially a longer one-way channel with passing places [7, 8]. To simulate the complex port system, the "process description

method" or "object-oriented method" is considered to be appropriate and efficient [4, 5, 7]. Moreover, other important procedures, such as model verification and validation and simulation replication determination, should be conducted before productive simulation runs are started. It seems obvious that these procedures are impossibly time-consuming and complex for the designers. Therefore, we first developed a process-interaction-based simulation model for ship operation (PI-SMSO), which involves moving in and out of a port through entrance channels and handling cargoes at berths and automatically evaluates the performance of the stochastic port system. Finally, the effectiveness and applicability of the PI-SMSO are supported by a case study conducted at a coal terminal in China.

The remainder of this paper is organized as follows. First, the processes of ship operation in entrance channels are discussed for one- and two-way channels and one-way channels with ship-passing anchorage (SPAC). Next, this study implements a process-interaction-based simulation model for ship operation (PI-SMSO), and it classes for PI-SMSO. Then, the proposed PI-SMSO is applied to a Chinese coal-import terminal and used to evaluate entrance channel system and available improvement strategies. Finally, concluding remarks and future researches are presented.

## 2. Ship operation in entrance channels

2.1 Entrance channel types

The process of ship operation depends on the types of entrance channels, such as one- or two-way channels, and one-way channels with ship-passing anchorage (SPAC) [2, 4, 5, 9]. As shown in **Figure 1**, one-way channels only allow vessels to move in the same direction (**Figure 1(a)**), which is used for low ship traffic or when excavation of larger channel would be very expensive; two-way channels reduce one-way restrictions and allow inbound and outbound ships to pass each other (**Figure 1(b)**), which is considerable for improving navigation efficiency. However, expanding into a two-way channel costs highly by dredging/excavation especially for the very long channel. In some cases, a compromise is created by constructing SPAC along the longer one-way channel [7]. As illustrated in **Figure 1(c)**, the SPAC divides the channel into two parts (Channel *A* and *B*) and provides temporary moorings for lower-time-value ships (outbound ships in **Figure 1**) waiting until other vessels from opposite directions pass by. In this case, when outbound ships are traveling in Channel *B*, inbound ships can enter Channel *A* rather than waiting in the outside anchorage as shown in **Figure 1(a)**. In this way, ships traveling in opposite directions in a one-way channel can pass each other similar to a two-way channel.

2.2 Ship operation process

2.2.1 Ship traffic flow for one- and two-way channels

Figure 2 describes the flow of ship operations in one- and two-way entrance channels, which focuses on the activities conducted in the anchorage area, entrance channel, and at berths. As illustrated in **Figure 2(a)**, ship operation begins with the arrival of an inbound ship. This inbound ship may or may not wait in the anchorage area, depending on the state of weather, berth congestion, and channel navigability. As illustrated in **Figure 2(b)**, on days with good weather, the berth-assigned ship enters entrance channel in the following two cases: (1) for a one-way channel, no outbound ships are in the channel, and both the navigable depth and the distance between fore-and-aft inbound ships (if there are inbound ships in the channel, we
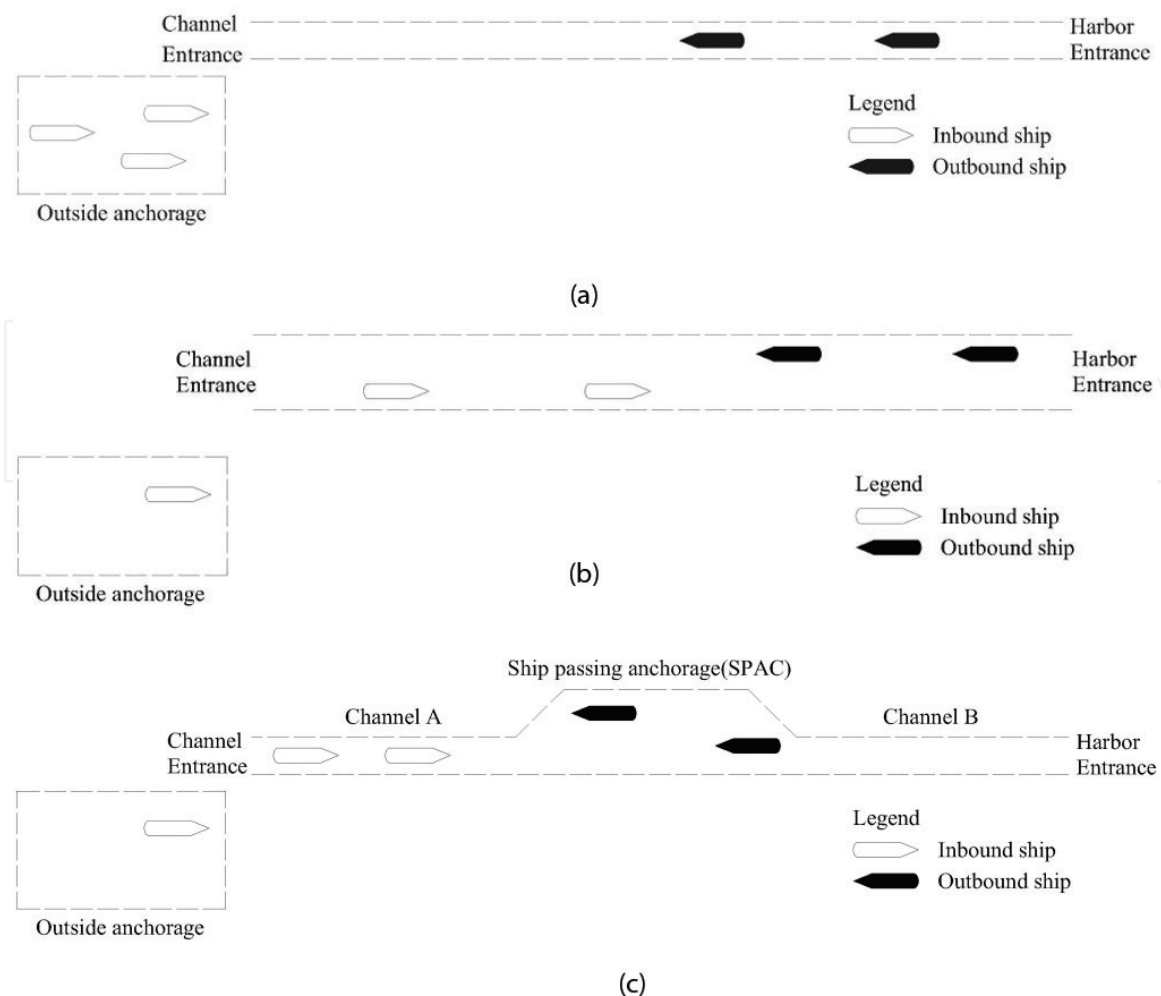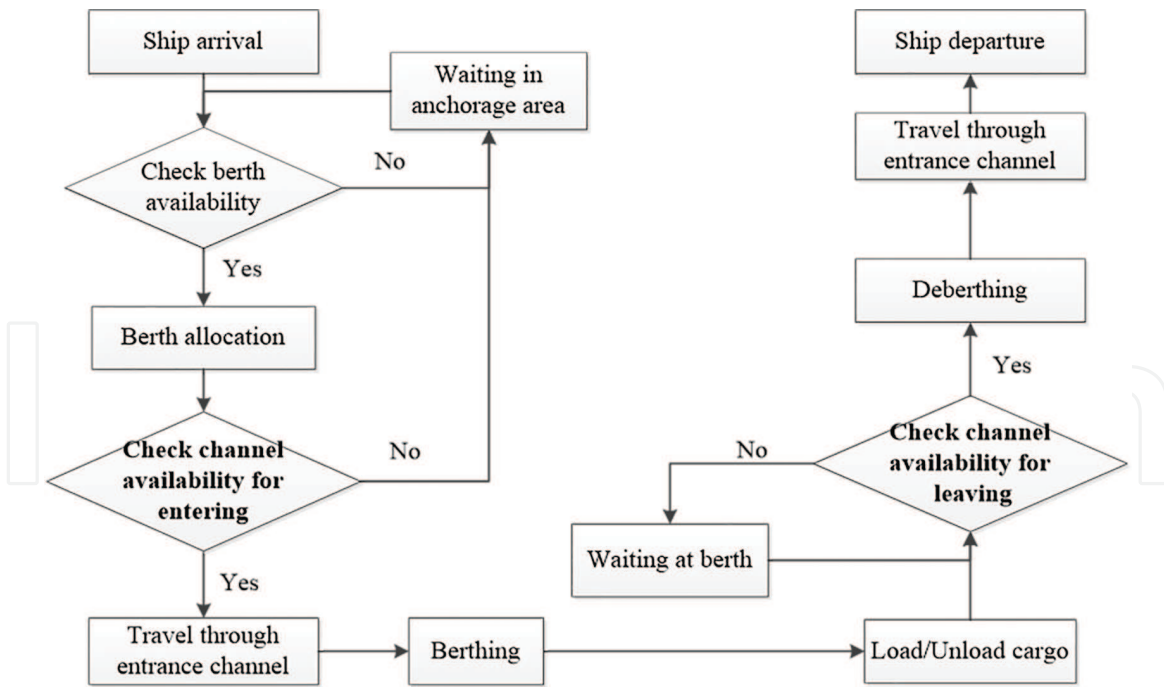
Figure 1.
A diagram of ship traffic flows in entrance channels including one- and two-way channels and a one-way channel with a SPAC. (a) Ship traffic flow for a one -way traffic channel. (b) Ship traffic flow for a two-way traffic channel. (c) Ship traffic flow for a one-way traffic channel with a SPAC.

call safety distance) satisfy the navigation requirement or (2) for a two-way channel, both the navigable depth and the safety distance satisfy the navigation requirement. Usually, this ship is guided by one or more tugboats to the assigned berth through entrance channel and then starts to unload (load) the cargoes onto (from) the quay after necessary preparation. Finally, once cargo unloading and loading is finished, outbound ship leaves berth, enters channel, and leaves port in the following three cases as illustrated in **Figure 2(c)** [7, 10]: (1) for a one-way channel, no inbound ships are in the channel, and both the navigable depth and safety distance satisfy the safety requirement or (2) for a two-way channel, both the navigable depth and safety distance satisfy the navigation requirement. If a port or entrance channel (or both) is closed due to adverse weather (i.e., strong winds, high waves, or heavy fog), we must know the number of days with adverse weather and how these heavy-weather days are usually distributed in a year.

2.2.2 Ship traffic flow for a one-way traffic channel with a SPAC

Figure 3(a) shows the overall logic of ship operations in a one-way channel with a SPAC. Setting a SPAC in a one-way channel changes the logic of checking channel availability in **Figure 2(a)**. The detail on changes is discussed in the following:

(1) **Figure 3(b)** illustrates the logic flowchart for checking channel availability for an inbound berth-assigned ship (CCA4IS). As shown in **Figure 3(b)**, on days with good weather, the berth-assigned inbound ship enters entrance channel in the

(a)
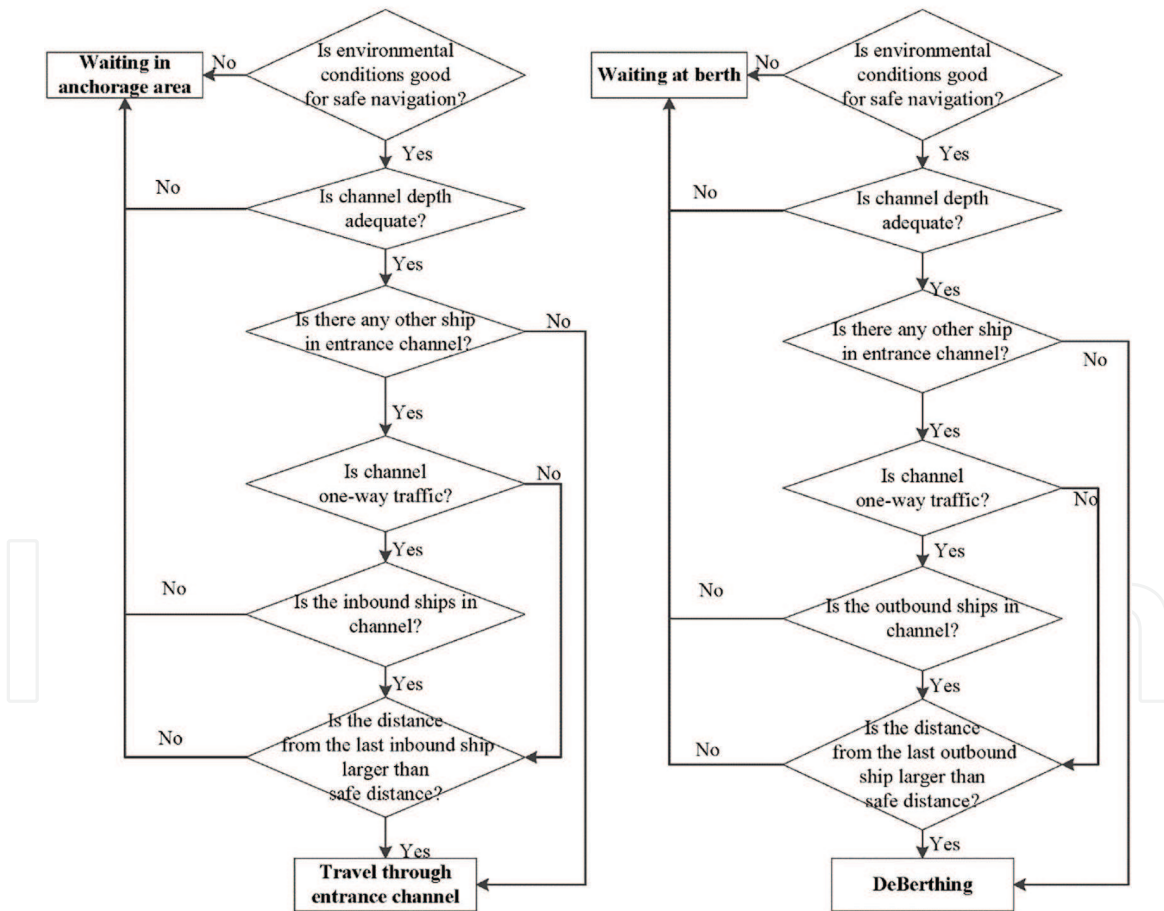
(b)

Figure 2.
The overall logic flowchart of ship operation simulation in one- and two-way traffic channels. (a) Overall logic flow. (b) Check channel availability for inbound ships. (c) Check channel availability for outbound ships.

following two cases: (1) if no outbound ships are traveling in both Channels *A* and *B*, both the navigable depth and safety distance satisfy the navigation requirement or (2) if only lower-priority outbound ships are traveling in Channel *B*, the SPAC
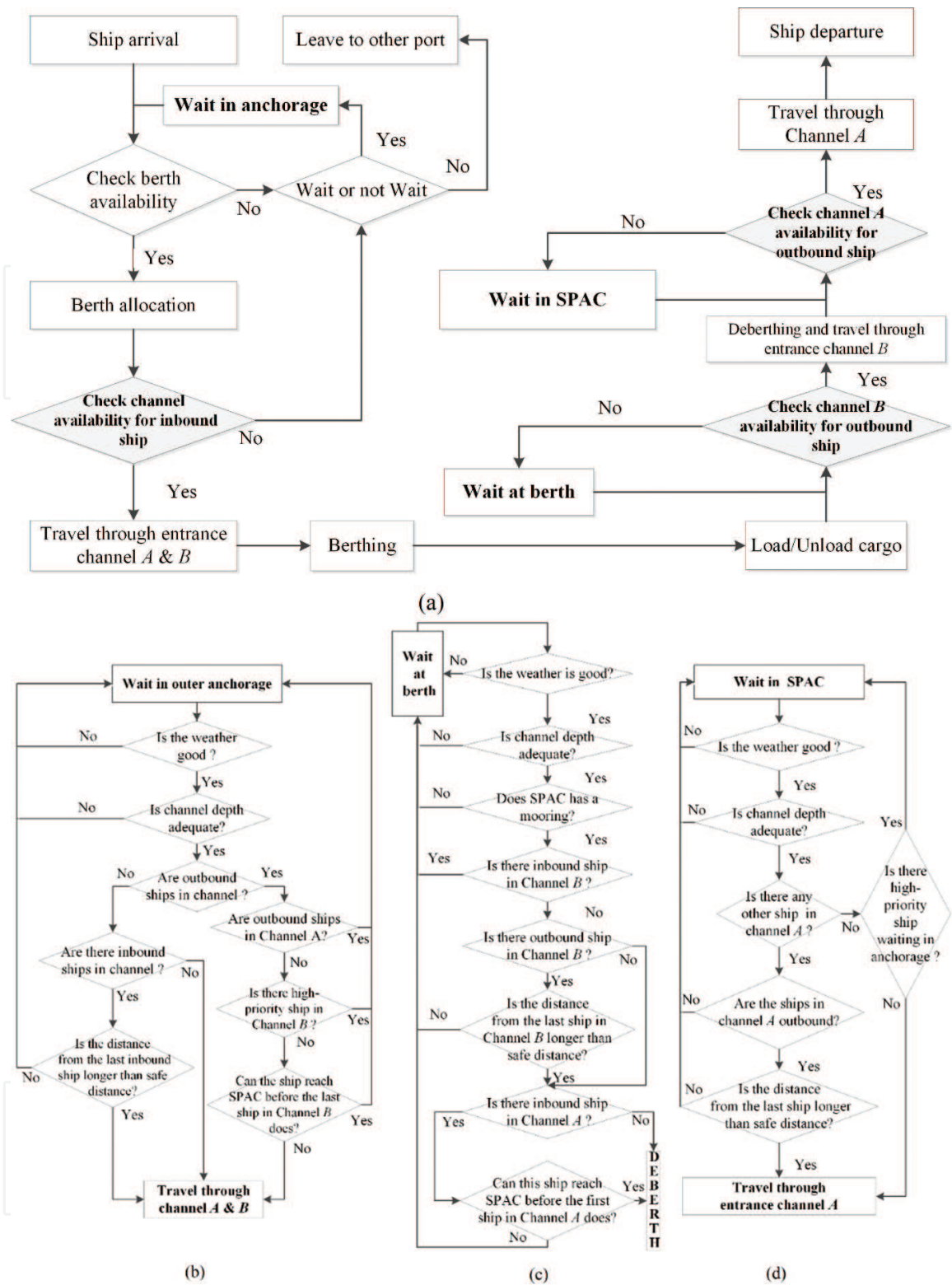
Figure 3.
The logic flowchart of ship operations for cargo-import ports with a SPAC (a) overall logic, (b) CCA4IS, (c) CCBA4OS, and (d) CCAA4OS.

can accommodate these outbound ships, and the last outbound ship in Channel B can reach the SPAC before this ship does.

(2) **Figure 3(c)** shows the logic of checking the availability of Channel B for an outbound ship at berth after finishing cargo unloading (CCBA4OS). As illustrated in **Figure 3(c)**, the ship deberths and enters entrance channel in the following two cases: (1) if no inbound ships are traveling in Channel A, the navigable depth and safety distance satisfy the safe navigation requirement or (2) if one or more inbound ships are traveling in Channel A, the SPAC has at least one idle mooring

position for this outbound ship, and this outbound ship can arrive at the SPAC before the first inbound ship in Channel *A*.

(3) **Figure 3(d)** checks the availability of Channel A for an outbound ship from the SPAC (CCAA4OS), and the ship leaves SPAC and enters Channel *A* in the following two cases: (1) no ships are traveling in Channel *A*, and no higher-priority ships are waiting in the outside anchorage or (2) if outbound ships are traveling in Channel *A*, both the navigable depth and the safety distance satisfy the safe navigation requirements.

3. Simulation modeling of ship operation

To evaluate the performance of the stochastic port system, we implement a process-interaction-based simulation model in Java™ [11], which simulates ship operations in one- or two-way channels, and a longer one-way channel with a SPAC according to the logic flowchart in Section 2.

### 3.1 Process-interaction-based simulation

There are basically three approaches that can be used for discrete event simulation: the event-based, the activity-based, and the process-interaction approach. Process-interaction simulation is a typical discrete event simulation paradigm. Since processes resemble objects in the real world, process-interaction simulation is often easy to understand, which is used in HLA (high-level architecture), DIS (distributed interactive simulation), and other object-oriented distributed simulations [12]. Therefore, we apply the process-interaction approach to the ship operation simulation model in this study.

The process-interaction worldview provides a way to represent a system's behavior from the active entities point of view according to the authors of SIMULA [13]. Thus, a system is modeled as a set of active entities in interaction, and the life cycle of each active entity consists of a sequence of events, activities, and delays. So in the ship operation simulation, a ship is an example of an active entity. Each ship performs the following sequence of activities: arrive at a port area, wait in the anchorage area, transit from anchorage area to berth, get cargo handled, leave the berth and enter the channel, and depart from port. Besides, the model also includes other components providing services for ships, such as anchorage area, entrance channel, and berth.

3.2 Simulation implementation

According to the process-interaction worldview, an active entity requires special mechanisms for interrupting, suspending, and resuming its execution at a later simulated time. Thus, Java programming language is suitable as it offers at least a SIMULA's coroutine-like mechanism. Therefore, we implement a process-interaction-based simulation model for ship operation (PI-SMSO) in Java programming language, and the implemented Java classes consist of foundational class library for process-interaction simulation (PIS library) and business class library for ship operation simulation (SOS library), as shown in **Figure 4**.

PIS library is a collection of public classes for process-interaction simulation, such as *Process*, *Entity*, *Queu*e, and *Simulation* as shown in **Figure 4**. The *Process* class is the base class for a process-interaction simulation which extends *java.lang. Thread* and provides all of the necessary operations for the simulation system to control the simulation entities within it, and for them to interact with it and each
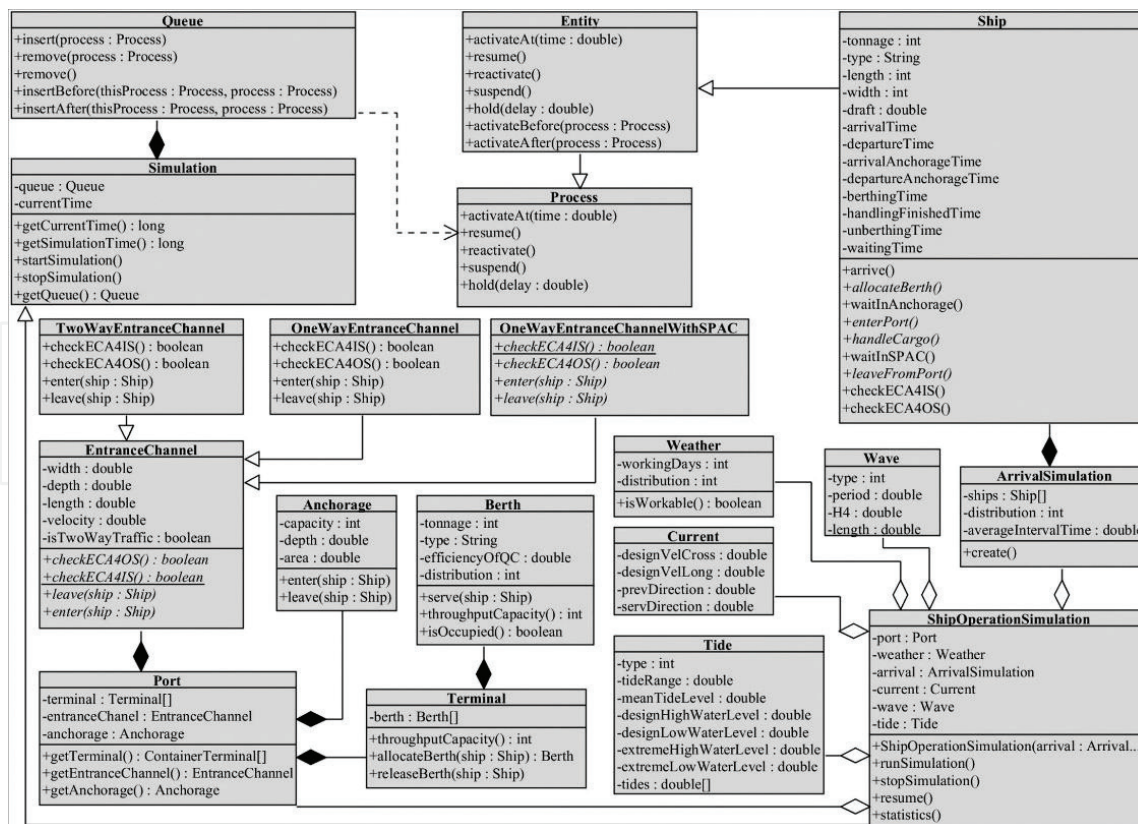
Figure 4.
Static structure diagram of classes implemented for ship traffic flow simulation.

other, such as activate, suspend, reactivate, and terminate a process. The *Entity* class represents the entities within a simulation which is derived from *Process* and has an independent thread of control associated with them at creation time, allowing them to convey the notion of activity necessary for participating in the simulation. The *Queue* class stores the inactive simulation processes within the simulation. The *Simulation* class derived from *Process*, which starts and stops a simulation, schedules the simulation processes: remove the process at the head of the queue and reactivate it. In simulation models, *Process*es are managed by a *Simulation* scheduler and are placed on a *Queue* (the event list).

SOS library is a collection of classes specialized for ship operation simulation, which are derived from the PIS library. Based on the components in a ship operation system, SOS library mainly consists of *Ship*, *Port*, *Terminal*, *Anchorage*, *EntranceChannel*, *ArrivalSimulation*, and *EntranceChannelSystem* classes as shown in **Figure 4**. The *Port*, *Terminal*, *Anchorage*, and *EntranceChannel* classes are permanent entity objects to provide services for *Ship* entities. The *ArrivalSimulation* class generates *Ship* entities randomly according to the ship arrival pattern. The *EntranceChannelSystem* class, a subclass of *Simulation*, schedules the processes of ship entities in and out of the port, makes a statistics analysis on simulation results, and outputs every ship's waiting time and berth's utilization ratio. The *Ship* class, a subclass of *Entity*, represents a ship entity, which is the core component of a process-interaction ship operation simulation model. The primary Java classes of PI-SMSO are illustrated in **Figure 4**, and it runs a simulation experiment as follows:

(1) Class *ShipOperationSimulation* is the control class of a simulation experiment. It initializes and activates the ship arrival process (Class *ArrivalSimulation*) and initializes port resources (e.g., Class *Port*, *Berth*, *Anchorage*, and *EntranceChannel*) and environmental conditions (e.g., Class *Current*, *Wave*, and *Tide*), then starts the simulation experiment.

(2) Class *ArrivalSimulation* generates a series of *Ship*s according to an inter-arrival time distribution [10, 14, 15]. For example, negative exponential distributions (NEDs) can be used to describe the arrival process [2], and its density function is $f(t) = \lambda e^{-\lambda t}$ (λ = arrival rate; t = inter-arrival time).

(3) Class *Ship* performs all activities of a ship as illustrated in **Figure 5** and records all necessary times related to performance measures.

Method *arrive* records the ship's arrival time and initializes its attributes (e.g., ship tonnage, dimensions, and cargo capacity).

Method *allocateBerth* requests for a berth according to berth allocation policy and queue priority [16], such as first-come-first-serve rule, longest/shortest processing time, and largest/smallest ship size. If a berth is assigned to this ship, the method records the time of berth availability and steps to Method *checkECA4IS*. Otherwise, this ship enters anchorage and waits (Method *waitInAnchorage*).

Method *checkECA4IS* checks weather, water depth, safety distance, and traffic situation for permission to enter channel as illustrated in **Figures 2** and **3**. In case a problem exists, the ship enters and waits in anchorage (Method *waitInAnchorage*). Otherwise, it steps to Method *enterPort*.

Method *waitInAnchorage* checks the availability of a free berth for no-berth-assigned ships (Method *allocateBerth*) and/or the availability of entrance channel
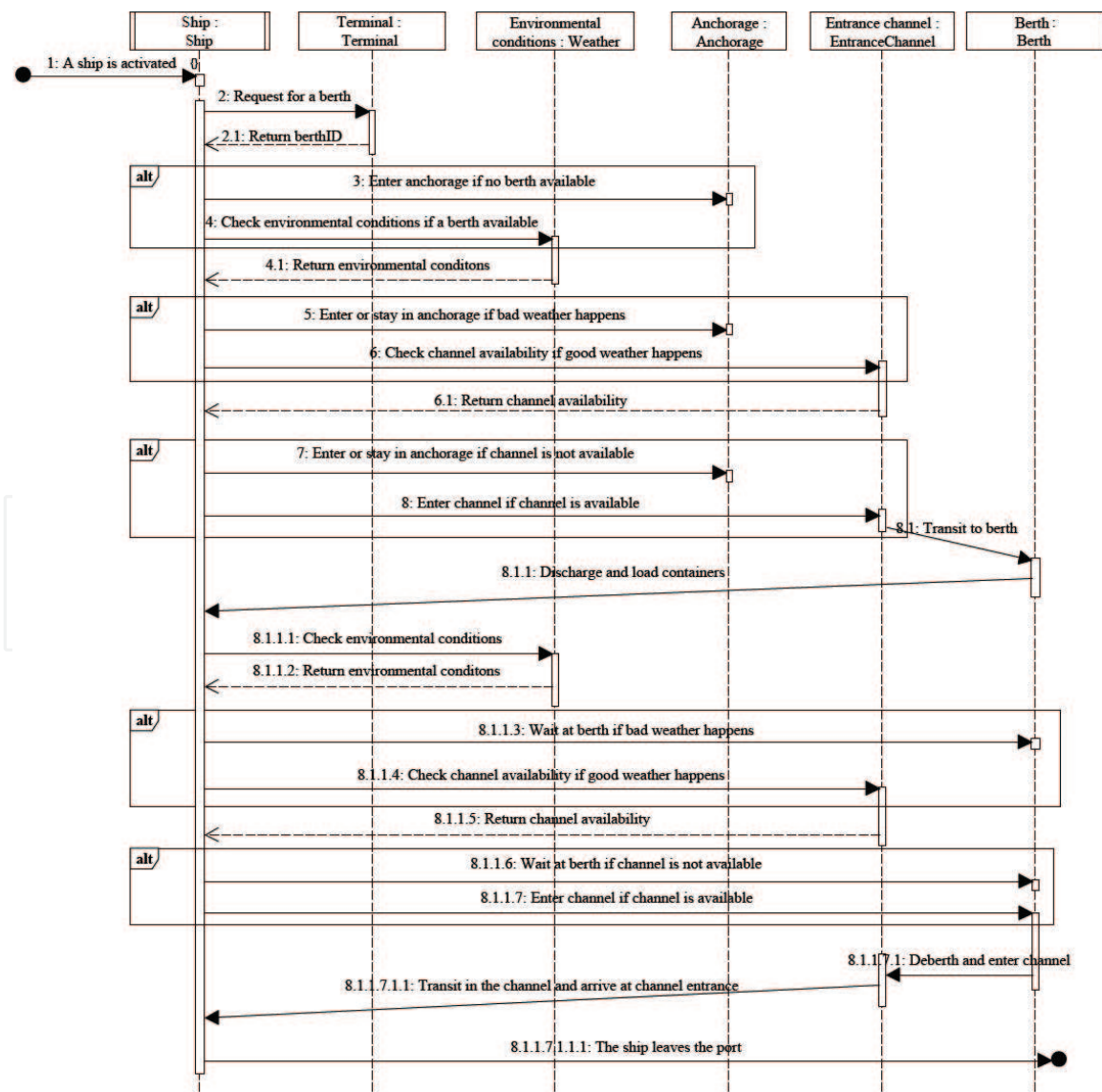
Figure 5.
UML sequence diagram for simulating ship operation in anchorage area, entrance channel, and berths.

for berth-assigned ships (Method *checkECA4IS*). Once all states meet safety require-ments, the ship leaves anchorage, records the waiting time caused by berth occupa-tion or channel unavailability, and enters Method *enterPort*.

Method *enterPort* transits this ship to the assigned berth via entrance channel and steps to Method *handleCargo*.

Method *handleCargo* discharges/loads cargoes from/onto the ship over a random berth service time and steps to Method *checkECA4OS*. For example, berth service time for each type of ship is fitted to an Erlang-k distribution [2, 17], and its prob-ability density function is $f(t) = (k\mu)^k t^{k-1} e^{-k\mu t}/(k-1)!$ (μ = the number of ship services per day, and k = shape parameter).

Method *checkECA4OS* checks weather, water depth, safety distance, and traffic situation for permission to enter channel and leave the port. For one- and two-way channels without SPAC, if the *checkECA4OS* is "RURE," the outbound ship leaves the berth, travels through channel, and steps to Method *leaveFromPort*. For one-way channels with a SPAC, if the Channel *B* is available, the outbound ship leaves the berth, seizes an anchorage in SPAC, then travels through Channel *B*, and steps to Method *waitInSPAC*.

Method *waitInSPAC* records the time of arrival at SPAC, accommodates outbound ship mooring, and waits until Channel *A* is accessible. If Chanel *A* is accessible, the ship leaves the SPAC and enters Channel *A* and records the time of departure from SPAC, releases the occupied SPAC's anchorage, travels through Channel *A*, and steps to Method *leaveFromPort* finally.

Method *leaveFromPort* makes the ship entity exit the port system and records its departure time.

(4) Class *ShipOperationSimulation* finally stops the simulation experiment, updates the turnaround time and number of inbound and outbound ships, per-forms necessary statistical analysis, and outputs the values of port performance indicators.

3.3 Model verification and validation

This PI-SMSO model is verified and validated to confirm that it is correctly implemented with respect to the process of ship operation; we can use it to evalu-ate the port performance and then do more analysis. First, the model is developed through sub-models and individually examined by a subject-matter expert. Second, tracing approach comparing the simulation results with manual calculations is used to check the logic implemented in the model throughout the development of simulation model. Finally, we performed several simulation experiments based on real data on hand and compare the simulated values of key performance indicators with the real operational data, to check the accuracy of the model's representation of the real system [14, 18]. In this study, the key performance indicators we focus on are average turnaround time, average waiting time, average service time, waiting-time/service-time ratio, and berth utilization ratio; see Section 3.4.

3.4 Port performance indicators

Port performance measures the quality of service provided by ports, which are used to select an optimal design alternative [2, 19]. The most used indicators are (1) average turnaround time (ATAT) [20], (2) average waiting time (AWT) [4, 5, 21], (3) average service time (AST), (4) waiting-time/service-time ratio (AWT/AST) [21], and (5) berth utilization ratio (ρ) [21, 22].

The ATAT is the total time between ship arrival and departure, which portrays the port capability and the ability to provide services with high productivity and

performance [5, 20]. The AST is the average value of the time between ship berthing and departure. The AWT is the average value of waiting time for the availability of a berth (AWTB) and the entrance channel (AWTC) [4, 5, 21]. AWT/AST is the ratio of the AWT to the AST, which is widely used as a measure of the service level of a terminal [21]. Berth utilization is the ratio of time the berth is occupied by vessels to the total time (1 year). High berth occupancy is a sign of congestion (>70%) and hence decline of services, while low berth occupancy signifies underutilization of resources (<50%) [22].

4. Case study

A specialized coal terminal in southern China serves local coal imports mainly from ports of Qingdao and Rizhao. Currently, this terminal has three berths and a one-way entrance channel, and its port throughputs is 16 million tons per year. According to its master planning, the throughputs of coal imports will be expected to increase to 20, 24.5, and 36 million tons per year in sequence as shown in **Table 1**, considering the rapid development of thermal power generation and steelmaking industries. Thus, as shown in **Tables 1** and **2**, more ships, even larger ships (e.g., 70,000- and 100,000-DWT bulk carriers), will call at this terminal, which leads to further pressures on the berths and entrance channel. Therefore, we initiate an evaluation of port system for Stages II, III, and IV, including entrance channel (see **Table 3**) and berths, to evaluate its performance (i.e., AWT/AST, AST, ATAT, AWTC, AWTB, and AWT, and the acceptable AWT/AST is 0.4) and identify the possible bottlenecks and then explore improvement strategies to improve its port performance based on a proactive long-term vision.

4.1 Simulation experiments

4.1.1 Stochastic characteristics

Table 4 lists the characteristics of environmental conditions including tides, waves, and current. We also collected historical data, such as the intervals between successive inbound ships, berth service times for each design ship, and port performance (ATAT, AWT, and AWT/AST). And we deduce that both intervals between ship arrivals and berth service time follow exponential distribution, and the parameters of each distribution (μ and λ) are listed in **Table 5**.

Item		Port scale				DWT of design ships calling at this berth (t)
		Stage I	Stage II	Stage III	Stage IV	
Number of berths	35,000-DWT	2	2	2	2	10,000, 20,000, 35,000
	50,000-DWT	1	1	1	1	20,000, 35,000, 50,000
	70,000-DWT			1	1	35,000, 50,000, 70,000
	100,000-DWT				1	50,000, 70,000, 100,000
Expected port throughput (10^4 t)		1600	2000	2450	3600	

Table 1.
The specifications of berths and their serving design ships and expected port throughputs.

Deadweight tonnage(t)	Overall length, Loa(m)	Molded breadth, B (m)	Static draft, T (m)	Actual load capacity, G (t)	Mean service time, t_s (h)
10,000	135	20.5	8.5	10,000	8.6
15,000	150	23.0	9.1	12,000	10.4
20,000	164	25.0	9.8	16,000	12.0
35,000	190	30.4	11.2	28,000	19.4
50,000	223	32.3	12.8	40,000	26.0
70,000	228	32.3	14.2	56,000	27.5
100,000	250	43.0	14.5	80,000	25.0

Table 2.
The specifications of the bulk ships calling at this coal terminal.

Channel type	Channel dimensions (m)				Port performance			
	Width	Depth	length	Navigable water level	AWT/AST	AWTC (h)	AWTB (h)	ATAT (h)
One-way traffic	178	15.6	8620	0.30	0.38	1.3	4.7	21.7

Table 3.
Existing entrance channel dimensions and its port performance.

4.1.2 Verification and validation

We run a series of simulation experiments based on **Tables 4** and **5** and compare the simulated results with real data from this coal terminal of Stage I to verify and validate the proposed simulation model. **Table 6** shows the simulation results for running the simulation model for 60 replications with each replication lasting for 1 year and gets the simulated average values of performance indicators. From the

Environmental condition	Item	Value
Tides	Tide type	Semidiurnal tide
	Average tidal range (m)	1.30
	Average level (m)	1.34
	Design high water level (m)	2.72
	Design low water level (m)	0.30
Waves	Height of $H_{4\%}$ (m)	2.0
	Period (s)	5.8
	Angle to channel (degree)	22.5
Current	Velocity (m/s)	0.66
	Angle to channel centerline (degree)	45
Adverse weather days (days/year)		20

Table 4.
Environmental conditions including tides, waves, and current.

Item	Unit	Value
1. *Port characteristics*		
-Berth specification		See **Table 1**
-Distribution of service time		Exponential distribution
-Mean service time per ship, μ	Hours	See **Table 2**
2. *Ship characteristics*		
-Distribution of inter-arrival times		Exponential distribution
-Mean inter-arrival time, $1/\lambda$		
• Stage I	Hours	8.3
• Stage II		7.1
• Stage III		9.2
• Stage IV		8.3
-Ship specifications		See Table 3
3. *Simulation parameters*		
-Simulation time, T_{sim}	Hours	365 × 24
-Simulation repetitions		
• One-way channel		20
• Two-way channel		40
• One-way channel with a SPAC		40

Table 5.
Simulation parameters of simulation model for this coal terminal.

Performance indicator	Actual data	Simulation results	Difference percentage (%)
AWT/AST	0.38	0.36	−5.4
AWTC (h)	1.3	1.21	−6.9
AWTB (h)	4.7	4.43	−5.7
AST (h)	15.79	14.77	−6.5
ATAT (h)	23.6	23.21	−1.6
ρ	0.52	0.50	−4.2

Table 6.
Comparison of simulation results and actual data.

results from **Table 6**, we find that all average values of simulation results lie within 7% difference from the actual values, which means the established simulation model built for this terminal is considered to be close to the actual system.

4.2 Results and discussions

4.2.1 Evaluation of current berths and channel system

We evaluate the performances of the berths and entrance channel system for Stages II, III, and IV using the proposed simulation model, provided that the dimensions of entrance channel remain unchanged. **Table 7** shows the channel dimensions, the values of port performance indicators for Stages II, III, and IV.

Item		Stage I	Stage II	Stage III	Stage IV
Entrance channel	Channel type	One-way channel			
	Width (m)	178	178	180	224
	Depth (m)	15.6	15.6	17.1	17.6
	Length (m)	8620	8620	9810	10,200
Port performance	AWT/AST	0.38	1.15	0.41	0.63
	ρ	0.52	0.62	0.55	0.58
	ATAT	23.6	35.4	28.9	39.4
	AST	15.7	15.6	18.6	22.2
	AWT	6.0	17.9	7.6	14.0
	AWTC	1.3	1.8	1.5	1.9
	AWTB	4.7	16.1	6.0	12.1

Table 7.
The channel dimensions and measures of port performance for Stages I, II, III, and IV.

(1) In Stage II, the annual port throughput is expected to hit 20 million tons of coal. If the berths and channel dimensions remain unchanged, the AWT/AST is as high as 1.15 beyond the accepted AWT/AST of 0.4 as shown in **Table 7**. So the terminal will be running with an extremely low efficiency, which leads to higher vessel wait. Note that 90% of the AWT (17.9 h) is spent waiting for the availability of a berth (AWTB = 16.1 h). Therefore, it seems that more berths should be provided in order to improve port performance.

(2) In Stage III, the expected port throughput is 24.5 million tons of coal; the channel is still a one-way channel, but a new 70,000-DWT berth is built to accommodate deeper-draft bulk carriers. Thus, for serving larger ships, the entrance channel has to be expanded as shown in **Table 7**: the channel depth being expanded to 17.1 m, channel width being expanded to 180 m, and channel length being expanded to 9810 m. Meanwhile, by building a new berth, the AWT/AST falls to 0.41 from 1.15, the ATAT falls to 28.9 h from 35.4 h, and the AWTB is only 6.0 h with a decrease of 10 h from 16.1 h. Therefore, in Stage III, the terminal with a one-way channel will be operated with an acceptable service level without expanding one-way to two-way channel.

(3) In Stage IV, the expected port throughput is 37 million tons of coal; the channel is still a one-way channel, but a new berth is built to serve the 100,000-DWT bulk carriers. So to serve 100,000-DWT ships, the dimensions of one-way channels are expanded to 17.55 m depth, 224 m width, and 10,200 m length. Meanwhile, the AWT/AST is 0.63, higher than the accepted service level of 0.4. And the ships take 86% of the AWT to wait for the availability of a berth. Therefore, expansion strategies are needed to improve port performance in Stage IV.

4.2.2 Improvement strategies and their performance

According to simulation results and analysis, we propose three types of improvement strategies for Stages II and IV, including setting a ship-passing anchorage (SPAC), expanding into a two-way traffic channel (E2TWC), and building new berths (BNB), and the detailed parameters are given in **Table 8**.

We run the simulation models to get simulation results for all proposed alternatives and to explore the performance improvements as follows.

Stage	Strategy	Entrance channel type	Berths (DWT, t)
II	SPAC	One-way with SPAC	35,000, 35,000, 50,000
	E2TWC	Two-way	
	BNB	One-way	35,000, 35,000, 50,000, 70,000
IV	SPAC	One-way with SPAC	35,000, 35,000, 50,000, 70,000, 100,000
	E2TWC	Two-way	

Table 8.
The details of the proposed improvement strategies.

Strategy	Entrance channel type	AWT/AST	
		AWT/AST	Percentage decrease (%)
Current	One-way	1.15	/
SPAC	One-way with SPAC	0.77	33
E2TWC	Two-way	0.56	51
BNB	One-way	0.25	79

Table 9.
The AWT/AST between current and proposed alternatives for Stage II.

Strategy	Entrance channel type	AWT/AST		Construction cost of channel (10^4 CNY)
		AWT/ AST	Percentage decrease (%)	
Current	One-way	0.63	/	0
SPAC	One-way with SPAC	0.37	40.8	0
E2TWC	Two-way	0.35	44.2	2200

Table 10.
The AWT/AST and channel construction costs between current and proposed alternatives for Stage IV.

As shown in **Table 9**, for Stage II, when comparing the current AWT/AST of 1.15, the AWT/ASTs for SPAC, E2TWC, and BNB strategies are 0.77, 0.56, and 0.25. Therefore, strategies SPAC, E2TWC, and BNB all improve the service level, and the BNB strategy is the best way. However, according to the required AWT/AST of 0.4, only the BNB strategy by building a new 70,000-DWT berth is practicable in Stage II.

Similarly, we also collect the AWT/ASTs for both SPAC and E2TWC strategies in Stage IV and list them in **Table 10**. As shown in **Table 10**, the AWT/ASTs for SPAC and E2TWC strategies are 0.37 and 0.35, so that both SPAC and E2TWC strategies are most effective alternatives in Stage IV from point view of AWT/AST. However, considering modeling costs of these two strategies, we suggest the strategy SPAC as a practical alternative for Stage IV.

Finally, we list the proposed entrance channel and berths for Stages II, III, and IV in **Table 11**. Therefore, this application shows that the implemented simulation model is helpful for evaluating the capacity of entrance channel, identifying the bottlenecks in port system, and determining an optimal improvement strategy effectively for improving port performance.

Stage	Entrance channel type	Berths (DWT, t)	
		Master plan	Proposed
I	One-way	35,000, 35,000, 50,000	35,000, 35,000, 50,000
II			35,000, 35,000, 50,000, 70,000
III		35,000, 35,000, 50,000, 70,000	
IV	One-way with a SPAC	35,000, 35,000, 50,000, 70,000, 100,000	

Table 11.
The proposed entrance channel and berths for Stages II, III, and IV.

5. Conclusions

Increases in ship size and number lead to further pressures on the entrance channel to minimize time in port. Moreover, the design of an entrance channel system is a complex challenge, considering the stochastic environment and time-consuming calculations. Therefore, we develop a process-interaction-based simulation model for ship operation (PI-SMSO) using Java programming language, to help the designers to evaluate the capacity of entrance channel and then to determine when to expand the channel and to select the dimensions of the expanded channel. The PI-SMSO simulates ship operation in the entrance channel including one- or two-way traffic channel, or a one-way channel with a ship-passing anchorage, and outputs the values of the selected port performance indicators. Finally, we apply the PI-SMSO to a Chinese coal terminal to explore its bottlenecks and to evaluate available improvement strategies for further development of this coal terminal. And the results prove that the implemented PI-SMSO performs well in evaluating the capacity of entrance channels and identifying the possible bottlenecks of a port system. Therefore, the proposed PI-SMSO provides a reference for government agencies involved with the design of port systems.

Moreover, the architecture PI-SMSO includes other water areas, such as outside anchorage area, maneuvering basin, and mooring basin; we can apply PI-SMSO to evaluate the capacity of water areas of a port. Besides, further researches will focus on optimizing the general layout of a port as a whole by integrating ship operation simulation in water area with port operation simulation in land area, considering the water areas and land areas are interlinked.

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