

Dynamic Ship Domain Models for Capacity Analysis of Restricted Water Channels

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Developing adequate ship domain models may significantly benefit vessel navigation safety. In essence, navigation safety is collectively affected by the navigable waterway condition, the size and shape of the ship, and operators' skills. The existing ship domains mainly use constant values for the model input parameters, making them incapable of handling site-specific conditions. This study proposes dynamic ship domain models that take into consideration navigable waterway conditions, ship behaviours, ship types and sizes, and operators' skills in a holistic manner. Specifically, the conditions of restricted waterways are classified into navigating along the channel, crossing the channel, joining another flow and turning. The ship types considered include ships that transport non-hazardous goods and Liquid Natural Gas (LNG) ships that are in need of additional security zones. A computational experiment is conducted for model application using data on water channel design and ship traffic volumes related to navigating along the channel, joining another flow and turning. Comparisons of results obtained between the proposed dynamic models with real ship traffic counts reveal that the proposed models could achieve a higher level of accuracy in estimating the capacity of restricted water channels. It therefore could potentially deliver safety enhancements of waterway transportation.

KEYWORDS

1. Restricted waters. 2. Ship behaviour. 3. Ship domain model. 4. Waterway condition.

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1. INTRODUCTION. Safety is a major priority of waterway transportation. In order to avoid traffic collisions in navigable waterways, ships are required to maintain

a safe zone between each other that is known as the ship domain. In the last decades, the modelling of ship domains has drawn increasing attention. This was motivated by waterway safety analysis aimed at gaining a higher level of understanding of how ship collisions occur, what are the most possible waterway navigation environments that may lead to collisions, and which ones are the most significant collision contributing factors. The developed domain models could generally be employed for assessment of ship collision risks, design and capacity analysis of inland navigable waterway channels and offshore waterway facilities and development of intelligent ship traffic control strategies. Countermeasures could then be identified to effectively enhance waterway transportation safety (Deng, 2009; Wang, 2012).

The first ship domain model was developed by Fujii and Tanaka (1971) to deal with the safe navigation of ships in open waters off Japan. In this model, the ship domain is represented by an ellipse with semi-major and semi-minor axle lengths set as 8 and 3.2 times or 6 and 1.6 times the ship length. With an ellipse-shaped ship domain defined for each ship, this gives guide distances to keep ships safe distances apart, giving a trigger for ship officers to take appropriate action to avoid a collision. Goodwin and Kemp (1975; 1977) proposed a sector-shaped domain model to investigate the maritime traffic in southern North Sea waters based on data generated by a radar simulator from collision experiments. In the Goodwin and Kemp model, the ship domain is defined as the area of three circular sectors with 112.5° , 112.5° , and 135° degrees of centre angles and 0.7 mile, 0.85 mile, and 0.45 mile radii in reference to the centre of gravity of the ship. Benefiting from this and the Fujii model, Tak and Spaans (1977) introduced a new model that still creates an elliptical-shaped ship domain in which the position of the ship was moved backward and the ship's head was turned to port by an angle, making the area starboard, port and astern in proportion to the three circular sectors of the Goodwin (1977) model. In order to handle the difference in ship behaviours, Fujii (1981) also constructed a long ovate domain model by modifying the elliptical-shaped domain model. Due to the fact that the boundary established by the three circular sectors in the Goodwin model with varying radii is not a smooth curve, it has significantly limited the model's practical applications. To overcome this limitation, Davis et al. (1980; 1982) refined the model by using simulated data to create a circular ship domain area identical to the area established by the Goodwin model.

More recently, ship domain modelling has focused on addressing ship collision avoidance incorporating ship operators' behaviours. For instance, Bi (2000) and Bi et al. (2003) developed dynamic collision avoidance ship domain models that could help determine the ship domain boundary varying with the threshold of collision risks. Smierzchalski and Michalewicz (2000) and Smierzchalski (2001) introduced a hexagon-shaped ship domain model in which the ship domain is determined by ship's speed and cycle parameters. The model is convenient for optimising the ship's path to avoid collisions using an evolutionary algorithm. Sun (2000) proposed a ship domain model to handle poor visibility from the perspective of collision avoidance and safety navigation. Guo (2001) analysed the boundary of the ship domain for crossing and overtaking situations by holistically considering ship dynamics, operator's psychological quality, and waterway condition. Kijima and Furukawa (2001; 2003) constructed a new ship domain model that could establish an obstructed area and a visible area with which the visible area could be used for protection warning when the obstructed area is in violation. Pietrzykowski and Uriasz (2004) proposed a polygon-shaped ship domain model for evaluating the ship collision risk using

empirical discrete data obtained from different directions around ships. Further, Pietrzykowski and Uriasz (2006; 2009) introduced a fuzzy domain model to effectively handle the navigation condition of a waterway to the level of safety required. Lisowski et al. (2000), Zhu et al. (2001), Pietrzykowski (2008) and Wang et al. (2011) analysed the fuzzy boundary of ship domain based on Fuzzy Theory and Neural Networks. Wang et al. (2009), Wang (2010; 2013), Liu (2014) and Xu (2014) proposed a quaternary ship domain model based on unified analytical framework to enhance the real world model operability.

While the development of ship domain models has been focusing on ship collision risk assessment and seeking countermeasures to achieve collision avoidance in open waters, efforts have also been made to ensure safe navigation of ships through restricted water channels. In this respect, Goldwell (1983) proposed a ship domain model applicable to restricted waters incorporating ship behaviours. Jia (1989) and Fan et al. (2013) proposed a variable ellipse-shaped ship domain model that maintained long and short axes proportional to the length and breadth of the ship to deal with situations of ship encounters in crowded water channels. Xu et al. (2004) introduced a three-dimensional domain model that could readily handle restrictions of waterway depth and vertical clearance. Chen and Guo (2008) proposed a ship domain model for ships using inland waterways with the vertical clearance restricted by bridge heights. For the domain of special purpose ships, Guo (2011) conducted research on the economical channel width for very large LNG carriers based on ship manoeuvring simulation and risk assessment criteria. Further, Wen et al. (2013) defined the width of a moving safety zone around LNG carriers based on the probability of ship collisions and risk assessment criteria. The research showed that the width of moving safety zone around a LNG carrier was determined by the distribution of ship traffic flow, displacement and cruising speed.

1.1. *Ship Domain Discussion.* According to the literature reviewed, existing research ship domain methods can be divided into statistical methods, analytical expression and intelligent technology.

Before the 1980s, statistical analysis or cluster analysis methods were normally adopted in ship domain research. This obtained data from marine traffic investigation or experiments based on radar simulators, analysed the data based on probabilistic methods, and determined the shape and size of the ship domain of the research water area based on consideration of the traffic density, ships' size, speed and Collision Regulations (COLREGS). In this period, the research was based on qualitative methods that did not consider the human factors, environment and ship properties, and the models were quite different in shape and size.

In order to avoid the disadvantages of qualitative methods, experts and scholars used analytical expression to model the ship domain. This took the positions, speeds, directions and other characteristics of the own vessel and vessels around as input and the size of the ship domain as output, calculated the minimum distances to the vessels and barriers around for safe navigation based on shipping manoeuvring equations, steering model and deceleration model, and then determined the size of the ship domain in different directions. Compared with the domains determined by statistical methods, it quantified the boundary of ship domain based on consideration of the ship properties. However, analytical expression models could not meet the requirement of ship domains in complex environments in that they ignored the influence of human factors and the environment.

In recent years, experts and scholars have introduced intelligent technology to the investigation of marine traffic to reveal the relationship between ship domain, human factors and environment. These include neural networks, complex networks, cellular automata, intelligent agents, etc. Existing research only constructed simple exercises on vessel parameters and empirical data, while human factors, navigation environment and other complex factors have not yet been considered.

1.2. *Motivation and Study Objective.* Although the ship domain models developed have greatly benefited safe operations of ships in both open waterways and restricted water channels, they also have some limitations. In particular, the shape and size considered for ship domain calculation were mainly based on data collected from numerical simulations associated with open waterways. Such data differs from ship operations in restricted water channels and real world circumstances. Also, the varying skill levels of ship operators in ship manoeuvring have not been readily incorporated into ship domain modelling. The inability to capture real world conditions of restricted waterways, ship shapes and sizes, and the operators' skills in the existing ship domain models will inevitably compromise the accuracy and precision of model analysis results (Zhou, 2012). This motivates developing new ship domain models using data more suited for restricted water channels and explicitly defining the shape and size of ship domains so that the refined models could be utilised to conduct waterway facility design and traffic operations analysis for restricted waterway channels.

The remainder of this paper is organised as follows. Section 2 briefly explains the characteristics of ship behaviours in restricted water channels and describes the proposed dynamic ship domain model. Section 3 elaborates on model application to restricted waterway channels of Tianjin Port, China. Section 4 compares the result of channel capacity estimation with other different methods. Finally, Section 5 summarises and concludes.

2. PROPOSED DYNAMIC SHIP DOMAIN MODEL

2.1. *Typical Ship Navigation Movements in Restricted Waters.* Generally, ship navigation behaviour aims to maintain the highest ship mobility while not compromising safety performance. Specifically, the ship behaviour may refer to proper navigation and manoeuvre of the ship for collision avoidance. In this context, the ship behaviour concerns not only the behaviour of a single ship. It deals with navigation actions of multiple ships within a certain range of the water channel to ensure waterway safety.

For restricted water channels, ship navigation behaviour can be mainly classified into four categories: i) navigating along the channel; ii) crossing the channel; iii) another flow joining; and iv) turning. As illustrated in Figure 1, navigating along the channel corresponds to ship movements along the main water channel direction entering into or departing from the inland waterway port. Crossing the channel refers to the ship crossing from one side of the restricted water channel at nearly a perpendicular angle to another side. Another flow joining involves two traffic flows at a certain angle arriving at the water channel and merging into one traffic flow under the navigation rules. Turning is related to ship turning motions in the wharf apron of a water channel, leading to a reduction in the channel capacity. Dynamic ship domain models are separately defined for these categories of navigation.

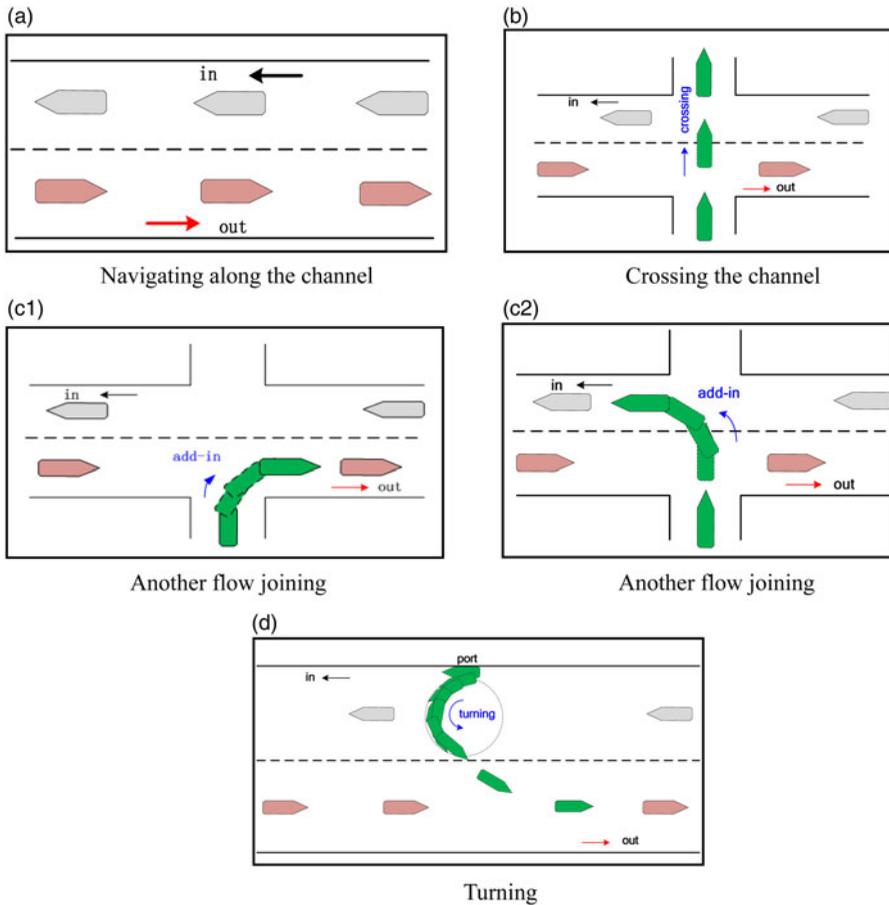


Figure 1. Illustration of typical ship navigation categories.

From the hydrodynamic perspective, the shape of domain for ships navigating along the channel is widely recognised as an ellipse, for which the most representative model is the Fujii Model. This paper sets the shape of the domain for ships navigating along the channel as an ellipse, and then constructs models for other ship navigation movements based on the ellipse model.

2.2. Domain Model for Ships Navigating Along the Channel. For ships navigating along the channel, ships are required to keep a minimum safe distance from ships travelling in the same longitudinal direction. This defines the major axis of the ship navigation domain. For a multi-lane water channel, ships in a lane need to keep a minimum safe clearance with other ships in adjacent travel lanes, which determines the minor axis of the ship domain.

Stopping visual range can be introduced to determine the major axis of ship domain for ships navigating along the channel. In road traffic engineering, stopping visual range refers to the minimum distance for a car to stop when the driver sees barriers or the preceding car stops. Stopping visual range consists of reaction distance, braking distance and safe distance.

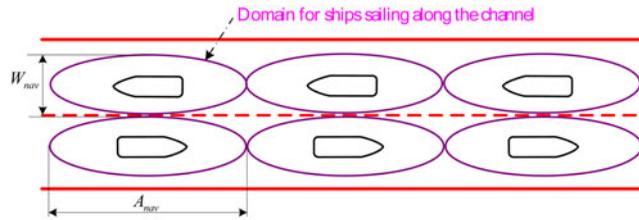


Figure 2. Dynamic ship domain for ships navigating along the channel.

Analogously, a ship should also keep a stopping visual range with the preceding ship when navigating along a channel. Therefore, the stopping visual range for a ship can be defined as:

$$\begin{aligned} S &= S_0 + S_1 + S_2 \\ S_1 &= vt \\ S_2 &= v^2/2a \end{aligned} \quad (1)$$

where S is the stopping visual range for a ship, S_0 is the safe distance which is about a quarter of the ship length, S_1 is the reaction distance, S_2 is the braking distance, v is the initial speed of the ship, t is the response time of the ship operator and a is the braking rate of the ship behind.

If the navigation standard of the channel stipulates a safe distance for ships to keep from the ships in front or behind, the stipulated safe distance can be used as the major axis of ship domain for ships navigating along the channel.

The minor axis of ship domain for ships navigating along the channel can be determined according to the Guidelines for Design of Approach Channel, Code for Design of General Layout of Sea Ports or any other design guidelines for restricted water channels suited.

As shown in Figure 2, the longitudinal and transverse ship domains are respectively defined as follows

$$A_{nav} = S_0 + S_1 + S_2 \quad (2)$$

$$W_{nav} = A + c \quad (3)$$

where A_{nav} is the major axis, W_{nav} is the minor axis, A is the width of track, and c is the safe reach width.

With the ship domain model proposed as above, size-variant ship domains for ships navigating along the channel can be determined for individual ships in longitudinal and cross sectional directions on the basis of ship length and safe reach width. This will, in turn, help create safety clearance standards for overtaking manoeuvres as part of navigating along the channel in restricted waters. It will also assist in developing design specifications for restricted water channels to safely accommodate the projected ship traffic.

The minor axis of the ship domain for ships overtaking should consider interaction between ships. As shown in Figure 3, the transverse distance kept between ships should ensure that suction cannot affect navigation safety. The time ship A reaches the meeting-point (O) should be longer than ship B. As shown in Figure 4, the minor

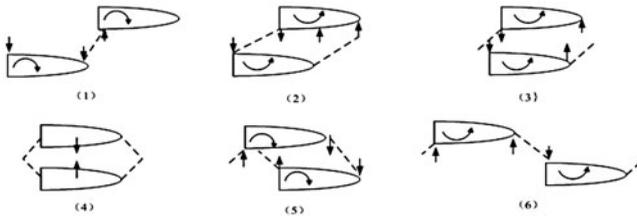


Figure 3. Suction between ships when overtaking.

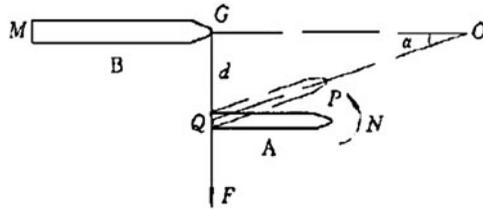


Figure 4. Process of overtaking.

axis of the domain for ships overtaking can be calculated as follows

$$T_{shipA} = (d / \sin \alpha - L_{shipA}) \cdot V_{shipA} \geq T_{shipB} = (d \cot \alpha + L_{shipB}) \cdot V_{shipB}$$

$$d \geq \frac{(L_{shipB} \cdot V_{shipA} + L_{shipA} \cdot V_{shipB}) \cdot \sin \alpha}{V_{shipB} - V_{shipA} \cdot \cos \alpha} = \frac{(L_{shipB} \cdot k + L_{shipA}) \cdot \sin \alpha}{1 - k \cdot \cos \alpha} \quad (4)$$

where T_{shipA} is the time ship A reaches the meeting-point (O); T_{shipB} is the time ship B reaches the meeting-point (O); L_{shipA} is the length of ship A; L_{shipB} is the length of ship B; V_{shipA} is the speed of ship A; V_{shipB} is the speed of ship B; d is the safe transverse distance; α is the included angle of the direction of ship A and ship B; and k is the speed ratio of ship A and ship B.

As a consequence, the longitudinal and cross sectional ship domains for ships overtaking are respectively defined as follows

$$A_{overtaking} = S_0 + S_1 + S_2 \quad (5)$$

$$W_{overtaking} = \frac{(L_{shipB} \cdot k + L_{shipA}) \cdot \sin \alpha}{1 - k \cdot \cos \alpha} \quad (6)$$

2.3. *Ship Domain Model for Crossing the Channel.* For ship crossing navigation shown in Figure 5, the ship crossing domain is defined as the safe water region that another ship could not enter the ship's virtual domain illustrated as the red dotted line range (it is assumed to be the domain of the crossing ship navigating along the channel) when it is crossing the waterway. This indicates that the time for the ships navigating around the crossing ship to the junction of channels should be longer than the time that the crossing ship takes to cross the main channel.

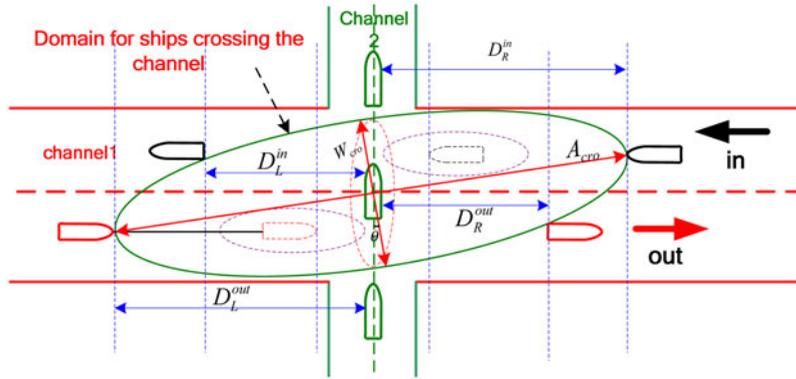


Figure 5. Dynamic ship domain for crossing navigation.

The scale of the crossing domain can be determined as follows:

$$A_{cro} = \frac{D^{in} + D^{out}}{\cos \theta} \tag{7}$$

$$W_{cro} = A_{nav-2} \cdot \cos \theta \tag{8}$$

$$D^{in} + D^{out} = \left(\frac{D_{cro} + L_{cro}}{V_{cro}} \right) \cdot V_{nav}^{in} + \left(\frac{D_{cro} + L_{cro}}{V_{cro}} \right) \cdot V_{nav}^{out} + A_{nav-1} + B_{cro} \tag{9}$$

$$\theta = \arctan \frac{W_{channel}}{2(D^{in} + D^{out})} \tag{10}$$

where A_{cro} is the major axis, W_{cro} is the minor axis, D^{in} is the safe distance from the approaching ships, D^{out} is the safe distance from the departing ships, θ is the angle of main channel 1 and the major axis of the crossing domain, A_{nav-1} is the major axis of ship’s navigation domain voyaging in main channel 1, A_{nav-2} is the major axis of domain for crossing ship navigating along channel 2, D_{cro} is the width of crossing channel 2, L_{cro} is ship length, B_{cro} is the ship width, V_{nav}^{in} is the in-flow ship cruising speed, V_{nav}^{out} is the out-flow ship cruising speed, and $W_{channel}$ is the width of channel 1.

The model considers the influence between crossing ships and ships navigating along the main channel where navigators must judge if crossing is safe. Meanwhile, the safe domains for ships cruising in the same direction in the main channel or crossing the channel could still be determined using the proposed domain model for ships navigating along the channel.

2.4. *Ship Domain Model for “Another Flow Joining”*. Where another channel joins a traffic flow, in general, “another flow joining” may be classified into two types. The first type does not need to go through the reverse traffic flow, while the second type needs to traverse through the reverse traffic flow.

As shown in Figures 6 and 7, the domain for another flow joining is defined as the safe water region that another ship could not enter the ship’s virtual domain illustrated as the black dotted line range (it is assumed as the domain of the crossing ship navigating along the channel) when the flows merge. This means that the time that ships around the crossing ship navigating along the channel reach the junction of channels should be longer than the time that the ship takes to join the flow.

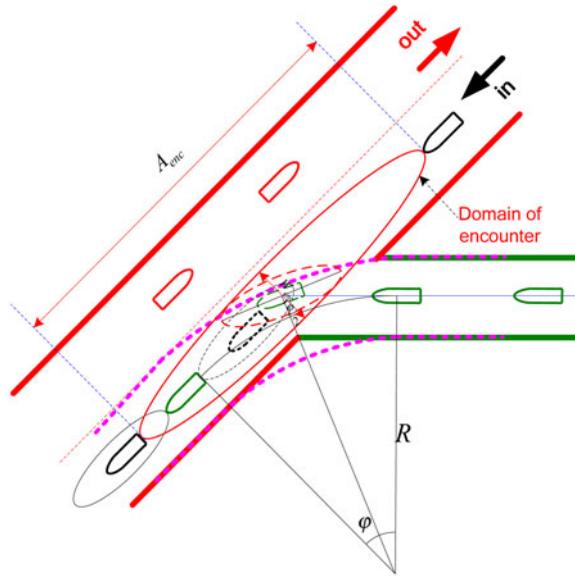


Figure 6. Type I dynamic ship domain for ships joining another flow without affecting reverse flow.

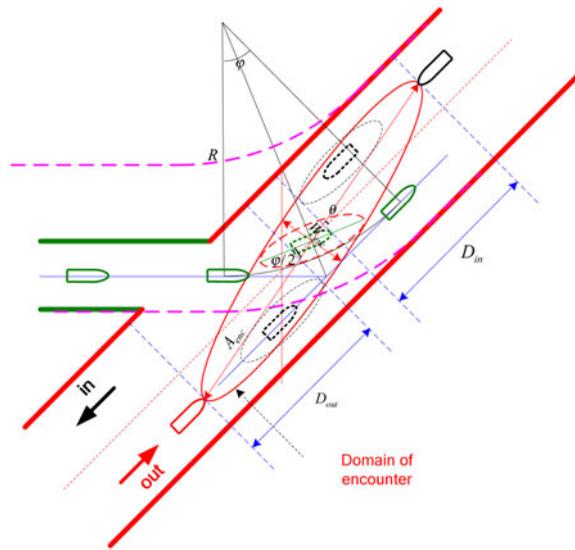


Figure 7. Type II dynamic ship domain for ships joining another flow affecting reverse flow.

As shown in Figure 6, the safe domain for ships joining another flow without the need to go through the reverse traffic flow can be determined as follows:

$$A_{join}^a = V_{nav}^{in} \cdot T_{join} + L_{join} + A_{nav-1} \tag{11}$$

$$W_{join}^a = A_{nav-2} \cdot \sin(\varphi/2) \tag{12}$$

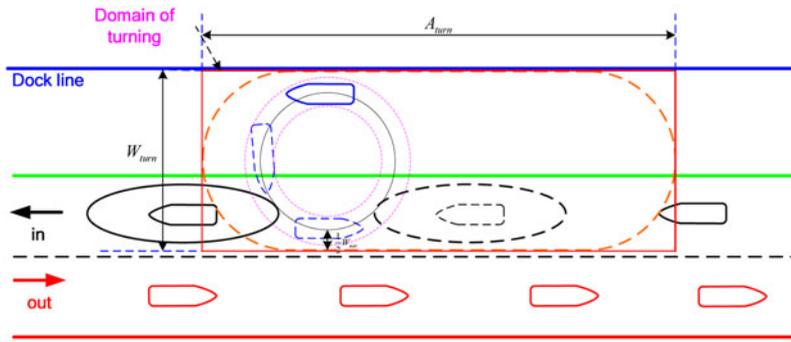


Figure 8. Type I dynamic domain for ship turning affecting one-way traffic.

where A_{join}^a is the major axis, W_{join}^a is the minor axis, V_{nav}^{in} is the speed of ships joining the flow, T_{join} is the time taken to join the flow, A_{nav-1} is the major axis of ship’s domain for the ships in the main channel, A_{nav-2} is the major axis of the domain for the “joining” ship navigating along the main channel, L_{join} is the length of joining ship, and φ is the steering angle.

Figure 7 presents the case when the ship joining another flow requires the ship to traverse through the reverse flow. The related safe domain can be determined as below:

$$A_{join}^b = \frac{V_{nav}^{in} \cdot T_{join}/2 + V_{nav}^{out} \cdot T_{join}/2 + A_{nav-1} + L_{join}}{\cos(\varphi/2)} \tag{13}$$

$$W_{join}^b = A_{nav-2} \cdot \sin(\varphi/2) \tag{14}$$

where A_{join}^b is the major axis, W_{join}^b is the minor axis, V_{nav}^{in} is the speed of ships navigating in, V_{nav}^{out} is the speed of ships navigating out, T_{join} is the time of joining the flow, A_{nav-1} is the major axis of ship’s domain for the ships voyaging in the main channel, A_{nav-2} is the major axis of domain for the joining ship navigating along the main channel, L_{join} is the length of joining ship, and φ is the steering angle.

The model addresses the influence between the joining ship and the ships navigating along the main channel, conforms to the conventional practice of restricted waterway dispatching and the standard that navigators judge whether joining the flow is safe. Moreover, the proposed model can handle cases with ships travelling from main channel to secondary channel or from secondary channel to main channel.

2.5. *Ship Domain Model for Turning.* For ships that are turning, the safe domain is the water area where other nearby ships cannot enter the ship’s virtual domain (it is assumed as the domain of the crossing ship navigating along the channel) when it performs turning operations. This means that the time that ships navigating around the turning ship reach the turning operation waters should be longer than the time at which the turning ship finishes turning. Two types of ship operations may be considered for ships’ turning, including turning affecting one-way traffic flow and turning affecting two-way traffic flow.

As seen in Figure 8, the ship turning affects one direction of the two-way water channel. The ship domain as illustrated by the red dotted area can be replaced by the rectangular area that encloses the dotted area and can then be determined by

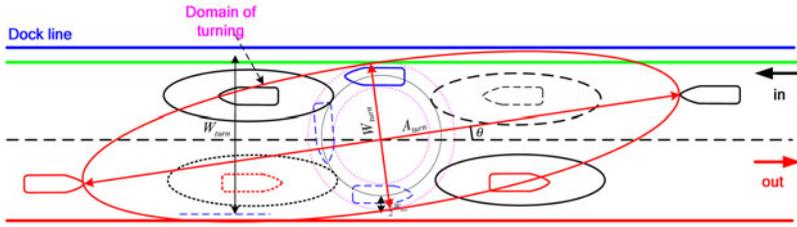


Figure 9. Type II dynamic domain for ship turning affecting two-way traffic.

the following:

$$A_{turn}^a = 2L + A_{nav-1} + V \cdot T_{turn} \tag{15}$$

$$W_{turn}^a = 2L + W_{nav-2} \tag{16}$$

where A_{turn}^a is the length of the ship turning domain, W_{turn}^a is the width, L is the length of ship, A_{nav-1} is the major axis of the domain for the turning ship navigating along the channel. V is the speed of the other ship navigating in the channel, T_{turn} is the time turning takes, and W_{nav-2} is the width of the domain for the turning ship navigating along the channel.

Figure 9 illustrates ship turning affecting two-way traffic flow in the water channel. The safe domain can be determined as follows

$$A_{turn}^b = \frac{2L + A_{nav-1} + V_{nav}^{in} \cdot T_{turn} + V_{nav}^{out} \cdot T_{turn}}{\cos \theta} \tag{17}$$

$$W_{turn}^b = 2L + W_{nav-2} \tag{18}$$

$$\theta = \arctan \frac{W_{channel}}{2(V_{nav}^{in} + V_{nav}^{out}) \cdot T_{turn}} \tag{19}$$

where A_{turn}^b is the major axis of turning domain, W_{turn}^b is the minor axis of turning domain, L is ship's length, A_{nav-1} is the major axis of the domain for the turning ship navigating along the channel, V_{nav}^{in} is the speed of ships navigating in, V_{nav}^{out} is the speed of ships navigating out, T_{turn} is the time taken in turning, and W_{nav-2} is the width of the domain for the turning ship navigating along channel.

The model addresses the characteristic of ship turning and the influence between the turning ship and ships navigated along the main channel. This conforms to the current practice of inland waterway port dispatching and the standard that navigators used to judge whether turning is safe.

2.6. *Security Zones for LNG Ships.* The security and safety of LNG ships is particularly important. In addition to defining safe domains for LNG ships involving navigating along the channel, crossing the channel, “joining another flow”, and turning, security zones extending from the safe domains need to be determined for LNG ships. Figure 10 illustrates the security zone of a LNG ship in yellow. In the longitudinal direction, clearance distances that extend eight times the ship length from the front end and three times the ship length from the rear end need to be maintained. In the cross sectional direction, clearance distances of one ship length are required on each side of the ship (Liu and Yu, 2011). The rectangular area enclosed by the longitudinal and cross sectional clearances is treated as the security zone of an LNG ship.

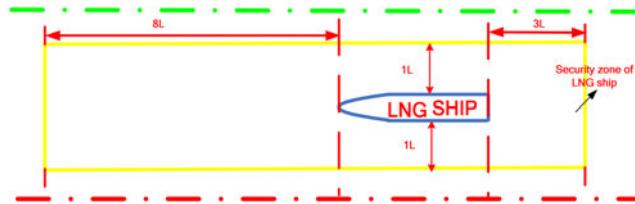


Figure 10. Security zone for an LNG ship.

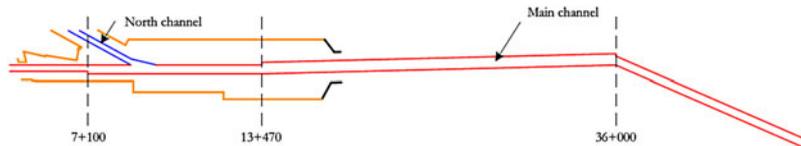


Figure 11. Diagram of port of Tianjin port waterway channels.

The safe domain can be determined by the following equations:

$$A_{LNG} = 12L_{LNG} \quad (20)$$

$$W_{LNG} = 2L_{LNG} + W_{LNG} \quad (21)$$

where A_{LNG} is the length of domain for LNG ship, W_{LNG} is the width of domain for a LNG ship, L_{LNG} is the length of a LNG ship, W_{LNG} is the width of a LNG ship.

3. MODEL APPLICATION. The proposed dynamic ship domain models were applied in a computational study using the port of Tianjin, China. The coastal city Tianjin is one of the four municipalities equivalent to a province located in northern China. The port of Tianjin is the largest port in northern China and the main maritime gateway to Beijing. The port of Tianjin is comprised of river ports along Haihe River and deep-water seaports located on the western shore of the Bohai Bay, centred on the estuary of the Haihe River. This makes it ideal for applying the proposed dynamic ship domain models. Currently, the whole port of Tianjin occupies 121 km² of land, with over 32 km of quay shoreline and 151 production berths. It handles 500 million tons of cargo and 13 million Twenty-Foot Equivalent Unit (TEU) of containers, making it the world's fourth largest port by throughput tonnage, and the ninth in container throughput (PSO, 2014).

3.1. *Basic Information on the Restricted Water Channels.* The waterway channels in the port of Tianjin contain the Main channel and the North channel. The Main channel is the main access of the port and the North channel is the access for ships navigating in or out of Beijiang and Dongjiang port areas. As shown in Figure 11, the Main channel is an approach channel for 250,000 dwt ships, which is about 44 km long. The North channel is an approach channel for 100,000 dwt ships, which is about 6.5 km in length and 390 m wide. The Main channel and North channel join at kilometre 9 + 000 of the Main channel, and the angle between Main channel and North channel is 29°. Tables 1 and 2 present technical data of the Main channel.

Table 1. The Axis of the Main Channel of Tianjin Port.

Serial Number	Kilometer mark of waterway	Channel Axis
1	0 + 000~2 + 600	293°53'56.9"~113°53'56.9"
2	2 + 600~13 + 493	281°04'17.7"~101°04'17.7"
3	13 + 493~23 + 924	279°38'56.3"~99°38'56.3"
4	23 + 924~36 + 000	281°04'17.7"~101°04'17.7"
5	36 + 000~44 + 000	306°04'17.7"~126°04'17.7"

Table 2. The Geometric Design Parameters of the Main Channel of Tianjin Port.

Channel Name	Kilometer mark of waterway	Length (m)	Bottom Elevation (m)	Width (m)	Navigation Level (Ton)
Zhadong	0 + 000~1 + 100	1,100	-5.0	60	3,000
Zhadong	1 + 100~2 + 600	1,500	-6.5	60	10,000
Main	2 + 600~2 + 900	300	-10.0	60/150	20,000
Main	2 + 900~4 + 239	1,339	-10.0	150	30,000
Main	4 + 239~5 + 000	761	-17.4	150	40,000
Main	5 + 000~15 + 100	10,000	-17.4	234	150,000
Main	15 + 000~40 + 000	25,000	-17.2	234	200,000
Main	40 + 000~44 + 000	4,000	-19.7	315	250,000

3.2. *Method for Calculating the Restricted Water Channel Capacity.* Channel capacity refers to the number of vessels able to be navigated through the channel or a section of the channel in the unit time. This is the maximum traffic volume of the channel considering weather conditions, vessel size, vessel’s behaviour, speed, safe distance and so on. The proposed dynamic ship domain models can be applied in a computational study of channel capacity.

According to space-time consumption theory (Hu, 2001), the water channel capacity can be calculated by

$$\begin{cases} C_{ch} = R_{ch}/R_{ship} \\ R_{ch} = Avail_S \cdot Avail_T \end{cases} \quad (22)$$

where C_{ch} is the water channel capacity, R_{ch} is the space-time resource of the water channel, R_{ship} is the space-time resource occupied by a single ship, and $Avail_S$ and $Avail_T$ are the available space and time resources of the water channel.

The available space-time resource can be determined by the following factors: i) the space-time resource that a single ship consumes during navigation. A ship must keep a safe distance from other ships in the front or rear to ensure navigation safety; ii) the additional space-time resource in terms of the safe distance that a ship consumes during overtaking, crossing, joining, or turning; and iii) the number of accesses of the water channel.

Considering the relationship between space resource of the water channel and ship domains needed to maintain safety for sailing along the channel, crossing, joining another flow, and turning, the available space resource in Equation (22) can be

determined by the following:

$$\begin{aligned}
 Avail_S = & \frac{Sing_S}{\frac{1}{4}\pi \cdot A_{nav} \cdot W_{nav}} \cdot L_{ave} \cdot B_{ave} \cdot N_{ac} - P_{cro} \cdot \frac{\pi}{4} \cdot A_{cro} \cdot W_{cro} \\
 & - P_{join}^a \cdot \frac{\pi}{4} \cdot A_{join}^a \cdot W_{join}^a - P_{join}^b \cdot \frac{\pi}{4} \cdot A_{join}^b \cdot W_{join}^b - P_{turn}^a \cdot A_{turn}^a \cdot W_{turn}^a \\
 & - P_{turn}^b \cdot \frac{\pi}{4} \cdot A_{turn}^b \cdot W_{turn}^b - P_{LNG} \cdot A_{LNG} \cdot W_{LNG}
 \end{aligned} \tag{23}$$

where *Sing_S* is the space resource of a single access, which is the product of the length and width of the access. *N_ac* is the number of the accesses of the water channel, *L_ave* is the average ship length, *P_cro*, *P_join*, *P_turn* are the probabilities of crossing, joining and turning, and the superscripts are the extents of influence to ship traffic along the water channel.

The time domain of a water channel can be described as the service time that a channel can provide except for impacts of geometric design and capacity, port operation condition, and conflict between ships. The available time resource in Equation (22) can be calculated as below:

$$Avail_T = P_{port} \cdot (Total_T - T_{nature} - T_{conflict} - T_{port}) \tag{24}$$

where *P_port* is the port operation efficiency, *Total_T* is the total time resource, *T_nature* is the time resource consumed due to wind, fog, tide and other natural factors, *T_port* is the time resource consumed because of the port operation condition limitations, and *T_conflict* is the time resource consumed as a result of conflicts between ships.

3.3. *Input Data for Calculating the Water Channel Capacity.* The following input values associated with the ship traffic flow, water channel geometrics, ship shape and size, and ship navigation behaviours were utilised for the capacity calculation.

According to the data statistics from 2006 to 2008, the average time of ships turning from the North channel to the Main channel is about 12 minutes. The ships' scale and its probability are given in Table 3.

The Probability Density Functions (PDFs) of ships' speed entering into or exiting from the water channel are given as follows.

As shown in Figure 12, the PDF for ships' speed entering into the Main channel can be determined as below:

$$f(v_{in}) = \frac{1}{2 \cdot 437\sqrt{2\pi}} e^{-\frac{(V-7.871)^2}{2 \cdot (2.437)^2}} \quad (5 \leq V \leq 15) \tag{25}$$

As shown in Figure 13, the PDF for ships' speed entering into the Main channel can be determined as below:

$$f(v_{out}) = \frac{1}{2 \cdot 436\sqrt{2\pi}} e^{-\frac{(V-7.902)^2}{2 \cdot (2.436)^2}} \quad (5 \leq V \leq 15) \tag{26}$$

For different categories of ship navigation, the number and probability of ships involved with crossing, encountering, and turning were separately estimated. Since the Main channel and North channel were designed as enclosed passages, no ship crossing existed in practice. According to the navigation standard of the Main

Table 3. The Ships' Sizes and Probability of Tianjin Port traffic.

Ship Type	Ship Tonnage DWT(t)	Length (m)	Width (m)	Probability
Bulk Carrier	2000	78	14.3	0.0927
	3000	96	16.6	0.1674
	5000	18.8	9.0	0.1860
	10000	135	20.5	0.0715
	15000	150	23.0	0.0549
	20000	164	25.0	0.0330
	35000	190	30.4	0.1013
	50000	223	32.3	0.0753
	100000	250	43.0	0.0244
	150000	289	45.0	0.0080
Oil Tanker	200000	312	50.0	0.0019
	300000	339	58.0	0.0027
	500	55	7.8	0.0027
	1000	70	13.0	0.0083
	2000	86	13.6	0.0104
	3000	97	15.2	0.0590
	10000	141	20.4	0.0175
	20000	164	26.0	0.0241
Chemical Tanker	80000	243	42.0	0.0072
	300000	334	60.0	0.0005
	5000	114	17.6	0.0238
	10000	127	20.0	0.0093
	20000	160	24.2	0.0133

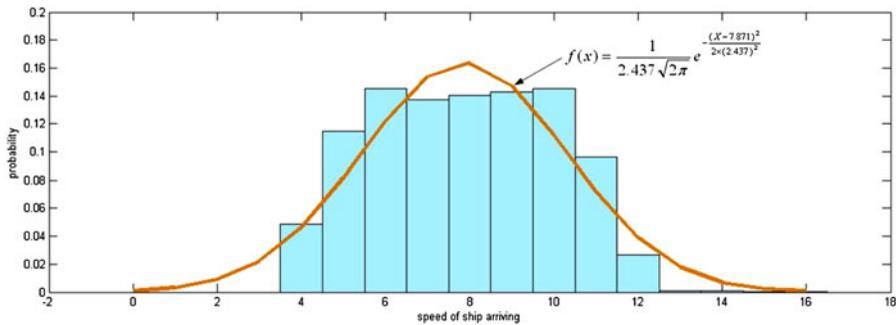


Figure 12. Curve fitting of the ships' speed entering into Main channel.

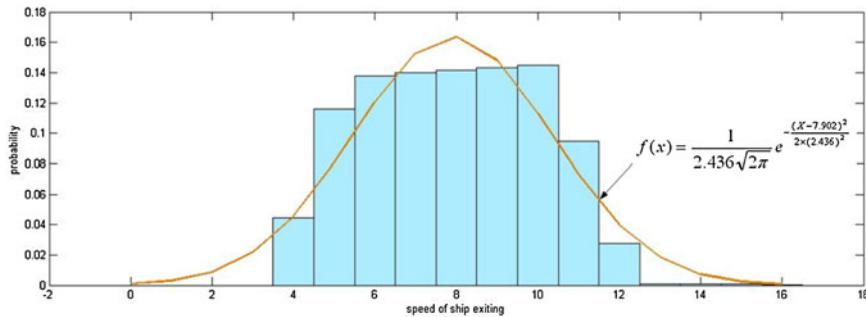


Figure 13. Curve fitting of the ships' speed exiting from Main channel.

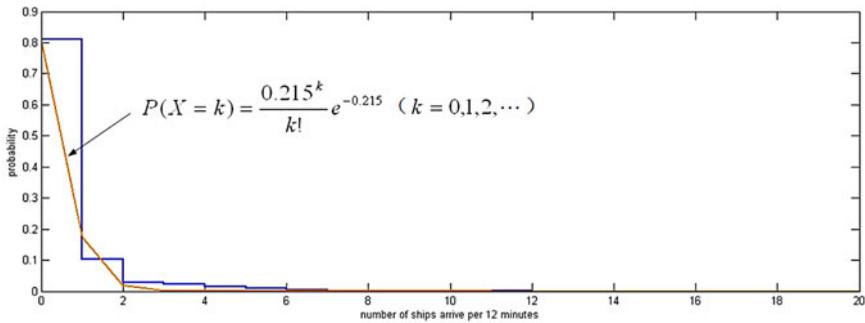


Figure 14. Curve fitting of the ships entering into Main channel.

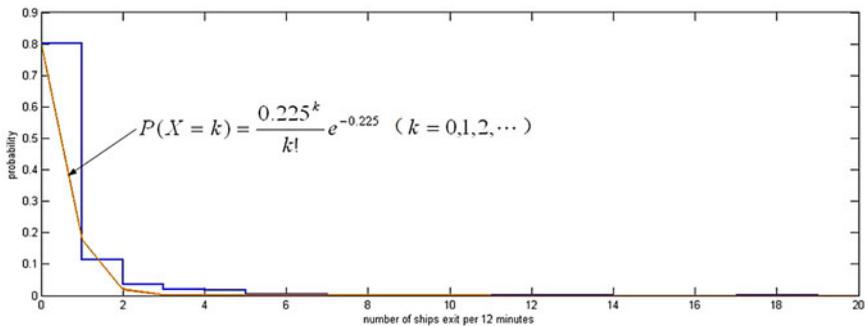


Figure 15. Curve fitting of the ships exiting from Main channel.

channel of Tianjin port, overtaking is prohibited and ships should keep at least six times of its length from the preceding ship. Also, there are no LNG ships sailing in the Main channel or North channel of Tianjin port. As such, the number and probability of ship-crossing navigation were set to zero. As related to the number and probability of ship encountering navigation, the PDFs of ship entering into or exiting from the water channel are given by:

As shown in Figure 14, the PDF for ships entering into the Main channel can be determined as below:

$$P(X_{WI} = k) = \frac{0 \cdot 215^k}{k!} e^{-0.215} \quad (k = 0, 1, 2, \dots) \tag{27}$$

As shown in Figure 15, the PDF for ships exiting from the Main channel can be determined as below:

$$P(X_{WO} = k) = \frac{0 \cdot 225^k}{k!} e^{-0.225} \quad (k = 0, 1, 2, \dots) \tag{28}$$

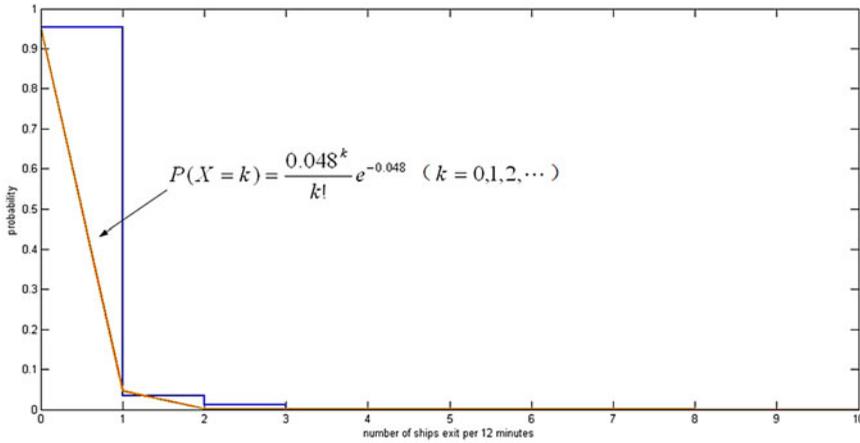


Figure 16. Curve fitting of the ships exiting from North channel.

As shown in Figure 16, the PDF for ships exiting from the North channel can be determined as below:

$$P(X_{NO} = k) = \frac{0 \cdot 048^k}{k!} e^{-0.048} \quad (k = 0, 1, 2, \dots) \tag{29}$$

Encounter conflict means two traffic flows arriving at a confluence of waters at the same time, so the encounter conflict probability can be calculated as:

$$P_e = P(X \geq 1, Y \geq 1) = 1 - P(X = 0) - P(Y = 0) + P(X = 0, Y = 0) \tag{30}$$

Consequently, the joint probability of ships encountering other ships for ships exiting from the North channel and entering into the Main channel can be calculated as:

$$P_{e1} = 1 - P(X_{WI} = 0) - P(X_{WI} = 0) + P(X_{WI} = 0)P(X_{WI} = 0) = 0 \cdot 0087 \tag{31}$$

The joint probability of ships encountering for ships exiting from the North channel and exiting from the Main channel can be computed as:

$$P_{e1} = 1 - P(X_{WI} = 0) - P(X_{WO} = 0) + P(X_{WI} = 0)P(X_{WO} = 0) = 0 \cdot 0091 \tag{32}$$

According to the ship turning statistics, the probability of turning which affects the traffic along the water channel was 0.001, and all such events affected the two-way traffic.

According to the statistics, except for the effect of wind, rain, visibility, storm tide, ocean current, port operation and human factor, the navigation time of Tianjin port is 305 days, where the one-way navigation time is 45 days. The port operation efficiency is 0.4.

3.4. Estimation of Water Channel Capacity. With the ship domain models proposed for restricted water channel capacity analysis and input data collected, the

theoretical capacity of the main water channel of port of Tianjin was computed as below.

$$\begin{aligned}
 C_{ch} &= R_{ch}/R_{ship} = \frac{Avail.S \cdot Avail.T}{L_{ave} \cdot B_{ave} \cdot T_{nav}} \\
 &= \left(\frac{Sing.S}{\frac{\pi}{4} A_{nav} \cdot W_{nav}} \cdot L_{ave} \cdot B_{ave} \cdot N.ac - P_{join}^a \cdot \frac{\pi}{4} A_{join}^a \cdot W_{join}^a - P_{join}^b \cdot \frac{\pi}{4} A_{join}^b \cdot W_{join}^b \right. \\
 &\quad \left. - P_{turn}^b \cdot \frac{\pi}{4} A_{turn}^b \cdot W_{turn}^b \right) \cdot P_{port} \cdot (Total.T - T_{nature} - T_{port} - T_{conflict}) / (L_{ave} \cdot B_{ave} \cdot T_{nav}) \\
 &= (457600 - 5515 \cdot 8 - 5959 \cdot 2 - 2944 \cdot 1) \times 0.4 \times 7189.7 / (137 \times 22 \times 4.5) \\
 &= 93971 [ships/year]
 \end{aligned}$$

3.5. *Forecast of Water Channel Capacity.* In order to ease the traffic pressure of the Main channel of Tianjin Port, Tianjin Port Holdings Co., Ltd. started a channel broadening project in 2008. The channel broadening project was finished in 2012, and the geometric design parameters of the main channel of Tianjin Port after widening is shown in Table 4.

According to the ship turning statistics, the probability of turning affecting two-way traffic after the channel broadening project is 0.0002, the probability of turning affecting one-way traffic after the channel broadening project is 0.0008.

With the ship domain models proposed for restricted water channel capacity, the theoretical capacity of the Main channel of Tianjin Port can be forecast as below.

$$\begin{aligned}
 C_{ch} &= R_{ch}/R_{ship} = \frac{Avail.S \cdot Avail.T}{L_{ave} \cdot B_{ave} \cdot T_{nav}} \\
 &= \left(\frac{Sing.S}{\frac{\pi}{4} A_{nav} \cdot W_{nav}} \cdot L_{ave} \cdot B_{ave} \cdot N.ac - P_{add-in}^a \cdot \frac{\pi}{4} A_{enc}^a \cdot W_{enc}^a - P_e^b \cdot \frac{\pi}{4} A_{enc}^b \cdot W_{enc}^b \right. \\
 &\quad \left. - P_{turn}^a \cdot A_{turn}^a \cdot W_{turn}^a - P_{turn}^b \cdot \frac{\pi}{4} A_{turn}^b \cdot W_{turn}^b \right) \cdot P_{port} \cdot (Total.T - T_{nature} - T_{port} - T_{conflict}) \\
 &\quad / (L_{ave} \cdot B_{ave} \cdot T_{nav}) \\
 &= (761389 - 5515 \cdot 8 - 5959 \cdot 2 - 501 \cdot 4 - 2355 \cdot 3) \times 0.4 \times 7189.7 / (137 \times 22 \times 4.5) \\
 &= 158405 [ships/year]
 \end{aligned}$$

4. COMPARISON OF CHANNEL CAPACITY ESTIMATION USING DIFFERENT METHODS

4.1. *Channel Capacity Estimation Methods.* At present, channel capacity estimation methods contain empirical formulae based on ship manoeuvring, ship trials and computer simulation. Here, some common channel capacity estimation formulae are introduced to calculate the capacity of the main channel of Tianjin port, in order to validate the accuracy of the proposed model.

4.1.1. *Calculation method based on Fujin model (Wu, 1986).* This method is the most convenient and frequently used, which is constructed on considering the safe

Table 4. The Design Parameters of the Main Channel of Tianjin Port after Broadening.

Channel Name	Kilometrage of waterway	Length (m)	Bottom Elevation (m)	Width (m)	Navigation Level (Ton)
Zhadong	0 + 000~1 + 100	1,100	-5.0	60	3,000
Zhadong	1 + 100~2 + 600	1,500	-6.5	60	10,000
Main	2 + 600~2 + 900	300	-10.0	60/150	20,000
Main	2 + 900~4 + 239	1,339	-10.0	150	30,000
Main	4 + 239~5 + 000	761	-17.4	150	40,000
Main	5 + 000~7 + 100	2,100	-17.4	234	150,000
Main	7 + 100~13 + 470	6,370	-18.5	325	250,000
Main	13 + 470~36 + 000	22,530	-19.5	420	250,000
Main	36 + 000~44 + 000	8,000	-19.5	315	250,000
compound	15 + 230~22 + 000	6,770	-9.0	100	10,000
compound	16 + 000~24 + 000	8,000	-9.0	100	10,000

distance based on the Fujin domain.

$$C_{ch} = R_{ch}/R_{ship} = \frac{L_{ch} \cdot T}{r \cdot L_{ch}/V_{ave}} = T \cdot \frac{V_{ave}}{r} \tag{33}$$

where C_{ch} is the water channel capacity, R_{ch} is the space-time resource of the water channel, R_{ship} is the space-time resource occupied by a single ship, L_{ch} is the length of the channel, T is the time channel service, r is the major axis of ship domain, V_{ave} is the average speed of the ships.

4.1.2. *Calculation method based on features of different ship types (Liu et al., 2006).* This method is constructed based on considering of the distribution of ship categories, ship scales and ship speeds from the Fujin domain. The formula is widely used in calculating the channel capacity of the downstream Yangtze River.

$$C_{ch} = N_{ac} \cdot \sum_{i=1}^n \frac{r_i v_i}{l_i} (i = 1, 2, 3, 4 \dots) \tag{34}$$

where C_{ch} is the water channel capacity, N_{ac} is the number of the accesses of the channel, r_i is the distribution of the ships of type i , v_i is the average speed of the ships of type i , l_i is the major axis of the ships of type i .

4.1.3. *Calculation method on considering “afflux and gush” (Wen and Liu, 2010).* This method is constructed based on considering traffic organisation of the port, which can reflect the influence of one-way navigation. The formula is widely used in calculating the channel capacity of a seaport.

$$C_{ch} = (1 - T_{sig}) \times (C_{ch}^{in} + C_{ch}^{out}) + T_{sig} \times C_{ch}^{sig} \tag{35}$$

where C_{ch} is the water channel capacity, T_{sig} is the time of one-way navigation per unit time, C_{ch}^{in} is the capacity of the entrance access per unit time, C_{ch}^{out} is the capacity of the exit access per unit time, C_{ch}^{sig} is the capacity of the channel while in a one-way situation per unit time.

4.2. *“Saturability” of Channel Capacity.* Saturability of channel capacity is an important index to reflect the service level of the channel. Saturability of channel capacity is the ratio of the actual channel capacity and probable channel capacity

Table 5. Evaluation index of saturability of channel capacity.

Ratio of Actual Capacity and Probable Capacity	Saturation Status (Channel Service Level)
<0.9	Unsaturated
0.9~1.0	Near Saturated
1.0	Saturated
1.0~1.1	Over Saturated
>1.1	Serious Saturation

Table 6. The Calculation Result of Different Methods.

Method		based on Fujin model	based on features of different ship types	on considering of afflux and gush	based on dynamic ship domain model
Result	before	114242	114577	105453	93971
	broaden	[ships/year]	[ships/year]	[ships/year]	[ships/year]
	after	250253	260979	161137	158405
	broaden	[ships/year]	[ships/year]	[ships/year]	[ships/year]
Annual Traffic Flow	2006	77231	77231	77231	77231
		[ships/year]	[ships/year]	[ships/year]	[ships/year]
	2007	91362	91362	91362	91362
		[ships/year]	[ships/year]	[ships/year]	[ships/year]
	2012	128541	128541	128541	128541
		[ships/year]	[ships/year]	[ships/year]	[ships/year]
Saturability	2006	67.6%	67.4%	73.2%	82.2%
	2007	80.0%	79.7%	86.6%	97.2%
	2012	51.4%	49.3%	79.8%	81.1%
Saturation Status	2006	Unsaturated	Unsaturated	Unsaturated	Unsaturated
	2007	Unsaturated	Unsaturated	Unsaturated	Near Saturated
	2012	Unsaturated	Unsaturated	Unsaturated	Unsaturated

(Li, 2008). Saturability of channel capacity can be calculated as below:

$$DS = \frac{W_s}{W_m} \quad (36)$$

where, DS is the saturability of channel capacity, W_s is the actual channel capacity, W_m is the probable channel capacity.

According to the determination method of port channel capacity balance coefficient, the channel service level can be divided into five grades (Li, 2008) as shown in Table 5.

4.3. *Accuracy inspection of the result.* Calculation results for the above methods for Tianjin are shown in Table 6.

According to the conclusion of “Research on the Saturability and Navigation Risk of the Main Channel of Tianjin Port” (Tianjin Port Holdings Co., Ltd., 2007), the ship saturability of the Main channel of Tianjin port was approximately 80–90% in 2006, nearly at capacity.

However, in 2007, shipping volume increased 18.3% compared to 2006, and the channel capacity saturability was about 94.6% to 106.5%; the channel broadening project was badly needed and thus started in 2008.

After the channel broadening project was finished in 2012, the saturability of the channel capacity reduced but the vessel traffic volume increased rapidly again. The channel remains close to saturation even after the channel broadening project. Tianjin Port Holdings Co., Ltd has recently started a new project to further broaden and deepen the Main channel.

According to Table 6, it would appear that the proposed model was more accurate than earlier ones.

5. SUMMARY AND CONCLUSION. Developing adequate ship domain models has the potential to significantly benefit ship navigation safety that is collectively affected by the navigable waterway condition, the size and shape of the ship and operators' skills. The existing ship domain models developed over the last several decades mainly use constant values for the model input parameters, making them incapable of handling site-specific conditions. This study proposed dynamic ship domain models that explicitly considered restricted waterway conditions and ship types and sizes in an integrated manner. In particular, the proposed models could help determine ship domains for navigating along the channel, crossing, joining and turning in restricted water channels. In addition, security zones in excess of the ship domains for safe navigation were addressed for LNG ships. A computational experiment was conducted for model application using data on water channel design and ship traffic volumes associated with the Main channel of Port of Tianjin, China. Comparisons of results obtained between the proposed dynamic models with real ship traffic counts reveal that the proposed models could achieve a high degree of accuracy in estimating the capacity of restricted water channels.

The proposed dynamic ship domain models extended from the widely-used Fujii model taking account of ship behaviour and waterway conditions in restricted waters. From a practical point of view, the proposed dynamic ship domain models provided a heuristic methodology to determine ship safety domains for navigating along the channel, crossing, joining and turning in restricted waters that maintain the following characteristics:

- Addressing the characteristics of restricted waters by determining the values of input parameters according to the restricted water channel design specification and navigation standard;
- Considering different ship types and sizes ranging from general cargo ships to other special purpose ships, as well as differences in different grades of ships;
- Dealing with navigating along the channel, crossing, joining and turning that could help analyse ship conflicts between related categories of ship movements;
- Rigorously handling the influences of other ships on the specific ship conducting a certain category of navigation;
- Tackling the impacts of waterway traffic in a single direction or both directions for encountering and turning navigation;
- Performing refined analysis of ship turning navigation by considering different ways of berthing and unberthing;
- Capable of being used in simulation and evolution analysis of traffic flow, estimation of water channel capacity, and improvement in the efficiency of ship management entities;
- Applicable for analysing ship domains associated with open waters.

The model can also be used in forecasting channel capacity and optimising traffic organisation, which is quite important for channel construction and vessel traffic management.

In future work, in order to further enhance real world application, the proposed dynamic ship domain models should consider navigation risk and human factors.

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