Heterogeneous port traffic of general ships and seaplanes and its simulation

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***Abstract*— Along with the development of the civil seaplane industry in China and all around the world, the number of seaplane piers in port areas will increase. As a consequence, the port traffic will not only increase, it will also become more heterogeneous, consisting of ships and seaplanes. This paper presents a simulation model to describe this mixed traffic and investigates the impact of seaplanes on the ship traffic quantitatively. Given the different maneuverability of ships and seaplanes, the impact of seaplanes on port traffic operations is analyzed from three aspects, being traffic separation between seaplanes and ships, traffic interruption, and traffic priority of seaplanes. A simulation model has been developed using a Cell Transmission Model (CTM). To evaluate the navigational impact of seaplanes quantitatively, the traffic recovery time from the disturbance of a seaplane takeoff or landing event is used as an assessment indicator of the model. The model sensitivity analysis indicates that the capacity of a cell is more important than the density of ships. This implies the capacity needs to be estimated more accurately to get a better simulation result.**

I. INTRODUCTION

Seaplanes are aircrafts which take off, land or park on the water surface. According to the definition in COLREGs by *IMO (2012)*, a seaplane includes ‘any aircraft designed to maneuver on the water’. In this respect, seaplanes are regarded as a special type of ships, not as aircraft.

Seaplanes have been on the civil market for more than 80 years. The development of seaplanes is prosperous in the United States, Canada and Australia. Many airlines in these countries are performing passenger transportation using seaplanes, e.g. Sydney Seaplanes, Seair Seaplanes and Harbor Air Seaplanes. In China, the construction of seaplane piers has also started in various ports, with one pier finished in the Port of Sanya and four piers being planned in Eastern and Central China. When the civil seaplane industry develops further, the takeoff and landing of a seaplane will no longer be an exception, but become part of the daily operations of a port. This will increase the complexity of the traffic in a port with seaplane piers considerably, which leads to the question whether the capacity of the port can be maintained.

Currently, the research on seaplanes focuses on more technical aspects, such as the improvement of its maneuverability and more economical aspects, such as its application in the daily transport system. The European research project FUSETRA (Future Seaplane Traffic) has been performed within the 7th Framework Program. This project aimed to improve the application of seaplanes as a means of transport. *Wagner et al. (2011)* have identified the requirements for seaplanes, passengers, operators and manufacturers based on the current situation in Europe. In addition, the strengths, weaknesses, opportunities and threats of seaplanes to be a new transportation mode were analyzed using a SWOT analysis. *Gobbi et al. (2011)* present a great potential for the civil seaplane industry and the development of a transport network in Europe due to the abundance of shore line and rivers, which will benefit especially the short flights. *Gobbi et al. (2011)* also present a theoretical study in Poland identifying 11 seaports that are qualified to handle seaplanes. In the US, the *FAA (1994)* wrote the ‘Advisory Circular on seaplane bases’ to give recommendations on the layout of seaplane bases. For the navigation safety of seaplanes and ships in one port, the collision risk and its causes were analyzed by adopting the method of DEMATEL-ISM, developed by *Weng et al. (2013)*. The result is a hierarchical structure of all risk factors to identify the root factor and direct factor, which helps to decrease the risks by changing or improving the condition of the controllable factors. So far, only limited research has been performed on seaplane traffic characteristics and its interaction with regular port traffic.

Several methods have been adopted to study ship traffic operations or simulate the traffic flow in ports, e.g. queueing theory by *Liu (2009)*, multi-factors weighted synthesis by *Liu et al. (2010)*, and simulations predominantly using Arena by

Zheng (2011), in which queueing theory is the most commonly used. Compared to research on maritime traffic, the research on vehicular traffic is more mature. More theories and methods are used to simulate the traffic, e.g. Logit model by *Xu (2007)*, principal component analysis by *Tian (2011)*, Cell Transmission Model and Cellular Automata. Before existing research methods for vehicular traffic can be applied to maritime traffic, the feasibility of the methods to represent mixed traffic of ships and seaplanes needs to be assessed.

The paper starts with an introduction of the heterogeneous port traffic. Given the different navigational characteristics of seaplanes and ships, the impacts of seaplanes on the maritime traffic can be analyzed. In order to further analyze the impact of seaplanes quantitatively, a simulation model is developed to describe a mixed traffic of ships and seaplanes in a port based on the Cell Transmission Model. After establishing the conceptual model based on CTM, the model formulation is introduced for heterogeneous port traffic, followed by a sensitivity analysis of the developed model. We end with conclusions and recommendations for future research.

II. HETEROGENEOUS PORT TRAFFIC OF SHIPS AND SEAPLANES

In the current maritime traffic system in a port, the main traffic participant is a ship sailing in the water by the force of water flow on propellers. Due to the different designs of ship structure, engine power, etc., the maneuverability of each type of ship is different to some extent. The maneuverability differences are due to sailing velocity, accelerating and stopping, and turning. Since the port area is a restricted water area, the differences in navigational characteristics of ships will not be as substantial as at sea.

Compared to the navigational characteristics of ships, seaplanes perform differently in both maneuverability and operations. The differences lead to negative impacts on the maritime traffic operations, and contribute to the heterogeneous port traffic.

A. *Navigational characteristics of seaplanes sailing on the water*

The navigational characteristics of seaplanes sailing on the water are introduced from two points of view, being maneuverability and traffic operations.

(a) Maneuverability characteristics.

When a seaplane sails in the water, it is regarded as a ship. After it leaves the water surface, it is an aircraft like other normal planes. The maneuverability characteristics of seaplane differ from normal ships with respect to velocity and operation area during takeoff and landing.

- High velocity

The trips of seaplanes in the waterway can be divided into three phases, being taxiing, taking off and landing. During the taxiing phase, the velocity of seaplanes is almost similar to the sailing velocity of general ships. However, for takeoff and landing, the velocity will be much higher. According to statistical data on seaplanes, the cruise velocity of seaplanes during takeoff and landing is around 150 to 300 km/h (*Jackson (2003)*). Compared to the velocity of ships in ports (generally 5 to 10 kn), the velocity of seaplanes during take-off and landing (about 40 to 108 kn) is much higher.

- Large operation area

The seaplane needs a large area for operations of takeoff and landing. According to the data from *Jackson (2003)*, the takeoff distance requirement is around 400 to 600 meters, while the landing distance is around 350 meters. When there is a seaplane taking off or landing in its operation area, no vessel is allowed to appear in this area. *Mohr (2010)* has stated that the protecting area is even expanding 350 meters from the boundary of the take-off and landing area in France.

(b) Sailing characteristics.

Seaplanes use the wind power to sail. Thus, the wind direction influences the moving direction of seaplanes during takeoff and landing: the seaplane chooses to sail against the wind as much as possible. The seaplane traffic thus moves mostly parallel to the direction of the prevailing wind, contrary to the trajectories of ship traffic which are determined by the shape of the banks.

According to the operating procedures of seaplanes, seaplanes will not be able to change their course or velocity for collision avoidance once the procedure for takeoff or landing has started. Because of the maneuverability restrictions of seaplanes, only one seaplane is allowed in the takeoff and landing area. In other words, each seaplane has an exclusive right-of-way of the operation area.

B. *Impacts of seaplanes on maritime traffic operations in ports*

From the perspective of system engineering, *IMO (2002)* shows that the port traffic system consists of four elements, being human factors, machinery, environment and management. The first three factors are interacting with each other, while management is restricting other factors and may only function properly given good feedback from the other factors. This interacting mechanism applies when the system is (mostly) in a stable operational state at an acceptable safety level.

However, due to the considerable differences in navigational characteristics of seaplanes compared to ships, the usual stable state of the maritime traffic system will be interfered by the seaplane operations. These impacts are analyzed qualitatively from three aspects, namely traffic separation, traffic interruption, and traffic priority.

(a) Traffic separation between seaplanes and ships.

As indicated by *IMO (2012)*, a traffic separation scheme is used to distribute the ship traffic flow over several planned routes according to the different directions of traffic flow. In vehicular traffic, traffic separation is handled via the lanes. However, in each separated lane or zone in maritime traffic, the ship behavior is not as restricted as vehicular traffic in traffic lanes. In port areas, most ships sail without the need to occupy or block a large navigable area around them. This implies different ships can sail in a restricted water area when their individual basic navigation safety is guaranteed.

However, since the seaplane has an exclusive right-of-way of the operation area during takeoff or landing, the traffic of seaplanes has to be spatially separated from the normal ship traffic. This separation only happens during the period of seaplane takeoff or landing. In these circumstances, a general traffic separation scheme for marine traffic cannot be applied, thus temporal rules will be effective. This might affect the stability of the maritime traffic system. Additionally, the seaplane cannot give way to ships for collision avoidance once the takeoff or landing started. The safety of the ships navigating in the area or the safety of the system cannot be guaranteed if the two types of traffic are not separated.

(b) Traffic interruption.

Generally, the traffic flow of ships is in an uninterrupted state. This implies that port operations can get the maximum economic or social benefit at the minimum expenses of time and money. In some busy ports, there can always be some ships staying in the anchorage to wait for berthing. Usually the ships wait in the anchorage due to the occupation of the berth, or sometimes the water depth can be another reason. Once the berth is available or the tide height is sufficient, the ship can sail into the port. In the ship traffic system, the port can reach maximum benefit when the waiting time is short. This kind of ship traffic can be seen as uninterrupted.

When a seaplane pier is constructed in an existent port, the operation area may be located in the customary ship routes area. In this circumstance, the exclusive right-of-way of the seaplane operation area will block the navigable water during a certain period of time. As the operation area is large, and the availability of alternative routes in a port usually limited, it will be hard if not impossible for the ships to make a detour in port. When the seaplane takeoff and landing is part of port operations, the traffic in the ship traffic system will be interrupted.

(c) Traffic priority of seaplanes.

In marine traffic, the traffic priorities between ships are generally determined by COLREGs, including the collision avoidance responsibility. Normally, all ships sail or behave according to these rules. As stated in COLREGs, a seaplane is just one kind of ship. There are no special rules providing the seaplanes with priority in collision avoidance. In daily port operations, the ship traffic operations depend on the arrival time, the origin-destinations of the ships and the berth occupation.

However, in port traffic consisting of seaplanes and ships, ships are prohibited to sail in the operation area during a seaplane takeoff or landing. This way, seaplanes have priority in the use of navigable water compared to general ships. As the seaplane operations give a disturbance to the normal traffic order in a ship traffic system in ports the seaplane operations need to be carefully planned, both in time and in space.

C. *Definition of heterogeneous port traffic*

The term ‘heterogeneous port traffic’ refers to port traffic consisting of more than one kind of participant. Its obvious differences in traffic characteristics are caused by the presence of different types of ships navigating in the same port area at the same time. Here, the traffic characteristics include velocity, traffic distribution, and the density of traffic participants.

As seaplanes affect the normal operations of a port, seaplanes need to be identified as a different type of maritime traffic participant, other than just being identified as a certain type of ship. Seaplanes and ships have different operational and navigational characteristics at least with respect to sailing purpose, maneuverability and navigational requirements. Each of these aspects will be discussed in detail in the sections below.

(a) Different sailing purpose.

In most ports, especially the trade ports with high economic value, ships usually sail to transport cargo. For this purpose, all ships are restricted by navigational rules, independent whether it is a container vessel, a bulk vessel, or a tanker. However, for seaplanes, the sailing purpose is personal entertainment or sightseeing mostly, and daily passenger transport only in some areas. In most situations, the sailing time is hard to predict exactly in advance, and not very relevant for the passengers either. The seaplane’s normal behavior on the water will only happen in the taxi channel and operation area. When there is an emergency landing, the operation area can hardly to be foreseen. However, the latter situation will not be considered in this paper.

(b) Different ship maneuverability.

Compared to cargo ships, seaplanes are designed to have a better maneuverability during the taxiing period. The velocity of seaplanes are likely to be the same as the velocity of general ships, while their maneuvering is more flexible. During takeoff, seaplanes can perform quick accelerations or sharp turnings, which can hardly be performed by a cargo ship. This leads to considerably different maneuverability patterns. Due to the different maneuvering mechanism of seaplanes, it is hard for them to take actions for collision avoidance once the procedure of takeoff or landing has started.

(c) Different navigational requirements.

For most ships, the safe distance to other ships is determined by their velocity, stopping distance, and the cargo type. This safe distance needs to guarantee collision avoidance with ships in the nearby neighborhood. However, for seaplanes, this safe distance is much larger than for general ships. When there is a seaplane taking off or landing, the operation water area with a safe distance is blocked for safety reasons.

The analysis above shows that the mix of seaplanes and ships may cause differences in traffic characteristics both for individual ships and for a port as a whole (i.e. ship flows and capacity). When the differences are large enough and the port already functions near its capacity, the stability of port system will most likely be affected, resulting in a decrease in throughput and/or safety.

An obvious difference between the seaplane traffic characteristics and the ship traffic characteristics can thus be observed, which makes the traffic in ports with seaplane piers constructed at least temporarily heterogeneous. The indication of the level of heterogeneity in the port traffic is the maneuver of takeoff or landing of a seaplane.

III. TRAFFIC MODELING BASED ON CTM

A Cell Transmission Model (CTM) is a discretized approximation of a macroscopic dynamic model, which is similar to a fluid mechanics model. This model describes traffic operation on a macroscopic (flow) level. CTM was first put forward by *Daganzo (1994)* to simulate car traffic on freeways, and then applied to the research of dynamic traffic networks (*Daganzo (1995)*). Now, CTM has been widely applied in research on vehicular traffic flow characteristics. The CTM consists of two kinds of models, being the section model and the junction model, corresponding to the two types of infrastructure that can be distinguished for vehicular traffic. Since the takeoff and landing of seaplanes usually occurs in open water, only the road section model of CTM is considered in this paper.

A. Conceptual model

The core of the CTM theory relies on the iterative calculation of the cell state, which is the number of ships in a cell. Here, a road or waterway is split into cells, and for each cell the change in traffic characteristics over time is calculated. When adopting CTM, a variety of model parameters is needed, including the maximum density of ships in a cell and the maximum inflow in a cell. When comparing the model results with real-life data and tuning the input parameters, the simulation results of the model can be adjusted such that these are most close to the real-life situation. As the model is used to quantitatively evaluate the impact of seaplanes on the maritime traffic operation, the traffic recovery time is set as the assessment indicator. Given the process description in the previous section, the conceptual model is shown in Fig. 1.

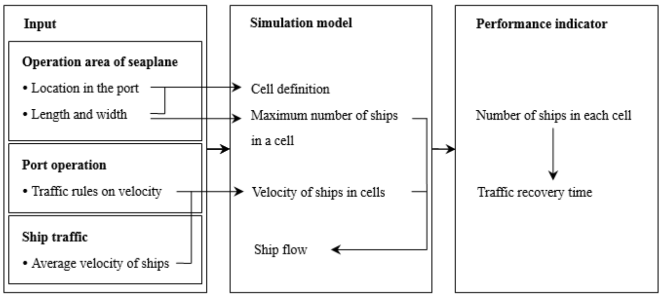

Figure 1. Conceptual model based on CTM.

In the model based on CTM, all input data can be defined or acquired from the layout design or the historical data in the simulated water area. The size and number of cells in the model are defined by both the location of the operation area in the port and the size of the operation area. Given the maximum density of ships in a cell, the maximum number of ships in a cell can be calculated in the simulation model. Considering the average velocity of ships from the statistical data or the velocity determined by the traffic rules when historical data are not available, the ship flow is simulated with the parameter the maximum inflow in a cell. The simulation result of the model consists of the number of ships in each cell over time and the traffic recovery time.

B. Model formulation

When applying the CTM, the waterway needs to be divided into sections or cells. However, the takeoff and landing area for seaplanes is usually in open water, which is more difficult to divide into sections than the traffic lanes of a freeway. As stated before, the main cause of traffic heterogeneity is the exclusive right-of-way on a waterway section during takeoff and landing of a seaplane. Assuming that the seaplane operation area is a rectangle, the major impact on maritime traffic is along the long side of the area. Thus, based on the size of the operation area, the cell is twice as large, as shown in Fig. 2, taking the length of operation area as the cell length, and twice the area width as the cell width. The latter is needed to guarantee safe maneuvering: when ships are waiting just outside the boundary of the operation area, it is hard to avoid collision if the takeoff or landing of the seaplane is disturbed. In the takeoff and land area, seaplanes move in the vertical direction as in Fig. 2.

Based on the cell definition given above, the length of the time step is set equal to the average travel time of a ship passing this cell, which is equal to the length of the cell divided by the average velocity of ships or the velocity according to the port regulations when historical data are not available.

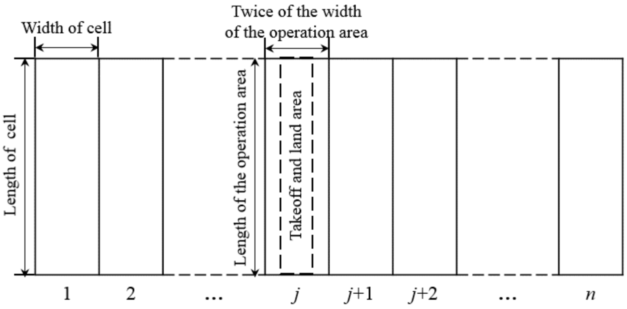

Figure 2. Cell definition in the simulation model.

As shown in Fig. 2, each cell corresponds to a certain waterway section area with exactly the same size. The total number of cells describing the whole waterway is set as n, and all the cells are numbered as 1, 2, … , n in the direction of the ship traffic flow.

As CTM uses a time discretization, all cells update their state based on units of time steps. The two variables that need to be set in the CTM are shown in Equations (1) and (2), being the maximum number of ships in a cell $N_i(t)$ and the capacity of cell i at time t $q_i(t)$. $N_i(t)$ is calculated by the maximum density of ships multiplying the area of the cell. And $q_i(t)$ is determined by the minimum capacity of cell i and the next cell i+1. For the last cell, the capacity is only determined by itself.

$$N_i(t) = \rho_{max}(t) \cdot l_{cell} \cdot w_{cell} \; (i = 1, 2, \cdots, n) \tag{1}$$

$$q_i(t) = \begin{cases} min\left\{ q_i(t)\,, q_{i+1}(t) \right\} & (i{=}1, 2, \cdots, n{-}1) \\ q_i(t) & (i{=}n) \end{cases} \tag{2}$$

In which

$\rho_{max}(t)$ the maximum density of ships at the time t [ships/km^2]

l_{cell}, w_{cell} the length and width of the cell respectively [km]

C. Model for ship traffic without seaplanes

According to the CTM theory, the simulation process can be divided into two steps, being ship flow calculation and navigational state update. When running the model, the two steps are performed consecutively until the end of the simulation, with the navigational state as the result of each cycle. This update of the navigational state is reflected by the change in the number of ships in each cell.

(a) Ship flow calculation.

Based on the car flow calculation method by *Daganzo (1994)*, the ship flow can be calculated as Equation (3). This implies that the inflow number of ships into a cell is determined by the minimum of the following three variables, being the number of ships in the upper-stream cell, the capacity of cell at that time, and the remaining number of ships the cell can contain:

$$f_i(t)=min\left\{n_{i-1}(t),q_i(t),\omega\left[N_i(t)-n_i(t)\right]/v\right\}(i=2,3,\cdots,n) \quad (3)$$

In which

$f_i(t)$ the number of ships flowing into cell i at time t

$n_i(t)$ the number of ships in cell i at time t

ω the wave velocity of traffic flow in congestion [kn]

v the average velocity or given velocity of ships in the area [kn]

For cell 1, its flow $f_1(t)$ equals the input of ships in the research area.

For a certain cell the inflow is equal to the minimum of the maximum outflow of the upstream cell and the maximum amount of ships that this cell can manage. The outflow is calculated in a similar way.

(b) Navigational state updating.

After calculating the ship flow in the first time step, the number of ships flowing in and out of each cell is acquired. The state of each cell is updated according to Equation (4). This way, the model simulates the proceeding of the ship traffic flow through the whole system.

$$n_i(t+1)=n_i(t)+f_i(t)-f_{i+1}(t) \quad (4)$$

D. Model for heterogeneous port traffic

To model the heterogeneous port traffic, the event of takeoff or landing needs to be included. This implies two additions to the model:

- When the seaplane starts to taxi to the operation area (cell j) for takeoff or approaches for landing, the maximum number of ships in cell j $N_j(t)$, and the number of ships flow into cell j $f_j(t)$ are set to zero because of the exclusive use right-of-way of the water way by the seaplane.
- When the seaplane leaves the water surface or starts to taxi to the pier, the maximum number of ships in cell j $N_j(t+t')$ and the number of ships flow into cell j $f_j(t+t')$ are reset to their original values. From this moment onwards, the ship traffic congestion will dissipate gradually until the system has recovered (unless another seaplane event takes place).

According to Equation (4), parameter changes in cell j will affect the state of the upstream cell i ($i<j$). This way, the congestion caused by seaplane takeoff or landing moves through the waterway network.

IV. SENSITIVITY ANALYSIS OF THE SIMULATION MODEL

The sensitivity analysis provides a means to examine to what extent each parameter affects the simulation results. This way, the parameters of most significance to be accurately estimated can be identified. The developed model has two model parameters, being the maximum density of ships and the capacity of a cell.

In order to set realistic parameters, a reference case study is carried out in the Port of Sanya in China with a seaplane pier constructed. According to the layout of the port and the location of the seaplane pier, the CTM cell has a length of 750m and a width of 120m. Since a waterway area in length of 1 n mile is taken as the simulation area, there are 15 cells in total and the takeoff and landing area of seaplanes is in cell 8.

In the reference simulation, the average velocity of ships is taken as the ship velocity in the model, being 4.0 kn. The time unit is set to 1 min. According to the historical data in the port, the parameters are set as follows. The maximum density of ships in a cell $\rho_{max}(t)$ is 40 ships per square kilometers, and the capacity of cell i $q_i(t)$ is 3 ships per minute.

In the simulation we assume that the event of takeoff or landing starts in time step 6 and ends in time step 12. The reference simulation result is shown in Fig. 3. In the figure, the red color indicates that the maximum number of ships (4 in this model) is present. 3 ships are present in the orange cells, while the green cells contain 2 ships. Only 1 ship is present in the light blue cells, and the dark blue cells are empty. As shown in Fig. 3, the traffic recovery time of the reference situation is 19 minutes.

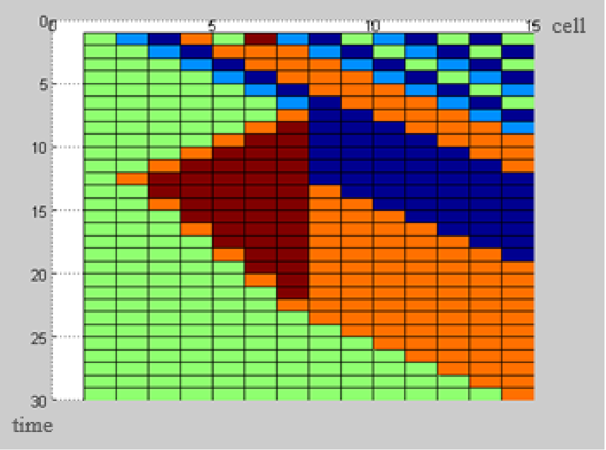

Figure 3. Reference simulation result for heterogeneous port traffic.

In order to analyze the sensitivity of the model parameters, four other situations are modeled with the following parameter sets.

- $\rho_{max}(t)$=50; $q_i(t)$=3
- $\rho_{max}(t)$=30; $q_i(t)$=3
- $\rho_{max}(t)$=40; $q_i(t)$=4
- $\rho_{max}(t)$=40; $q_i(t)$=2

The model performance indicator, the traffic recovery time, in the four situations, as well as for the reference situation, are shown in Tab. I. Tab. I indicates the sensitivity analysis on two parameters, being the maximum density of ships and the capacity of a cell respectively.

TABLE I. SIMULATION RESULTS OF HETEROGENEOUS PORT TRAFFIC

$\rho_{max}(t)$	$q_i(t)$	**Traffic recovery time**	**Value change**
40	3	19	Reference
50	3	19	0
30	3	15	-21%
40	4	14	-26%
40	2	28	+47%

- When the density of ships increases with 10 ships/km^2, there is no change in the traffic recovery time. However, when the density decreases by 10 ships/km^2, the traffic recovery time is declining with 21%.
- When the capacity of a cell is changed, a change in the traffic recovery time always occurs. 1 ship increase in capacity leads to a drop of 26% in the traffic recovery time. And 1 ship decrease results in a considerable increase of 47% in the traffic recovery time, clearly showing the non-linear aspects of the model.

In conclusion, the simulation model does not rely on the parameter $\rho_{max}(t)$, especially when the parameter reaches a certain value, being around 40 in this case. However, any change in the value of cell capacity will give a large impact on the final simulation results, with the traffic recovery time as an indicator. This implies that the capacity needs to be predicted much more accurate than the maximum density.

V. CONCLUSION AND RECOMMENDATION

In this paper, we have introduced a new concept of the heterogeneous port traffic (consisting of ships and seaplanes). Given the navigational characteristics of seaplanes sailing on the water, the impacts of seaplanes on the maritime traffic is analyzed qualitatively, discussing traffic separation between seaplanes and ships, traffic interruption, and traffic priority of seaplanes. Considering the differences between the traffic characteristics of seaplanes and ships, including the operational and navigational aspects, 'heterogeneous port traffic' is the port traffic consisting of more than one kind of participant, being seaplanes and general ships here. In this paper, we also presented a model to simulate heterogeneous traffic with the traffic recovery time as an indicator. For this model, CTM theory is adopted for the maritime traffic for the first time. Based on the proposed conceptual model, the model is formulated for maritime traffic without seaplanes and then the necessary adaptations to cope with heterogeneous traffic have been done. Taking the case in the Port of Sanya (China) as a reference, the sensitivity of the model is analyzed. Compared to the capacity of cell, the density of ships is of less importance to the simulation model results. When the capacity of a cell is varied, the traffic recovery time changes, with 26% and 47% in the given scenarios.

This means that the capacity of a cell needs to be predicted more accurately than the maximum density of ships for a simulation result more close to the real-life situation. In this paper, the model only takes one case for research in parameter. It needs to be further calibrated and validated by applying in other port areas, with the objective of obtaining a generalized set of parameters.

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