Heterogeneous port traffic of ships and seaplanes and its simulation

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ABSTRACT

Along with the development of the civil seaplane industry, the number of seaplane piers in port areas will increase. As a consequence, port traffic will not only increase, it will also become more heterogeneous, consisting of different types of ships and seaplanes. This will lead to more complex traffic in such areas. This paper presents a simulation model that has been developed to describe the heterogeneous port traffic of general ships and seaplanes. Given the different maneuverability of ships and seaplanes, the heterogeneity of the port traffic is characterized by the vulnerability degree. A method to compute this vulnerability degree is introduced. The simulation model has been developed according to the theory of Cell Transmission Models (CTM). This type of model has shown to be feasible for this research, in terms of application characteristics, the model input requirements, and the matching of output and traffic management demand. Aimed at highly efficient port traffic, the recovery time from the disturbance of a seaplane taking-off or landing is determined as assessment factor of the traffic. The model has been calibrated for the current traffic situation in Port of Sanya in China, where a seaplane pier has been constructed.

INTRODUCTION

Seaplanes are aircrafts which take off, land or park on the water surface. According to the definition in COLREGs, the term 'seaplane' includes any aircraft designed to maneuver on the water (*1*). In this respect, seaplanes are regarded as a special type of ships, not as aircraft.

These aircraft have been in the civil market for more than 80 years. The development of seaplanes is prosperous in the US, Canada and Australia. Many airlines in these countries are performing passenger transportation using seaplanes, e.g. Sydney Seaplanes, Seair Seaplanes, Harbor Air Seaplanes, etc. China has also started the construction of seaplane piers in various ports, with one finished and four being planned. When the civil seaplane industry develops further, the take-off 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, where the question is whether the capacity for the vessel traffic 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 transport. The European FUSETRA research project (Future Seaplane Traffic) has been performed within the 7th Framework Program from December 2009 to August 2011 This program aimed to improve seaplane operations in Europe and to develop it as a means of transport. In this research project, requirements for seaplanes, passengers, operators and manufacturers have been identified, based on the current situation of European seaplanes and operators (*2*). In addition, the strengths, weaknesses, opportunities and threats of seaplanes as a new transportation mode were analyzed using on a SWOT (Strength, Weakness, Opportunity, and Threat) analysis (*3*). The report shows a great potential for the seaplane industry and the development of a transport network in Europe due to the abundance of shore line or rivers, which will benefit especially short flights. A theoretical study performed in Poland identified 11 seaports that are also qualified to handle seaplanes (*3*). In the US, the FAA carried out the Advisory Circular on seaplane bases in 1994 to give recommendations on the layout of seaplane bases (*4*). For the navigation safety of seaplane and ships in one port, the collision risk and its causes were analyzed by adopting the method of DEMATEL-ISM (Decision Making Trial and Evaluation Laboratory – Interpretative Structural Modeling). The result is a hierarchical structure of all risk factors to identify the root factor and direct factor and help to decrease the risks (*5*). 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 in ports, e.g. queueing theory (*6*), multi-factors weighted synthesis (*7*), and simulations predominantly using Arena (*8*), 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, e.g. Logit model (*9*), principal component analysis (*10*), Cell Transmission Model and Cellular Automata. Before existing research methods for vehicular traffic can be applied to maritime traffic, the feasibility of the methods needs to be assessed.

This paper presents a simulation model describing a mix of ships and seaplanes in a port. The simulation model uses the well-known Cell Transmission Model as starting point. In order to show its applicability, we present the consequences of take-off and landing of seaplanes in a port.

The paper starts with an introduction of the heterogeneous port traffic. The navigational characteristics of seaplanes sailing in the water are the basis of a characterization method of heterogeneous port traffic consisting of ships and seaplanes. After showing the feasibility of the CTM theory to describe the interactions between seaplanes and ships, the model formulation is introduced for heterogeneous port traffic consisting of ships and seaplanes. We apply the model in Port of Sanya in China, using statistical data from the port. Finally, we end with conclusions and recommendations for future research.

HETEROGENEOUS PORT TRAFFIC

Definition of the concept

From the perspective of system engineering, the port traffic system consists of four elements, being human factors, machinery, environment and management (*12*). The first three factors are interacting with each other, while management is restricting others and is itself affected by the feedback of other factors. This interacting mechanism applies when the system is (mostly) in a stable operational state at an acceptable safety level.

In 1999, the U.S. Department of Transportation assessed the U.S. maritime transportation system, and identified the development trends of the port traffic system until the year 2020 (*13*). In their report, the function of a port was no longer assessed by its economic value, its national security value and its environmental value, but also by its recreational value. As is currently the case in a port, the operations of ships with recreational value might result in a decreased system stability and an increase of the potential vulnerability.

The concept of 'vulnerability' was first introduced by Timmerman in 1981 when studying natural calamities (*14*). The specific connotation of vulnerability changes depending on the research subject. However, according to its original common meaning, there are four key issues in the concept of vulnerability of a system:

- The vulnerability of a system is only revealed when it suffers external interference or internal disorder.
- A system that is vulnerable will lose the ability to operate in a stable and normal manner when a disturbance occurs.
- When a system is facing a disturbance, the system will meet some problems or risk, most of which will lead to loss or damage.
- When a system is facing a disturbance, the system can hardly recover to a stable operating state independently (that is without external control or help).

The operations of a ship traffic system in ports is influenced by various factors. When there is a sudden and serious external interference (such as communication signal interference, interaction between ships with special maneuverability or navigational requirements) or when internal changes occur (such as weather change or machinery failure), the system vulnerability is reflected by longer waiting times of ships or an increase in the amount of incidents or accidents. To be more specific, the connotation of vulnerability of a ship traffic system contains the following aspects:

- Only when one or more of the elements in the port traffic system (human, machinery, environment or management) is interfered or its state suddenly changes, the ship traffic system will reveal its potential vulnerability.
- When the port traffic system is disturbed, the ship traffic operations in part or even the whole port area will be influenced negatively.
- When the system is in a vulnerable state, congestion might occur or accidents, which do not only lead to an increase in travel time, but also to loss of lives and properties.
- When a port traffic system is disturbed, the stability of the system can be recovered by taking traffic management measures.

When the navigational characteristics of ships in a port are different (heterogeneous traffic), and the vulnerability of the system might be larger, thus easier revealed. In other words, vulnerability is more likely to occur in a ship traffic system consisting of different traffic participants with different traffic characteristics. This is mainly caused by the following:

(1) 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. Route choices of the bridge teams on the ships are very strict.

However, for recreational ports with round-trip boats, yachts or seaplanes routes appear to be more random due to sightseeing purposes, thus without planning from the port operation's perspective. Sometimes, this leads to routes of entertainment ships crossing with common routes of cargo ships.

(2) Different ship maneuverability.

Compared to cargo ships, entertainment ships are designed to have a better maneuverability. For example, the speeds of entertainment ships are higher, while their maneuvering is more flexible. Entertainment ships can perform quick accelerations or sharp turnings, which can hardly be performed by a cargo ship. This leads to considerably different maneuverability patterns.

(3) Different navigational requirements

For most ships, the safe distance to other ships is determined by their speed and stopping distance. The safe distance needs to guarantee collision avoidance with ships in the nearby neighborhood.

However, for some vessels, such as dangerous cargo vessels, LNG vessels or seaplanes, this safe distance is much larger than for general ships, due to the nature of the cargo or the ship's maneuvering for the sake of safety.

The analysis above shows that the diversity of traffic participants may cause differences in traffic characteristics both for individual ships and for a port (i.e. vessel flows and capacity). When the differences are large enough, changes in the machinery or environment are therefore more likely to lead to higher vulnerability of the port system.

The term 'heterogeneous port traffic' refers to the above mentioned traffic. It is a mixed traffic with obvious characteristic differences caused by different types of ships navigating in the same port area at the same time. Here, the traffic characteristics include traffic flow velocity, traffic distribution pattern, and the density of traffic participants.

Characterization method

As heterogeneous port traffic consists of mixed traffic with different characteristics, the vulnerability of the port traffic system is most likely to be higher than the vulnerability of a similar port system with homogeneous ship traffic, which is ships with similar sailing characteristics. Therefore, one of the ways to characterize the heterogeneous port traffic is to use the vulnerability degree of the system, which is also related to the triggering factor.

According to its connotation, the vulnerability degree is related to three factors, including the normal traffic state, the traffic unreliability degree, and the recovery ability of the traffic system. The three elements of the vulnerability degree can be calculated as follows.

(1) Normal traffic state

The probability of large traffic flows can be a parameter to reflect the daily traffic state. When marine traffic is congested, waiting queues do not always appear, like in road traffic. A traffic state is characterized as 'busy' when the actual traffic flow is bigger than the average traffic flows during a long period of time.

The probability of busy traffic for an area P_h is calculated by:

$$P_h = \frac{N_h}{N} \quad [1]$$

Where N_h is the number of busy days during a predefined time period of N days.

(2) Traffic unreliability degree

Unreliability of traffic in a waterway is caused by either the fact that a waterway is not available (that is, no ship can sail it) or the fact that the travel time of a ship is longer than the average travel time in this waterway. This is similar to a road network when the direct connection between two points is impossible, or the travel time between two points is longer due to the traffic rather than due to the vehicle itself. The calculating method of saturation is adopted (*15*). The saturation of a road section is represented by q/c, in which q is the actual traffic flow, and c is the designed capacity of the waterway section. However, in marine traffic, the so-called designed capacity for each section of a waterway is not known. Therefore, we change the meaning of the two parameters such that q refers to the average traffic flow in a waterway, and c refers to the maximum traffic flow without congestion in the area, calculated using historical data. In this sense, when the traffic flow is higher than the average traffic, the waterway is saturated and unreliable to some degree. Then the unreliability degree P_{ur} is a function of the saturation degree $f(q/c)$.

The recommended form of calculating $f(q/c)$ is (*14*):

$$f(q/c) = \begin{cases} \frac{(q/c)^2}{2(1-\beta)^2}, & 0 \le q/c < \beta \\ -\frac{(q/c-1)^2}{2\beta^2} + 1, & \beta \le q/c < 1 \\ 1, & 1 \le q/c \end{cases} \quad [2]$$

In order to make the function continuous, the value of β is 0.5.

(3) Recovery ability of the traffic system

When the traffic system is disturbed, congestion is usually the result. When all ships are still able to sail at their desired or required speed, the traffic can be seen as stable. After a system is disturbed, it needs to recover. To assess the recovery ability of the ship traffic system for a specific event, the traffic recovery time t_r is used as a criterion. The faster the traffic recovers, the higher the recovery ability (and thus the reliability) of the port system. Here, the recovery time is the time between the occurrence of the cause of the congestion and the time moment the traffic system is returned to a stable situation.

Since the first two parameters are calculated as probabilities, the recovery ability characterization should also be dimensionless. Taking one hour of traffic recovery time as an extreme situation, the recovery time is related to a series of discrete reduction weights to the vulnerability $a(t_r)$. If the time t_r is longer than 60 minutes, the weight is 1.0. If the time t_r is between 30 minutes and 60 minutes, every 10 minutes decrease leads to a decrease of 0.1 to the weight. If the time t_r is less than 30 minutes, every 5 minutes decrease leads to a 0.1 decrease to the weight.

The vulnerability degree of heterogeneous port traffic V is based on the probability of heavy traffic P_h and the unreliability degree P_{ur}, and corrected by the reduction weight of the traffic recovery time t_r. It can be presented as $V = f(P_h, P_{ur}, t_r)$.

When the probability of the cause of congestion is set as ω, the traffic unreliability is expressed as the consequence of the disturbance. After calculating the probability of unreliability per cause, the probability of heavy traffic in the area is multiplied in the computation. Finally the result is corrected by the weights of the traffic recovery time. The vulnerability degree can be computed as:

$$f(P_h, P_{ur}, t_r) = P_h \cdot [\omega P_{ur} + (1-\omega)(1-P_{ur})] \cdot a(t_r) \quad [3]$$

The computational result of the vulnerability degree V should be in the interval of (0, 1). The smaller the vulnerability degree is, the less the stability of ship traffic system is influenced by the cause of disturbance. This way, the vulnerability degree illustrates the characteristics of the heterogeneous port traffic in a traffic system.

HETEROGENEOUS PORT TRAFFIC OF GENERAL SHIPS AND SEAPLANES

Navigational characteristics of seaplanes sailing in the water

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

(1) Maneuverability characteristics

When a seaplane sails in the water, it is seen as a ship. After it leaves the water surface, it is an aircraft like other normal planes. It is the maneuverability characteristics of seaplane differ from normal ships with respect to speed and operation area.

- High speed

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 seaplane is almost similar to the sailing velocity of general ships. However, for taking off and landing, the speed will be much higher. According to the statistical data on seaplanes , the cruise speed of seaplanes during take-off and landing is around 150 to 300 km/h (*16*). Compared to the velocity of ships in ports (generally 5 to 10 kn), the velocity of seaplane during taking off and landing (about 40 to 108 kn) is much higher.

- Large operation area

The seaplane needs a large operation area for take-off and landing. The take-off distance requirement is around 400 to 600 meters, and the landing distance is around 350 meters (*16*). When there is a seaplane taking off or landing in its operation area, no vessel or swimmer is allowed to appear in this area. In France, the protecting area is even expanding 350 meters from the boundary of the take-off and landing area (*17*).

(2) Sailing characteristics

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

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

Heterogeneous port traffic of ships and seaplanes and its characterization

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 mixed. The indication of the heterogeneity of the port traffic is the maneuver of taking off or landing of a seaplane.

To describe the heterogeneous port traffic characteristics, the vulnerability degree V is used. The parameters P_h and P_{ur} for a specific water area in a port can be acquired by AIS data over a long period of time. However, the traffic recovery time t_r cannot be directly acquired from historical data. Based on the AIS data, t_r is calculated from the time the seaplane starts to taxi to the take-off and landing area. The end of traffic recovery is when the speed of all the vessels in the research area back to the level before the event.

CTM AND ITS FEASIBILITY FOR MODELING

When assessing the current state of a port with seaplane piers , the traffic recovery time of the taking off or landing event can be calculated based on the historical AIS data. However, for comparing different management plans, a simulation model is needed.

CTM (Cell Transmission Model) is a discretized approximation of the macro dynamic model, which is similar to a fluid mechanics model. CTM was first put forward by Daganzo to simulate the car traffic flow on freeways (*18*), and then applied to the research of dynamic traffic networks (*19*). Now CTM has been widely applied in research on vehicular traffic characteristics. The CTM has two kinds of models, being section model and junction model, corresponding to the two types of infrastructure that can be distinguished for vehicular traffic. Since the take-off and land of seaplanes usually occurs in open water, only the road section model of CTM needs to be considered.

Characteristics of the port traffic system

The feasibility of CTM is analyzed based on the characteristics of discrete traffic, a chain reaction of traffic event, and exclusive use of the waterway during taking off and landing.

(1) Discrete traffic

In waterway, only the movement of a fleet of ships can be seen as continuous. There is seldom a queue of ships sailing in line such as car traffic moving in lanes. In other words, both seaplanes and the ships are modelled individually.

CTM divides a waterway section (a road section) into several cells with the same length. When applied for a specific problem, the cell length is defined by the distance traveled by a ship during a time period. In the heterogeneous port traffic, the sailing velocity of ships can be determined using historical data or the port regulations. However, this velocity does not hold for seaplanes during takeoff and landing. Also the travel directions are not exactly the same. This way, the distance definition method of CTM is not feasible in this research. However, the basic cell size can be set equal to the size of the area that seaplanes need for take-off and landing. This way, the requirement of only one single seaplane in this area during taking-off and landing operation is met. Given the velocity of ships, the time step length can be calculated. The traffic operations are represented by the change in the number of ships in every cell between two consecutive time steps.

(2) Chain reaction of traffic event

When the amount of ships sailing in the port is large, the navigational state of a ship is strongly affected by the ships in its neighborhood. In these circumstances, the taking off or landing event of seaplane will not only influence the traffic in the area for taking off or landing, but also the ship traffic around this area. A chain reaction happens because the ships around need to decrease the speed even stop to wait for the safe completion of seaplane taking off or landing.

In a CTM, the change of a cell state is related to the state of the cell upstream as well as the state of the cell downstream. This relationship is presented by the recursion formula of CTM. In this way, the chain reaction of the takeoff or land event can be modeled.

(3) Exclusive right-of-way of the operation area during taking off and landing

In order to guarantee the safety during take-off and landing of seaplanes, ships are not allowed to sail in the take-off and landing area. During these two phases, the seaplane has an exclusive right-of-way of the operation area, which blocks the traffic in the neighboring sections of the waterway. All ships thus need to wait or slow down until the seaplane has departed or arrived.

Due to the relationship between the consecutive cells, the takeoff and land operation can be represented by identifying the occupancy of a cell, and thus inflow and outflow capacity of the neighboring cells.

Model input requirements

The core of the CTM theory relies on the calculation of the cell state. When adopting CTM as a method, several model parameters need to be specified, including the maximum allowed number of ships in a cell, the maximum inflow into a cell, the maximum outflow of a cell, and the relation between the number of ships in a cells and the inflow. For a specific application, all parameters in the CTM can be acquired using the historical data.

Matching of output and traffic management demand

In this research the CTM is used to predict the heterogeneous port traffic flows under different management plans. In order to derive optimal traffic management measures, the model is capable of assessing two types of measures, related to demand management and traffic rules.

(1) Demand management.

Demand management is a planning methodology used to manage the traffic demand. When congestion occurs, or the recovery times are long, the traffic demand is higher than the supply. In order to let the system recover, the demand needs to be lower than the supply. The lower the demand, the faster the recovery. In this model, demand management corresponds to a reduction in the traffic demand. How this reduction is achieved, is outside the scope of this research.

(2) Traffic rules

The capacity (or supply) of a port system is among other things affected by the traffic rules. This covers sailing direction restriction, maximum allowed number of ships in certain sections of the waterway, but also the allowed sailing speed. The effect of the latter measure on the recovery time of the system is assessed.

We can now conclude that the CTM is feasible with respect to three aspects, namely the application characteristics, the model input requirements, and the matching of output and traffic management demand.

MODELING SEAPLANES AND SHIPS BASED ON CTM

When applying the CTM, the waterway needs to be divided into sections. The take-off and land area for seaplanes is usually in open water, which is more difficult to divide into sections than the traffic lane of a freeway. The main cause of the traffic heterogeneity is the exclusive right-of-way on a waterway section during take-off and landing of a seaplane. Assuming that the seaplane take-off and landing water is a rectangle, the major impact on ship traffic is along the long side of the area. Thus, based on the size of the take-off and landing area, the cell is twice as big as shown in FIGURE 1, taking the length of operation area as the cell width, and twice of the area width as the cell length. The width is taken twice large as needed in order to guarantee safe maneuvering: when ships are waiting just outside the boundary of the take-off and landing area, it is hard to avoid collision if an emergency happens.

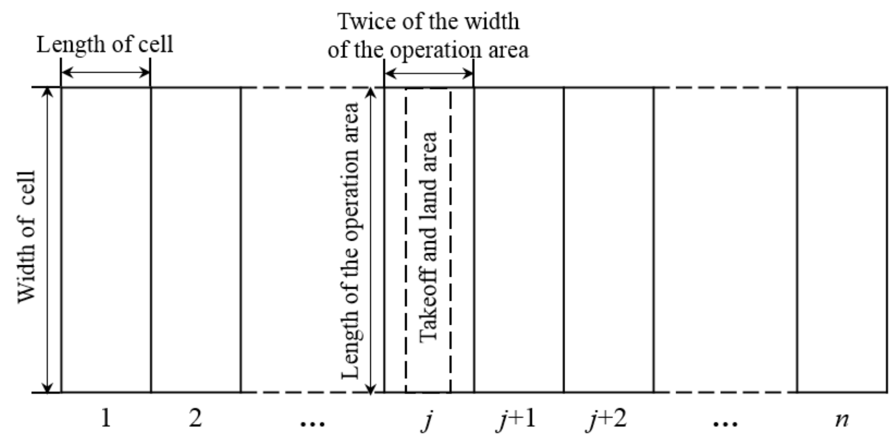


FIGURE 1 Cell definition in the simulation model of heterogeneous port traffic of general ships and seaplanes.

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.

Model for ship traffic without seaplanes

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

(1) Parameter setting

Each cell corresponds to a certain waterway section with exactly the same size. The total number of cells describing the whole waterway is set to n , and all cells are numbered as $1, 2, \cdots, n$ in the direction of the ship traffic flow.

The two parameters that need to be set in the CTM are the maximum number of ships in a cell $N_i(t)$ and the capacity of cell *i* at time *t* $q_i(t)$.

$$N_i(t) = \rho_{max}(t) \cdot l_{cell} \cdot w_{cell} \; (i = 1, 2, \cdots, n) \quad [4]$$

$$q_i(t) = \begin{cases} min\{ q_i(t), q_{i+1}(t)\} \; (i = 1, 2, \cdots, n-1) \\ q_i(t) \quad (i = n) \end{cases}$$

In which

$\rho_{max}(t)$	the maximum density of ships in cell *i* at the time *t* [km^{-2}]
l_{cell}, w_{cell}	the length and width of the cell respectively [km]

(2) Ship flow calculation

Based on the flow calculation method by Daganzo (*17*), the ship flow can be calculated as:

$$f_i(t) = min\{n_{i-1}(t), q_i(t), \omega[N_i(t) - n_i(t)]/v\} \; (i = 2, 3, \cdots, n) \quad [5]$$

In which

$f_i(t)$	the number of ships flow into cell *i* at the time *t*
$n_i(t)$	the number of ships in cell *i* at the time *t*
$q_i(t)$	the capacity of cell *i* at the time *t*
$N_i(t)$	the maximum number of ships in cell *i* at the 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 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.

(3) Navigational state update

After calculating the ship flow in the second step, the number of ships flowing into each cell is acquired. The state of ship number in each cell is updated according to eq. [6]. This way, the model simulates the ship traffic flow through the whole system.

$$n_i(t+1) = n_i(t) + f_i(t) - f_{i+1}(t) \quad [6]$$

In which

$n_i(t)$	the number of ships in cell *i* at the time *t*
$f_i(t)$	the number of ships flow into cell *i* at the time *t*

Model for heterogeneous port traffic of general ships and seaplanes

To model for the heterogeneous port traffic, the event of takeoff or land needs to be included. This implies two corrections to the parameter setting:

- When the seaplane starts to taxi to the operation area for taking off or approach for landing, the maximum number of ships in cell j $N_j(t)$, the 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 right-of-way of the waterway 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 recovered.

According to eq. [6], parameter changes in cell j will affect the state of the upstream cell i ($i < j$). This way, the congestion caused by seaplane taking off or landing moves through the waterway network.

Model for traffic management plans

Since the routes of ships are designed by individual ships according to their origin and destination, it is impossible to take measures to change all the routes of involved ships. Two kinds of measures that can be taken in port area. One is to control the ship velocity (via the traffic regulation), the other is to control the demand (the number of ships arriving in the waterway).

(1) Controlling the ship velocity

Before a seaplane is taking off or landing, a Notice to Mariners can be announced to require a lower velocity of all ships.

When taking this measure, the state updating function does not change. It only affects the calculation of the ship flow, as the sailing velocity of ships needs to be corrected.

(2) Controlling traffic demand

The ship generation of the model $f_1(t)$ is determined by the actual navigational situation in a specific port.

When taking the measures to control the demand, the ship generation function $f_1(t)$ will change to decrease the demand temporarily, until congestion has resolved.

CALIBRATION OF THE SIMULATION MODEL

The calibration of the simulation model is carried out in two parts. The first step is to compare the modelled traffic recovery time to the observed recovery time based on historical data. The second step is to compare the vulnerability degree of the heterogeneous port traffic without and with management plan as a case study.

According to the layout of the seaplane pier and port of Sanya, a cell has a length of 120m and a width of 750m, as shown in FIGURE 2. Since a waterway area in length of 1 n mile is taken as the research area, there are 15 cells in total and the take-off and landing area is in cell 8. FIGURE 2 also shows the section to collect the current traffic situation for the vulnerability degree computation. All ship traffic data are from the AIS information of the year 2013.

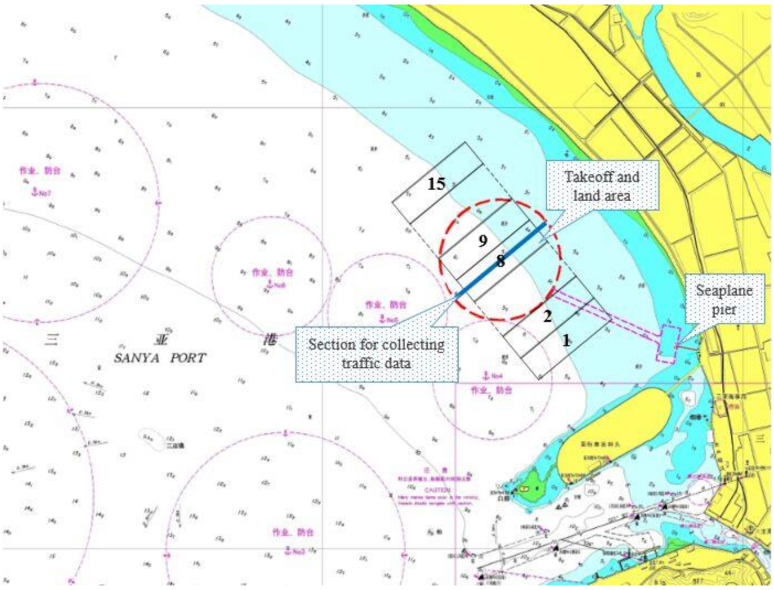


FIGURE 2 Details of data collection site and the cell definition. (Source: China Nautical Chart No. 00501)

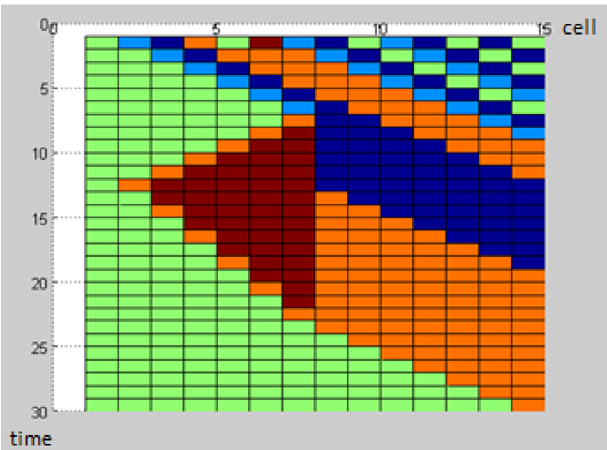
(1) Comparison between the modeled traffic recovery time and the observed data

In the port of Sanya, the velocity limit is 5 kn, and the average velocity based on the historical data is 4.03 kn. As the average velocity should be lower than the velocity by regulation, the average velocity is taken as the ship velocity in model. Given the cell length and the average ship velocity, the ships need 57.88 seconds to travel through a cell. In the model, the time step is set to 1 min.

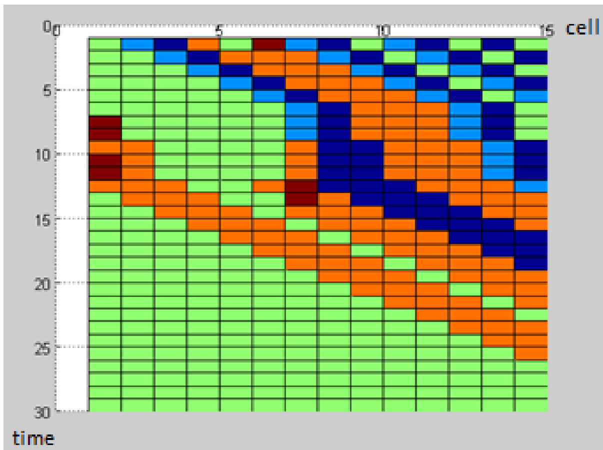
According to the historical data in the port of Sanya, the parameters in the model are set as follows. The calculated maximum number of ships in cell i $N_i(t)$ in the model of ship traffic is 3.6, which is set to 4 in the model. The capacity of cell i $q_i(t)$ is 3 per unit of time.

As to the model for the heterogeneous port traffic of general ships and vessels, the parameters change as indicated above. We assume that the event of taking off or landing starts in time step 6 and ends in time step 12. The simulation result is shown in FIGURE 3.

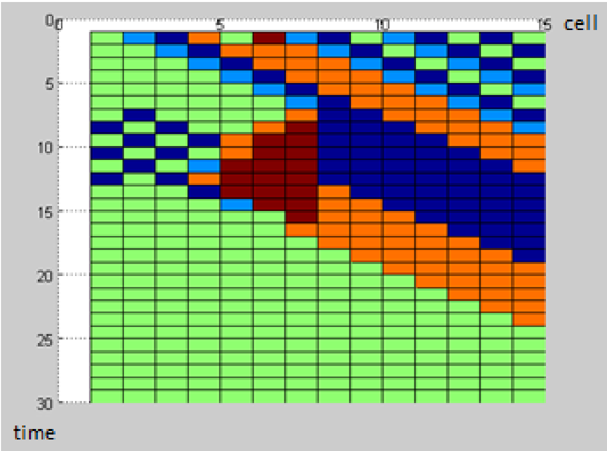
In order to decrease the recovery time, two kinds of measures are taken respectively, being reducing the velocity to half the original velocity and decreasing the ship demand with 50%. The simulation results of these alternative scenarios are shown in FIGURE 3 as well.



a. Simulation result for heterogeneous port traffic flow.



b. Simulation result when decreasing the ship velocity to half.



c. Simulation result when decreasing the amount of outgoing ships with 50%.

FIGURE 3 Simulation result of the model for the heterogeneous port traffic of general ships and seaplanes. The red color indicates that the maximum number of ships (4 in this model) is present. 3 ships are present in the orange cells for, while the green cells contain 2 ships. Only 1 ship is present in the light blue cells, and the dark blue cells are empty.

FIGURE 4 shows the recovery time for the three modeled scenarios, and compares this time to the observed recovery time. For each scenario, the bar on the left is the modeled traffic recovery time, the bar in the middle is the observed traffic recovery time, and the bar on the right indicates the difference between the modeled time and the observed one. FIGURE 4 shows that the results of the simulation model correspond well to reality. The simulation results in all three situations differ only slightly from the reality, as the differences for the three scenarios are 5.4%, 2.6%, and 3.2% respectively. In this case, the time difference is around 40 seconds. As the model parameters were not exactly equal to the ones calculated from historical data, the validity can be even further improved if the parameters of ship velocity and time step are taken more accurately.

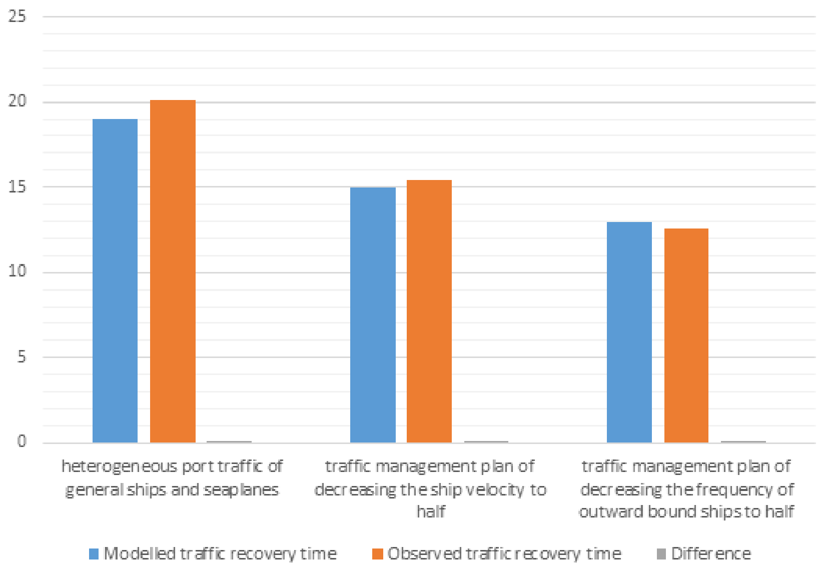


FIGURE 4 Validation test of the simulation model.

(2) Comparison of the vulnerability degree

According to the historical AIS data in the port of Sanya, the maximum traffic flow in the research section is 63 ships per day, while the average flow of the section q is 19.35 ships per day. The number of busy days when the actual traffic is higher than the average level is 288 days in one year Comparing the voyage number to the ship traffic, the probability of the event of seaplane taking off and landing is 0.42.

The modeled and observed traffic recovery time are used to compute the vulnerability degree for the three scenarios introduced before, see TABLE 1. It is clear that when taking traffic management measures, the vulnerability degree will decrease because of a shorter traffic recovery time. The table also shows the robustness of the vulnerability as assessment criterion: even when there is a slight difference between the modeled recovery time and the observed one for the reduced traffic demand scenario, the vulnerability degree remains the same.

TABLE 1 Validation test of the simulation model and the vulnerability degree computation method.

Situation description	Vulnerability degree based on modelled traffic recovery time	Vulnerability degree based on observed traffic recovery time
Heterogeneous port traffic of general ships and seaplanes	0.174	0.217
Traffic management plan of decreasing the ship velocity to half	0.130	0.174
Traffic management plan of decreasing the frequency of outgoing ships to half	0.130	0.130

CONCLUSIONS AND RECOMMENDATIONS

In this paper we have introduced a new concept of the heterogeneous port traffic (consisting of ships and seaplanes) and we have presented a method to quantify the vulnerability degree of heterogeneous traffic. The navigational characteristics of seaplanes traveling in the water form the basis of the analysis of the heterogeneous port traffic. In this paper, we presented a model to simulate and predict the traffic recovery time when a seaplane is taking off or landing. For this model, CTM theory is adopted successfully for the maritime traffic for the first time. The simulation model is calibrated by comparing the model results to the historical data with deviations of 5.4%, 2.6%, 3.2% for the three different scenarios. The absolute difference is about 40 seconds, which proves the model to have predictive validity. The proposed computation method of the vulnerability degree is applied for the same scenarios, showing that the vulnerability decreases when measures are taken. Even when there is still a slight difference in the traffic recovery time, the vulnerability degree does not change, showing the robustness of this assessment factor.

This paper only shows the basic CTM model, without coefficient to tune the parameters. This could be one of the reasons for the differences between the modeled and the observed results. The model is only calibrated in one port with one seaplane pier constructed. It needs to be further calibrated and validated by applying it in other port areas, with the objective of obtaining a generalized set of parameters. The reduction weight of traffic recovery time in the vulnerability degree computation still needs to be assessed based on more applications.

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