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Time efficiency assessment of ship movements in maritime ports: A case study of two ports based on AIS data

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ABSTRACT

Operational efficiency of a maritime port is an important issue for shipping lines and port authorities. It is desirable to move ships in and out of a maritime port as efficiently as possible. Automatic identification system (AIS) data recording the trajectory of ship movements allow us to assess the operational efficiency as ships move in and out of a port. This study proposes a time efficiency assessment framework that evaluates the amount of time each ship spends in the different areas within a port (i.e., berth, anchorage, and fairway) based on the space-time trajectories of ship movements derived from AIS data. According to the statistical distributions of time spent by different types of ship in each port area, the proposed framework can compare time efficiency across different zones within a port and between different ports. This study uses AIS data of four types of ships (i.e., container, cargo, tanker, and passenger ships) at two selected ports in China, Shanghai Yangshan Port and Xiamen Port, to demonstrate how the proposed approach can effectively assess and compare time efficiency levels of ship movements between the times entering and leaving the vessel traffic service (VTS) lines of a port. This study demonstrates the value of deriving space-time trajectories from AIS data based on the concepts of time geography to assess time efficiency levels of maritime ports and monitor their performance over time, which offer useful information to both shipping lines and port authorities for operations such as efficient scheduling and logistic support.

1. Introduction

Maritime transportation is an important part of international logistics. World seaborne trade volume expanded by 2.7% and the total volume grew to 11 billion tons in 2018 (UNCTAD, 2019). Cargo ships, tanker ships, and container ships ranked the top three among all ship deliveries in 2018, with cargo ships accounting for 26.7% of total gross tonnage, followed by tanker ships (25%) and container ships (23.5%) (UNCTAD, 2019). An estimate of 793.26 million twenty-foot equivalent units (TEUs) were moved at container ports around the world and global container port traffic increased by 4.7% in 2018 (UNCTAD, 2019). Furthermore, containerized trade increased by 2.6%, dry bulk trade increased by 2.6%, and global tanker trade increased by 1.5% in 2018 (UNCTAD, 2019). Although the main purpose of passenger ships is not for transporting goods and their share in dead-weight tonnage is negligible compared to container, cargo and tanker ships, passenger ships accounted for more than 11.9% of the fleet's market value in 2018 (UNCTAD, 2019). This large scale of maritime transportation contributes significantly to the development of world trade, global supply chain, and international economy. Efficiency of maritime port operation therefore is a core issue of maritime transportation in support of global trade flows.

Previous studies have focused mainly on operation efficiency at berth, while studies of the efficiency of other phases in a port (e.g., vessel traffic services (VTS) line-to-berth, berth-to-VTS line, and anchorage) are limited. Based on space-time trajectories of different types of ships derived from Automatic Identification System (AIS) data, it is possible to analyze the efficiency of ships undergoing various phases in a port. In addition, areas with low time efficiency of ship movements in a port can be identified, which enables port authorities to improve efficiency and provide better transportation services. This study uses AIS data of four types of ships (i.e., container, cargo, tanker, and passenger ships) at two selected ports, which are Shanghai Yangshan Port and Xiamen Port in China, to demonstrate how the proposed approach can

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effectively assess and compare time efficiency levels of container, cargo, tanker, and passenger ships from the point when they enter the vessel traffic service (VTS) line to the point when they leave the VTS line of each port. Major contributions of this paper are as follows:

1) A space-time trajectory framework based on the concepts of time geography (Hägerstraand, 1970) is developed to assess the time efficiency performance of ship activities as they move through different zones from the point they enter the VTS line to the point they leave the VTS line in each port;
2) A set of AIS-based time efficiency indicators is introduced to assess the operational performance of different types of ships (i.e., container ships, cargo ships, tanker ships, and passenger ships) that exhibit varying distribution curves of time efficiency; and
3) A case study of two major ports in China, which are Shanghai Yangshan Port and Xiamen Port, demonstrates how the proposed AIS-based approach can effectively assess and compare the time efficiency patterns of different types of ships and of different ship sizes as they pass through different zones in each port.

The remaining parts of this article are organized as follows. The next section reviews previous research related to AIS data analysis and port efficiency assessment. The third section presents a proposed time efficiency assessment framework based on AIS data and the related methods. The fourth section discusses the two selected ports and the data used in this study as well as the analysis results derived from the proposed time efficiency assessment framework. The final section summarizes this study and offers some future research directions.

2. Literature review

Analysis of time efficiency of vessel activities in ports is a vital part of port efficiency research. Research of port efficiency can help us better understand the operational and traffic situations in a port as well as the management efficiency of a port. Previous studies have focused on economic efficiency (Coto-Millán et al., 2000; Estache et al., 2004; Cheon et al., 2010; Nuñez-Sánchez and Coto-Millán, 2012), regulation efficiency (Niavis and Tsekeris, 2012; Coto-Millán et al., 2016; Serebrisky et al., 2016), terminal operation efficiency (Yuen et al., 2013), environmental efficiency (Song, 2014; Moon and Woo, 2014; Tichavska and Tovar, 2015; Coello et al., 2015), and energy consumption efficiency (Johnson and Styhre, 2015). This section will review the efficiency evaluation indicators of a port, and the related Port efficiency evaluation methods.

2.1. Efficiency evaluation indicators of a port

From an economic perspective, a variety of indicators have been proposed in the literature to evaluate the efficiency level. For example, some studies use traffic volumes to characterize and analyze operational efficiency of ports. Estrada et al. (2017) propose to use total volume of export/import operations, port cargo growth rate, and total factor productivity to characterize port openness, productivity level, cargo expansion, and adaptability to technological changes. Le-Griffin and Murphy (2006) use traffic volume per total length of quay to measure service level of different elements in ports, such as cranes, berths, yards, gates, and gang levels at Los Angeles and Long Beach and find that they are underperforming relative to other leading container ports. Furthermore, Ducruet et al. (2014) investigate the utilization rates of berths, cranes and ground areas based on the twenty-foot equivalent unit (TEU). Their measures include berth length utilization rate (TEUs per foot of container quay), crane utilization rate (TEUs per container gantry crane), crane productivity (TEUs per container gantry crane-hour), and land area utilization rate (TEUs per acre of terminal area). In addition, for liquid bulk vessels (such as tankers), the average dwell time in port terminal boundaries is used to evaluate tanker's efficiency across ports (USDOT, 2019). On the other hand, some researchers introduce efficiency evaluation indicators by measuring the economic output, for instance, tonnage worked, berth occupancy revenue per ton of cargo, cargo handling revenue per ton of cargo, labor expenditure, capital equipment expenditure per ton of cargo, contribution per ton of cargo, total contribution, and monetary and added value of cargo throughput (UNCTAD, 1976) for comparison of port efficiency around the world. The above indicators have been frequently used to assess port efficiency from facility utilization and economic output perspectives with a focus on the terminals. Efficiency in other parts of a port has received less attention in the literature.

Data collected from the Automatic Identification System (AIS) now provide rich vessel movement information. AIS data have been widely employed in various research, such as maritime data mining, navigation safety, ship behavior analysis, environmental evaluation, trade analysis, and ship and port performance (Yang et al., 2019). In studies of port performance, port performance indicators derived from AIS data include ship traffic, container throughput, berth utilization, and terminal productivity (Chen et al., 2016). Freight fluidity is also proposed to evaluate the performance of trade corridors and multimodal supply chains by measuring total transit time and travel time reliability using AIS data (Kruse et al., 2018). Other researchers compute travel time statistics from AIS data of various vessels using different maritime transportation systems (Mitchell and Scully, 2014). Vessel performance within a waterway also has been studied with AIS data. For instance, transit durations of inbound cargo vessels, outbound tankers, etc. are compared temporally and spatially to investigate performance trends (Scully and Mitchell, 2015). In addition, some researchers use AIS data to assess the resilience of port operations following major disasters and other disruptive events (Farhadi et al., 2016). From the perspective of transportation networks, researchers have developed a port connectivity index to evaluate a port's connectivity based on AIS data of multiple vessel types (Jia et al., 2017). A port's connectivity in a transportation network can help port authorities and policy makers in port planning and infrastructure investment.

2.2. Port efficiency evaluation methods

Researchers have developed various methods to assess port efficiency, such as data envelopment analysis (DEA), stochastic frontier analysis (SFA), ordinary least squares (OLS), multi-agent-based simulation model, analytic hierarchy process (AHP), and directional distance function (DDF) (Irannezhad et al., 2017; Liu, 2010; Suárez-Alemán et al., 2016; Tovar and Wall, 2017; Vaggelas and Pallis, 2010; Zahran et al., 2017). These methods in general attempt to determine relationships between inputs and outputs of port operation using either a parametric or non-parametric approach.

Data envelopment analysis (DEA) is a popular non-parametric method for estimating port efficiency (Dyck, 2015). Using a programming approach, efficiency in different units can be evaluated and compared (Zhou et al., 2008). For example, the operational efficiency of container vessels in the main ports of China and South Korea is analyzed and compared through DEA model based on the length of berth, yard area, number of quay cranes, and number of yard cranes (Zheng and Park, 2016). The results indicate that major terminals in South Korea and China have similar efficiency levels. Cullinane et al. (2005) use DEA method to assess the efficiency of 30 ports and find no detectable relationship between the degree of privatization and port efficiency.

Stochastic frontier analysis (SFA) acts as a parametric and stochastic approach to assess port efficiency, which improves over DEA by introducing distribution assumptions about inefficiency of economic agents and random errors of uncontrolled factors. Tongzon and Wu (2005) analyze the relationship between container port ownership structure and port efficiency and find that privatization can, to some extent, improve the efficiency of a container port. The relative

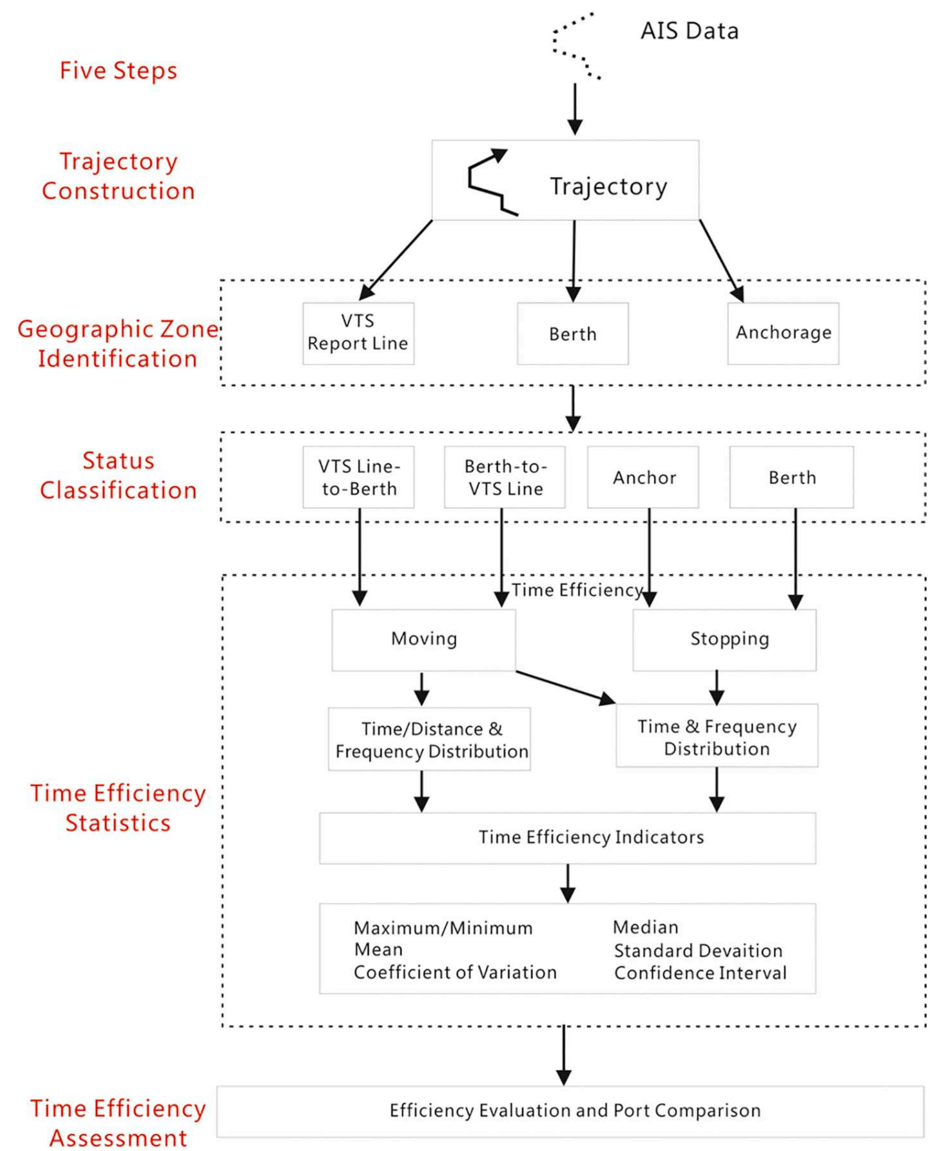

Fig. 1. AIS-based time efficiency assessment framework.

efficiency of major container terminals in Asia are assessed by SFA and the results suggest a terminal's size is closely correlated with its efficiency (Cullinane et al., 2002). Wiegmans and Witte (2017) focus on analyzing the influence of terminals' design on efficiency and find the most important factors for inland waterway container terminals are yard and crane based on a stochastic frontier analysis.

Ordinary least squares (OLS) is a regression method that fits an equation to reflect the degree of influence on efficiency based on selected independent variables. Using variables of distance, product weight, product type and difference between imports and exports, Blonigen and Wilson (2006) examine the efficiency among ports in the United States and other countries. The results indicate that the Gulf coast and west coast ports in the United States as well as European and Japanese ports are more efficient than other ports around the world.

Multi-agent-based simulation model is used to evaluate the collaboration efficiency among different departments in a port (Irannezhad et al., 2017). It evaluates port efficiency by examining the gap between actual behavior and optimal behavior of each department using a reinforcement learning algorithm. It reveals that collaboration can decrease total logistics cost and improve vehicle utilization.

Analytic hierarchy process (AHP) is an approach that decomposes a complex decision problem into a hierarchy of more comprehensible sub-problems such that each sub-problem can be addressed independently. Vaggelas and Pallis (2010) apply a modified AHP to evaluate port services at twenty major European passenger ports. Their study confirms that the provision of 17 core port services results in a mixture of public and private benefits.

Directional distance function (DDF) requires the specification of a direction vector to measure efficiency (Shephard, 1981). Tovar and Wall (2017) estimate an input-oriented directional distance to measure dynamic technical efficiency for a set of 26 Spanish port authorities over the period of 1993–2012. Ports in this study are assumed to invest with an attempt of minimizing the present value of future production costs.

In short, the above methods are useful in tackling various efficiency issues related to port operation. However, very few of them address the assessment of time efficiency as ships sail through different zones in a port between the time a ship first enters the VTS line and the time when the same ship leaves the VTS line of a port. Different from variables such as capital, equipment, labor force, energy, or fuel resources, time is an exogenous variable that usually depends on how the other variables perform (de Rus Mendoza et al., 2003). Time can reflect the influence of various factors on efficiency (Suárez-Alemán et al., 2014). This study extends previous studies to develop a time efficiency

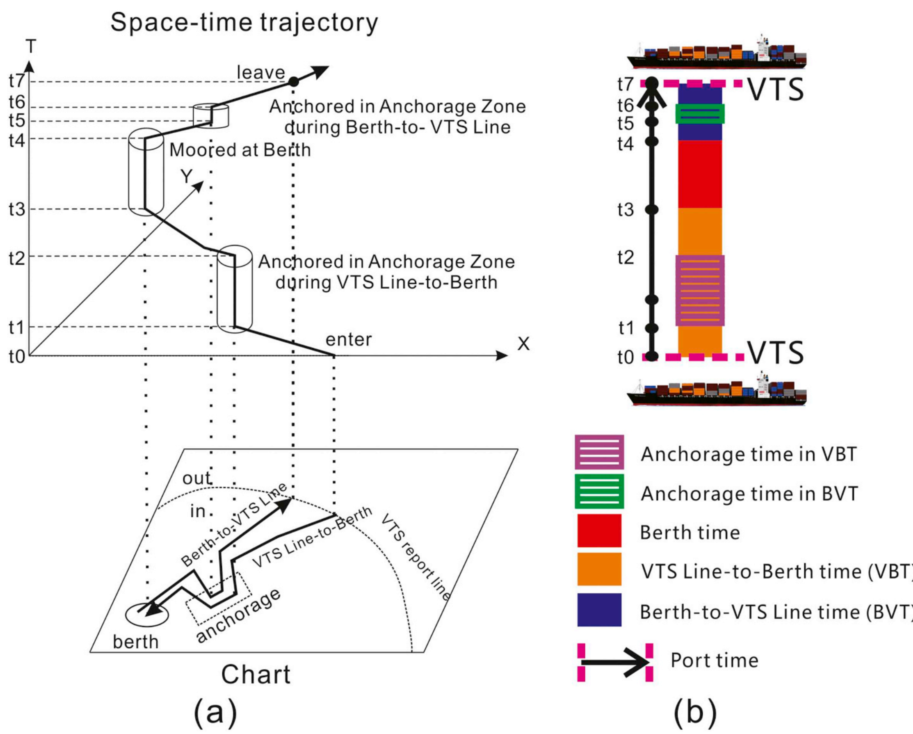

Fig. 2. Different statuses associated with the space-time trajectory of a ship.

assessment framework that uses AIS data to derive space-time trajectories of ships in a port such that it is feasible to quantitatively assess the time efficiency level as ships go through different statuses (i.e., VTS Line-to-Berth status, Anchored at Anchorage Zone status, Moored at Berth status, and Berth-to-VTS Line status) in a port.

3. An AIS-based time efficiency assessment framework

This study employs the concept of space-time path in time geography (Hägerstraand, 1970) to generate space-time trajectories of ships from AIS data. Based on this concept, a ship in a port is considered as a moving object whose location changes over time in a port. This study defines the boundary of a port by its vessel traffic services (VTS) line within which ships are monitored and provided with maritime transportation navigation advices. In addition, this study divides ship movements in a port into three major phases, which are "from VTS line to berth", "at berth", and "from berth to VTS line". At the individual level, the space-time trajectory of a ship can be used to analyze its operational characteristics in a space-time context, such as the dwell time or speed at different locations in a port to reflect the activity patterns in different phases. By extracting the space-time trajectory of each ship from the AIS data, this study analyzes the time component associated with activities in each phase to assess the time efficiency of four specific types of ships (i.e., container, cargo, tanker, and passenger) in each port. An AIS trajectory-based time efficiency assessment framework based on space-time paths is proposed below (Fig. 1).

This framework consists of five steps, namely, trajectory construction, geographic zone identification, status classification, time efficiency statistics, and time efficiency assessment. Data processing performed at each of these five steps is discussed below:

1. Trajectory construction. AIS data of each ship are first sorted by the time stamp in AIS records. AIS data records with obvious errors such as abnormal coordinates or velocity are removed from further analysis. The cleaned AIS data sorted by time are used to construct the space-time trajectories of all ships. Eq. (1) shows the structure of a ship's space-time trajectory derived from AIS data, where (x_n, y_n) represents the nth record of a ship's location; t_n is the time stamp of the nth record; v_n is the speed of the nth record, and s_n is the ship status of the nth record. While a ship's location, time stamp and speed can be derived from AIS data directly, a ship's status must be derived from both AIS data and different geographic zones in a port together.

$$Trj = \{(x_0, y_0, t_0, v_0, s_0),...(x_n, y_n, t_n, v_n, s_n)\} \quad (1)$$

2. Geographic zone identification. Each port in this study is classified into three different geographic zones, which are "within the VTS report line," "within the anchorage zone," and "within the berth zone." The "within VTS report line zone" is to help us identify if a ship is inside or outside a port area. If it is outside a port area, it is excluded from this study. For those space-time trajectories that are inside a port area, this study further identifies if it is anchored in an "anchorage zone" or docked within a "berth zone". A "berth zone" is defined by extending 100 m from the berth line into the adjacent water. The parameter of 100 m is selected based on the width of ships, because a ship needs to be moored along a berth line for loading and unloading goods. Each space-time trajectory is then segmented based on its location with respect to these three zones. This study uses spatial overlay operation in GIS to identify space-time trajectory segments that fall within each of the three zones based on the boundary lines shown on official nautical charts.
3. Status classification. This study classifies the movements of each ship within a port area into six different statuses, which include *Inside Port Zone*, *Moored at Berth*, *VTS Line-to-Berth*, *Berth-to-VTS Line*, *Anchored in Anchorage Zone during VTS Line-to-Berth*, and *Anchored in Anchorage Zone during Berth-to-VTS Line*, to reflect the status of a ship in a port area. Fig. 2 (a) illustrates these six statuses in a port.

The definition of each of the six statuses is provided below:

Definition 1. Inside Port Zone refers to the status from the point when a ship crosses the VTS line to enter a port area to the point when the same ship moves outside the VTS line and leaves a port. It should be

Table 1
Time efficiency indicators of ship movements in a port.

Status	Indicator	Meanings
Inside port zone (inside VTS report line)	Port time (*PT*)	Total time that a ship takes to complete all activities in a port
Moored at Berth	Berth time (*BT*)	Time that a ship is moored at a berth
VTS Line-to-Berth	VTS Line-to-Berth time (*VBT*)	Time that a ship takes to move from the VTS line to the status of Moored at Berth
Berth-to-VTS Line	Berth-to-VTS Line time (*BVT*)	Time that a ship takes to move from the end of Moored at Berth status to the point it crosses the VTS line to leave a port
Anchored in anchorage zone during VTS Line-to-Berth	Anchorage time in VBT (*ATVB*)	Time that a ship is anchored in an anchorage zone during VTS Line-to-Berth
Anchored in anchorage zone during Berth-to-VTS Line	Anchorage time in BVT (*ATBV*)	Time that a ship is anchored in an anchorage zone during Berth-to-VTS Line

noted that this phase includes all activities of a ship inside a port, including time spent at berth and/or anchorage. This definition allows researchers to assess the total time spent in a port area by each ship which is one indicator of time efficiency at a port.

Definition 2. VTS Line-to-Berth refers to the status from the point when a vessel crosses the VTS line of a port until the same ship docks at a berth, including anchorage time if any. If a ship moves around a port's VTS line and stays within the VTS line less than five minutes, it is excluded from this study. This status allows researchers to assess how fast a ship can move from the VTS line to a berth within a port area.

Definition 3. Berth-to-VTS Line refers to the status from the point when a ship departs a berth to the point the same ship crosses the VTS line to leave a port. A comparison of the time taken for ships in the "VTS Line-to-Berth" status versus the time in the "Berth-to-VTS Line" status can shed light on factors affecting the time efficiency of port operations.

Definition 4. Moored at Berth refers to the status when a ship is moored at a berth. Since AIS data can track very low speed movements caused by slight movements of a ship at berth, we consider a ship is at berth only if it is located within a berth zone and its speed recorded in the AIS data is less than 1 knot (Chen et al., 2016).

Definition 5. Anchored in Anchorage Zone during VTS Line-to-Berth refers to the status that covers the period from the point a ship is anchored in an anchorage zone to the point the same ship leaves the anchorage zone to sail to a berth area. An anchorage zone is delineated as a polygon object on a nautical chart. Due to limited berth space, ships sometimes need to be anchored in an anchorage zone and wait for available berth space when sailing towards a berth area.

Definition 6. Anchored in Anchorage Zone during Berth-to-VTS Line refers to the status that covers the period from the point a ship is anchored in an anchorage zone to the point the same ship sails out of the anchorage zone to leave a port.

After the status classification step, the space-time AIS trajectory of each ship should have at least the *Inside Port Zone*, *VTS Line-to-Berth*, *Moored at Berth*, and *Berth-to-VTS Line* statuses with or without anchorage status. Various segments of the space-time trajectory of each ship (including container, cargo, tanker, and passenger ships) now are identified with a status code value, s, as shown in $Trj = \{(x_0, y_0, t_0, v_0, s_0), \ldots (x_n, y_n, t_n, v_n, s_n)\}$ that can be used to assess time efficiency. Ships which do not have all four of the basic statuses suggest that they have missing data in the AIS dataset and are removed from further analyses in this study.

4. Time efficiency statistics. Based on the trajectory segments of each status derived from the above steps, this study computes the time spent in *Inside Port Zone, Moored at Berth, Anchored in Anchorage Zone, VTS Line-to-Berth, and Berth-to-VTS Line, Anchored in Anchorage Zone during VTS Line-to-Berth, and Anchored in Anchorage Zone during Berth-to-VTS Line*, respectively, to analyze time efficiency. Six statistics (i.e., max/min, *median*, *mean*, *standard deviation* (*SD*), *coefficient of variation* (*CV*), and *confidence interval* (*CI*)) are used as indicators to assess time efficiency as ships go through different statuses in a port.
5. Time efficiency assessment. The proposed time efficiency assessment approach can assess time efficiency in each port as well as compare time efficiency between different ports to identify which segments in a port that can move ships efficiently and find the port areas with room for improvements.

3.1. Selected time efficiency indicators

Fig. 2(b) shows the time components associated with a ship's movements within a port area. A ship passes the VTS report line (i.e., the dashed magenta lines) into a port area and starts the status of *VTS Line-to-Berth*. Before the ship moors at berth, this ship maintains its *VTS Line-to-Berth* status as shown by the orange segment in Fig. 2(b). Under the status of *VTS Line-to-Berth*, a ship may be *Anchored in Anchorage Zone during VTS Line-to-Berth* (i.e., the purple stripes segment). This ship then arrives at a berth and transitions into the "*Moored at Berth*" status (i.e., the red segment). After completing unloading/loading operations at berth, this ship begins to leave the berth area and changes into the *Berth-to-VTS Line* status (i.e., the blue segment). A ship may be in *Anchored in Anchorage Zone during VTS Line-to-Berth* status (i.e., the green stripes segment) during the *Berth-to-VTS Line* status. Finally, as the vessel crosses the VTS line and leaves the port, the *Berth-to-VTS Line* status ends. We then can compute the total time under the "*Inside Port Zone"* status. Based on the time span of these 6 statuses in a port, several time efficiency indicators can be derived from the defined space-time trajectory of each vessel (Table 1).

For each of the indicators in Table 1, we compute the following statistics to compare the time efficiency between different ports based on these six indicators:

Min/Max (${}_{Size}^{Type}Min_p^S$ and ${}_{Size}^{Type}Mean_p^S$) are the minimum and maximum time of the ships with a particular ship type (i.e., *Type*), a particular class of ship size (i.e., *Length or Draught*), and a particular status (i.e., *S*) in a particular port (i.e., *p*). The difference between the max time and the min time (i.e.,${}_{Size}^{Type}Range_p^S = {}_{Size}^{Type}Max_p^S - {}_{Size}^{Type}Min_p^S$) shows the time range which is one indicator of time efficiency. A smaller time range suggests that a port can handle ships with a smaller time fluctuation. In other words, it indicates that time efficiency is more consistent and reliable.

Mean (${}_{Size}^{Type}Mean_p^S$) is the average time of ships in each status. A smaller mean value implies less time, which could suggest either a more efficient operation or a lower quantity of goods is handled at berth.

Median (${}_{Size}^{Type}Median_p^S$) is the time that separates the upper half from the lower half of ships in each status. A smaller median value suggests less time, which could indicate either a more efficient operation or a lower quantity of goods is handled at berth. Compared to the mean, the median is less skewed when there are extreme values in a dataset.

Standard deviation (${}_{Size}^{Type}SD_p^S$) reflects how far a set of time spans is dispersed around the mean. This statistic also can be used to analyze the consistency of port operations with respect to time efficiency.

Coefficient of variation (${}_{Size}{}^{Type}CV_p{}^{S}$) is computed as a ratio of the standard deviation to the mean. A smaller *CV* value indicates that the variance is relatively small compared to the mean. Since *CV* is a standardized measure, it is a better indicator for comparisons between ships of different types or between different ports.

Confidence interval (${}_{Size}{}^{Type}CI_p{}^{S}$) is a type of interval estimate that is computed from the observed data of ships. It consists of an interval (${}_{Size}{}^{Type}CI_{1p}{}^{S}$, ${}_{Size}{}^{Type}CI_{2p}{}^{S}$) that acts as an estimate of the unknown population parameter. Since the distribution of time spans does not satisfy a normal distribution and the data covers all ships, the confidence intervals are estimated in this study by removing the data at the top 5% and the bottom 5%. The larger the gap between ${}_{Size}{}^{Type}CI_{1p}{}^{S}$ and ${}_{Size}{}^{Type}CI_{2p}{}^{S}$, the less consistent service is provided by a port.

3.2. Time efficiency evaluation methods

This study aims to assess: (1) port efficiency of moving container, cargo, tanker, and passenger ships in two selected ports, (2) the effects of different types of ships on port efficiency, and (3) the effects of ship's size on time efficiency. We expect that a more efficient operation corresponds to a shorter time and a higher consistency of the total time spent in *Inside Port Zone*, *Moored at Berth*, *Anchored in Anchorage Zone during VTS Line-to-Berth*, and *Anchored in Anchorage Zone during Berth-to-VTS Line*.

Since the time spent at a berth is affected by the carrying capacity of ships that require different amounts of unloading/loading time, we therefore also assess the time spent during the status of *Moored at Berth* based on four categories of ship size, which are (0,100] m, (100,200] m, (200,300] m, and (300, $+\infty$) m in length, as well as (0,5] m, (5, 10] m, (10,15] m, and (15, $+\infty$) m in draught according to the industry practice. In addition, different ports are likely to have different spatial configurations and different sizes. It is unfair to simply compare the time spent across different ports because a port may have a much larger physical size and a longer fairway from the VTS line to the berth area than other ports. This study therefore also computes the *time spent per unit distance* to compare the time efficiency for the *VTS Line-to-Berth* status and the *Berth-to-VTS Line* status between different ports. These performance indicators allow researchers to conduct a consistent assessment of time efficiency of ship activities in different statuses at each port and then compare the time efficiency performance across different ports. Specifically, the following indicators are computed to perform the time efficiency assessment:

- Six statistics of time at the status of *Moored at Berth*, abbreviated as Berth Time (BT), are computed to assess the time efficiency of *Moored at Berth*.
- Six statistics of the time per kilometer spent during the *VTS Line-to-Berth* status (abbreviated as VBT) and the *Berth-to-VTS Line* status (abbreviated as BVT) are computed to assess the time efficiency of these two statuses, respectively.
- The different between VBT and BTV is computed to indicate the time efficiency difference between the *VTS Line-to-Berth* status and the *Berth-to-VTS Line* status.
- Counts of the number of stops and total time length in *Anchored in Anchorage Zone during VTS Line-to-Berth* and *Anchored in Anchorage Zone during Berth-to-VTS Line* statuses are computed to assess the delay of moving ships between the VTS line and berth area.

The above indicators also are computed to compare the time efficiency between the four types of ships (i.e., container, cargo, tanker, and passenger ships) included in this study. Furthermore, this study groups each of these four types of ships by their ship size to take into account the effect of carrying capacity on unloading/loading time. Time efficiency assessment based on ship size is performed for the status *of Moored at Berth* only.

4. Data and analysis results

4.1. Study area and data

In this study, Shanghai Yangshan Port and Xiamen Port in China are selected as the case study ports. These ports are large seaports that service a large number of vessels every month. This study collects AIS data of these two ports for the month of May 2014 and the nautical chart maps to assess the time efficiency of these two ports based on the proposed framework.

AIS is a tracking system that reports specific information of vessels for vessel traffic services. It is required by the International Maritime Organization's International Convention for the Safety of Life at Sea that all international voyaging ships with 300 or more gross tonnage (GT), and all passenger ships regardless of size, should be equipped with AIS devices (SOLAS, 1974). Integrated with a positioning system such as a GPS receiver and other electronic navigation sensors such as a gyrocompass, AIS data include the following information (Fiorini et al., 2016):

- Maritime Mobile Service Identity (MMSI): a unique nine-digit identification number;
- Navigation status: “0: under way using engine”, “1: at anchor”, “2: not under command”, etc.;
- Rate of turn: right or left (0 to 720 degrees per minute);
- Speed over ground: 0–102 knots or 0–189 km/h (0.1-knot or 0.19 km/h resolution);
- Position coordinates: Latitude/Longitude (up to 0.0001 min accuracy);
- Course over ground: up to 0.1 degree relative to the true north;
- Heading: 0 to 359 degree;
- Bearing at own position: 0 to 359 degree;
- UTC seconds: the second field of the UTC time.

AIS transponders transmit the above information at specific time intervals. For instance, AIS report interval is 10 s for not changing course and 3 1/3 s for changing course when ship speed is between 0 and 14 knots (7.194 m/s), 6 s for not changing course and 2 s for changing course when ship speed is from 14 knots (7.194 m/s) to 23 knots (11.822 m/s). When ship speed is over 23 knots (11.822 m/s), report interval for both not changing course and changing course is 2 s (Sang et al., 2015). Additional information of AIS report intervals for different types of AIS transponders is available at HPVUMT (2018). Vessels' space-time trajectories can be constructed from the AIS data.

Nautical chart maps record basic port information, such as anchorages, fairways, and VTS report lines, as geographical features that contain their coordinates for geographic zone identification. This study also collects the detailed berth locations from the port authorities separately when the detailed berth locations are not available on nautical chart maps. Fig. 3 shows the nautical charts of Xiamen Port and Shanghai Yangshan Port. The geographic zone identification and status classification are completed in this study based on the vessels' space-time trajectories and port information in nautical charts.

This study further identifies the type, length, and draught of each ship based on the MMSI. A ship is removed from this study if it misses the key information such as ship type. There are twenty-four types of ships reported in AIS data. This paper focuses on four types of ships (i.e., container, cargo, tanker, and passenger), which are selected as examples to illustrate the time efficiency assessment based on AIS data. The counts reported in Table 2 are the number of complete ship visits that cover the entire process from a ship entering a port to the same ship leaving the port. Both Shanghai Yangshan Port and Xiamen Port have a sufficient sample size to carry out this study.

4.2. Time efficiency analysis of the four statuses in two ports

This section discusses the time efficiency assessment results by each of the five statuses (i.e., *Moored at Berth* status, *Berth-to-VTS Line* status,

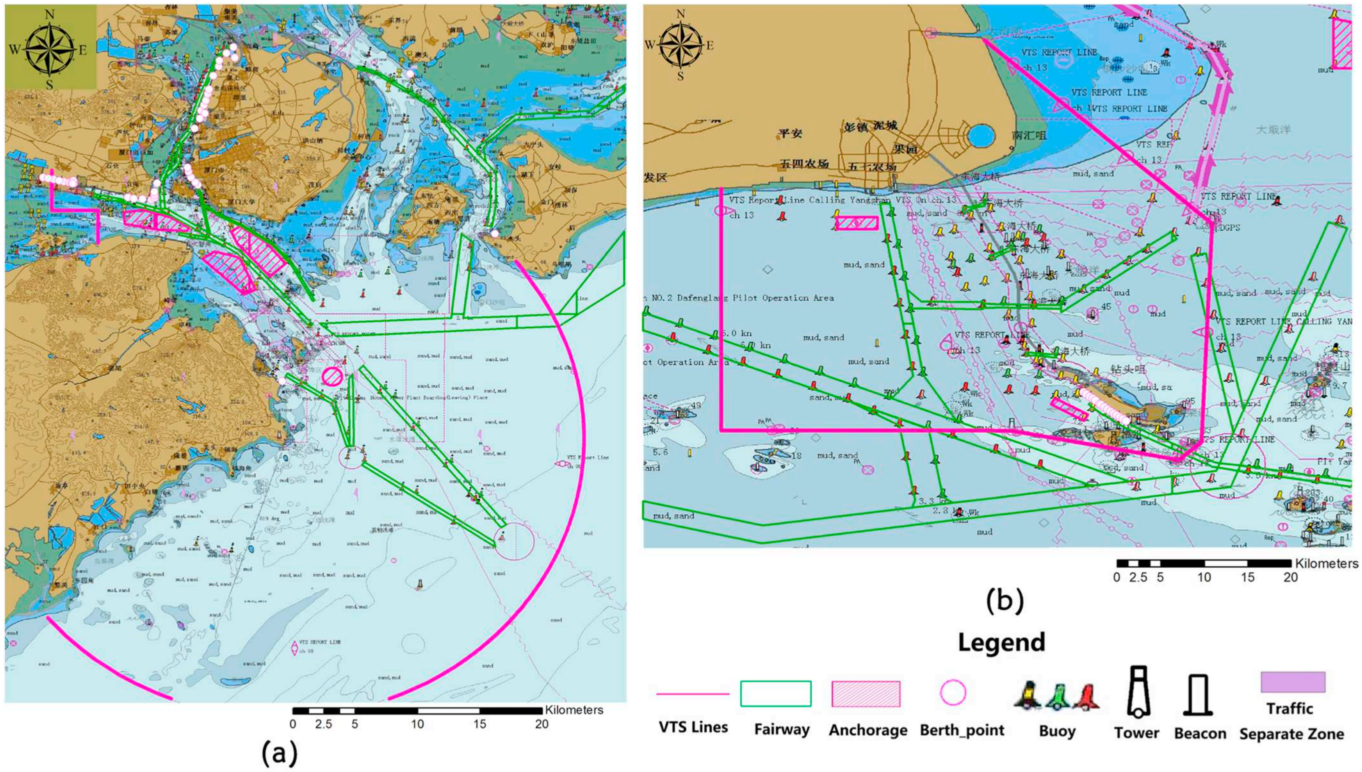

Fig. 3. Nautical charts of (a) Xiamen Port and (b) Shanghai Yangshan Port in China.

Table 2
Number of complete ship visits by each of the four selected ship types in Yangshan Port and Xiamen Port.

Ship type	Yangshan port	Xiamen port
Container	199	264
Cargo	75	257
Tanker	21	28
Passenger	27	120
Total number of all four types	322	669

Table 3
Statistics of *Moored at Berth* time for container, cargo, tanker, and passenger ships in Yangshan Port and Xiamen Port (unit: hour).

Port	Min	Median	Mean	Max	SD	CV	CI_1	CI_2
Part I: container ships								
Yangshan	5.75	15.91	18.39	46.02	7.92	43.07	10.09	27.79
Xiamen	1.62	11.25	12.40	48.26	6.08	49.03	6.81	19.78
Part II: cargo ships								
Yangshan	1.55	12.22	14.85	62.35	10.48	70.61	3.32	27.92
Xiamen	1.50	13.64	24.31	154.22	29.09	119.63	3.20	63.11
Part III: tanker ships								
Yangshan	3.44	10.52	12.66	47.84	10.72	84.62	3.87	25.29
Xiamen	1.59	8.60	16.01	137.89	26.36	108.43	2.12	26.65
Part IV: passenger ships								
Yangshan	2.26	16.22	16.01	20.14	3.01	18.80	15.68	18.54
Xiamen	1.52	8.01	11.31	44.97	11.90	105.27	1.88	18.08

Anchored at Anchorage Zone during VTS Line-to-Berth status, and *Anchored at Anchorage Zone during Berth-to-VTS Line* status) for each ship type (i.e., container, cargo, tanker, and passenger) in Shanghai Yangshan Port and Xiamen Port, respectively. First of all, a time efficiency assessment of the *Moored at Berth* status for each ship type between Shanghai Yangshan Port and Xiamen Port is reported in Table 3. Figs. 4-7 illustrate the distributions of berth time for each of the four ship types at the two ports, respectively. The horizontal axis is the time spent during the *Moored at Berth* status in hours, and the vertical axis is the percentage of ship visits corresponding to each time amount.

For container ships, Fig. 4 shows that Shanghai Yangshan Port has a more dispersed distribution pattern with a two-peak distribution rather than a single-peak distribution of Xiamen Port in terms of the amount of time spent at the *Moored at Berth* status. Table 3 also indicates that Shanghai Yangshan Port has a larger mean, median, and standard deviation (SD) than Xiamen Port for container ships. The larger mean and median of *Moored at Berth* time at Shanghai Yangshan Port could be a reflection of larger amounts of containers unloaded and loaded at berth due to larger container ships at Shanghai Yangshan Port than those at Xiamen Port. According to UNCTAD (2014), Shanghai Yangshan Port handled 35.30 million TEUs in 2014 while Xiamen Port's container throughput was at 8.57 million TEUs in the same year. On the other hand, the coefficient of variation (CV) of *Moored at Berth* time in Shanghai Yangshan Port is smaller than that of Xiamen Port. In other words, although Shanghai Yangshan Port has a larger mean, median, and standard deviation than Xiamen Port, variation of the time spent at the *Moored at Berth* status at Shanghai Yangshan Port is a little smaller than Xiamen Port with respect to their mean. This suggests that Shanghai Yangshan Port is slightly more consistent in the operation time at the *Moored at Berth* status than that of Xiamen Port.

For cargo ships, Fig. 5 indicates that Xiamen Port has a longer tail of its distribution than Shanghai Yangshan Port. Statistics in Table 3 also show that Xiamen Port has a larger mean, median, SD, and CV than those of Shanghai Yangshan Port in terms of the amount of time spent at the *Moored at Berth* status. They reflect that Xiamen Port is less time efficient than Shanghai Yangshan Port in handling cargo ships at the *Moored at Berth* status. However, we should notice in Fig. 5 that Xiamen Port has a general decreasing distribution pattern as time increases while Shanghai Yangshan Port exhibits multiple peaks in its distribution. This reminds us the importance of assessing not only the statistics but also the distribution curves to gain a more complete picture when

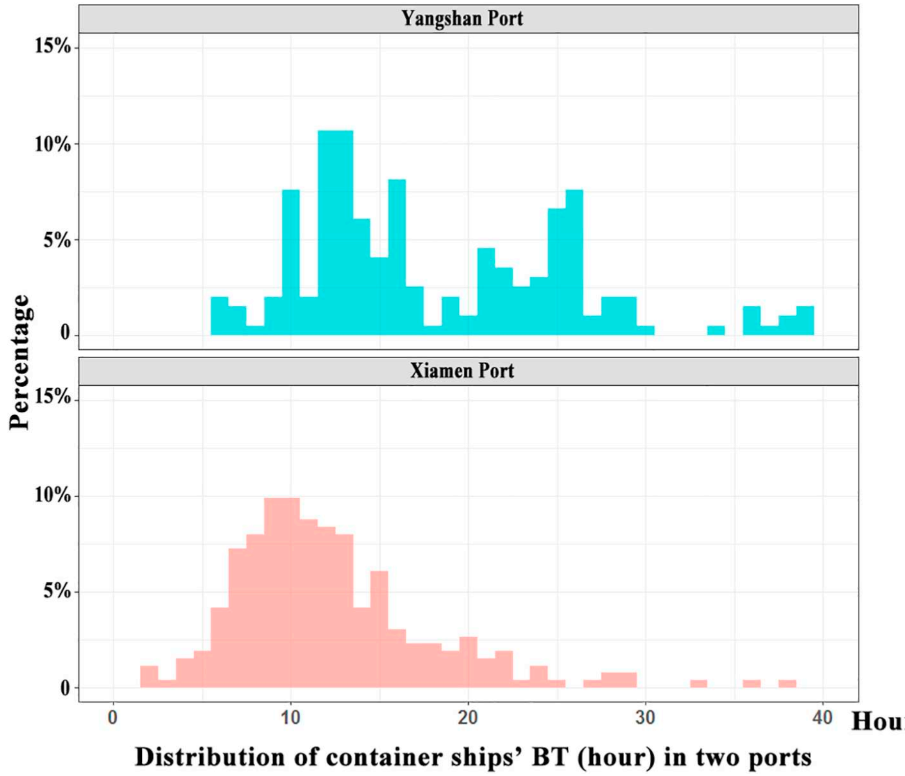

Fig. 4. Container ships' distribution of berth time in Yangshan Port and Xiamen Port.

comparing time efficiency across different ports.

Due to a smaller sample size of tanker ships, less details are shown in Fig. 6. A significant peak at 2–3 h stands out for Xiamen Port that is worthy looking into it in the future to investigate if it is due to a special tanker service at the port or data errors. The statistics in Table 3 indicate that Shanghai Yangshan Port has a smaller mean, SD, and CV, yet a larger median, than Xiamen Port at the *Moored at Berth* status. A smaller median at Xiamen Port is clearly influenced by the high percentage of 2–3 h at Xiamen Port.

For passenger ships, Fig. 7 shows one concentrated peak at Shanghai

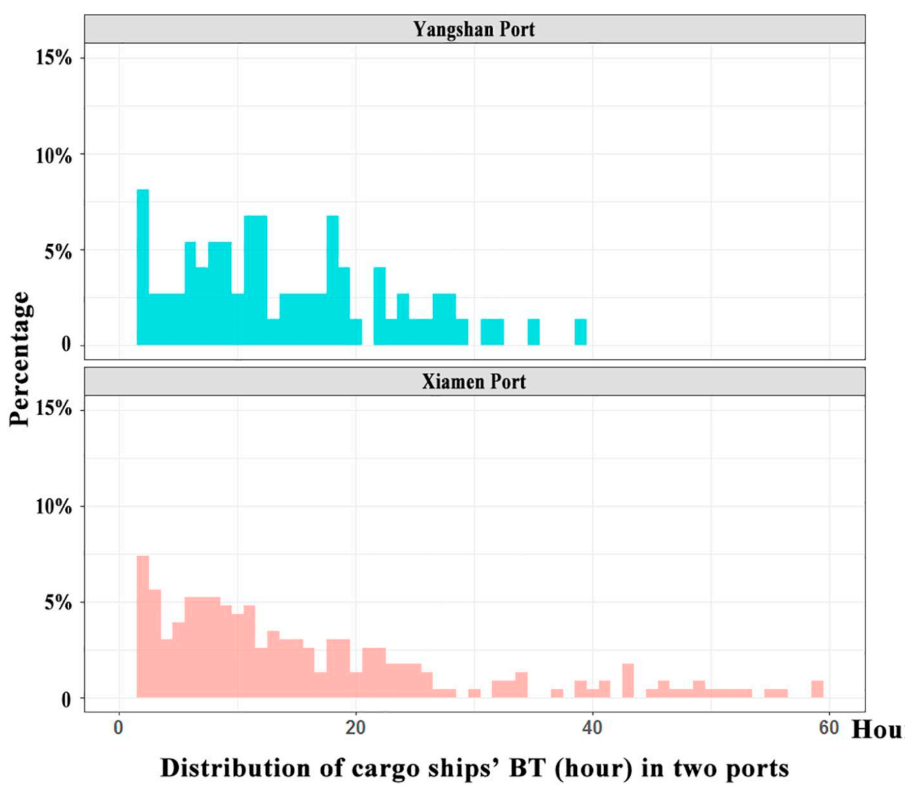

Fig. 5. Cargo ships' distribution of berth time in Yangshan Port and Xiamen Port.

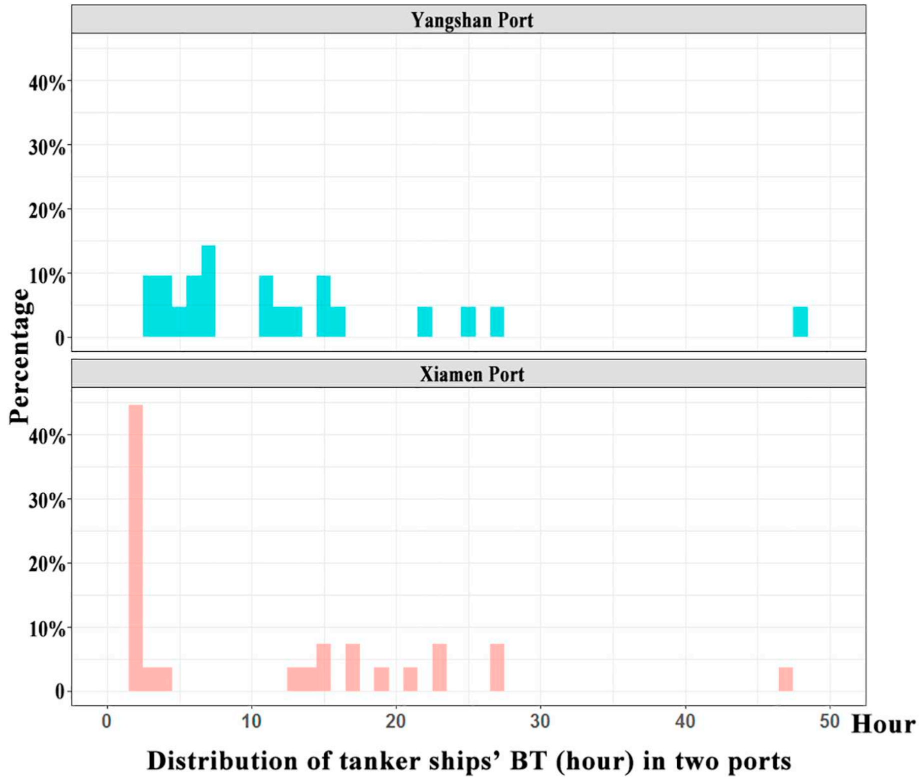

Fig. 6. Tanker ships' distribution of berth time in Yangshan Port and Xiamen Port.

Yangshan Port and a dispersed distribution at Xiamen Port. Again, due to a smaller sample size for passenger ships, less details are shown in Fig. 7. The statistics in Table 3 indicate that Shanghai Yangshan Port has a larger mean and median, yet a much smaller SD and CV, than Xiamen Port. They suggest Xiamen Port has a better overall time efficiency of handling passenger ships than Shanghai Yangshan Port at the *Moored at Berth* status. However, the consistency of time efficiency at Xiamen Port is lower than the consistency at Shanghai Yangshan Port.

The above analysis results also reflect some key differences between

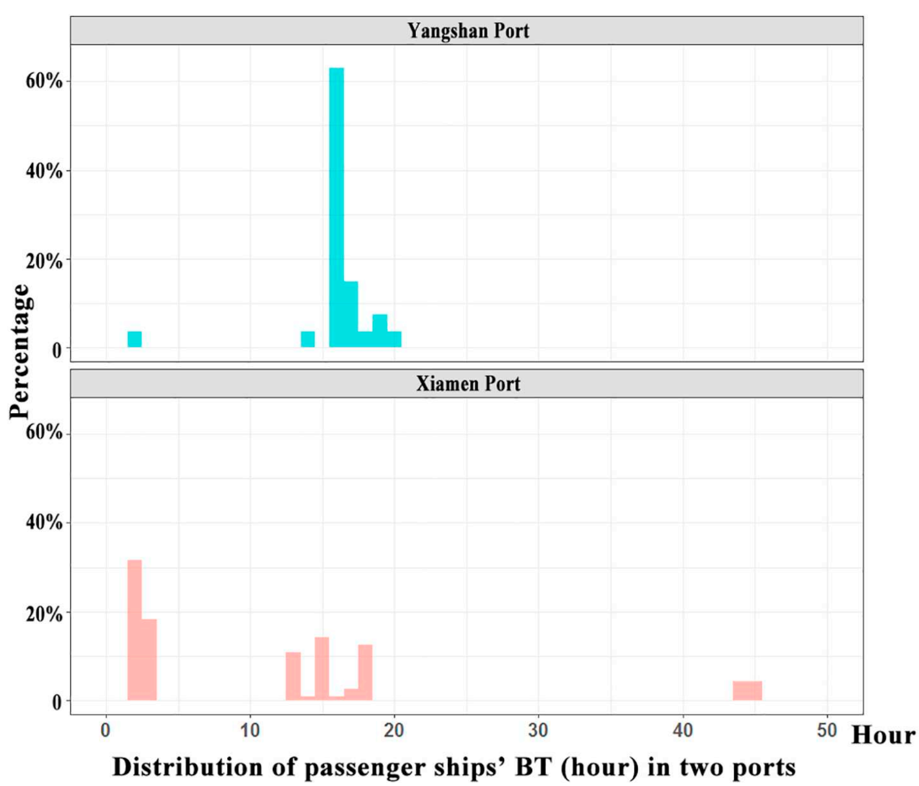

Fig. 7. Passenger ships' distribution of berth time in Yangshan Port and Xiamen Port.

Table 4
Statistics of *Anchored at Anchorage Zone during VTS Line-to-Berth* (ATVB) time and *Anchored at Anchorage Zone during Berth-to-VTS Line* (ATBV) time of cargo and tanker ships in Xiamen Port (unit: hour).

Type	Min	Median	Mean	Max	SD	CV	CI_1	CI_2	Count
Part I: ATVB									
Cargo	3.01	162.98	193.88	506.60	138.56	71.46	54.14	406.01	34
Tanker	8.95	57.57	57.57	106.20	68.76	119.43	18.67	96.47	2
Part II: ATBV									
Cargo	107.96	272.65	277.20	451.00	171.56	61.88	140.90	415.33	3
Tanker	125.68	263.81	263.81	401.95	195.35	74.04	153.31	374.32	2

Shanghai Yangshan Port and Xiamen Port. Shanghai Yangshan Port is mainly a container port with a large amount of transshipment of TEUs to/from cargo ships that sail in inland waterways. On the other hand, Xiamen Port is a comprehensive seaport that services a wide variety of ships. The types of goods shipped through Xiamen Port also is much more diverse than those through Shanghai Yangshan Port. In addition, Shanghai Yangshan Port does not provide passenger services and most passenger ships at this port are used for transporting port staff. Xiamen Port however provides several types of passenger services (e.g., local transportation, recreation). These contrasts between Shanghai Yangshan Port and Xiamen Port can help explain the differences in time efficiency at the *Moored at Berth* status for container ships, cargo ships, tanker ships, and passenger ships between these two ports.

Next, this study assesses time efficiency at the *Anchored at Anchorage Zone during VTS Line-to-Berth* status and the *Anchored at Anchorage Zone during Berth-to-VTS Line* status. Anchored at anchorage is normally needed only when the time in anchorage is longer than one hour. Based on the space-time trajectories derived from the AIS data in this study, we find only some cargo ships and tanker ships at Xiamen Port meet the one-hour requirement for the *Anchored at Anchorage Zone during VTS Line-to-Berth* status and the *Anchored at Anchorage Zone during Berth-to-VTS Line* status at Xiamen Port (Table 4). Ships are at the *Anchored at Anchorage Zone during VTS Line-to-Berth* status mainly due to no available berth space for loading/unloading goods or waiting for port instructions, while ships are *Anchored at Anchorage Zone during Berth-to-VTS Line* mainly due to ship schedules or customs checks. Table 4 indicates a relatively large mean, median, SD, and CV for cargo ships and tanker ships at Xiamen Port for both *Anchored at Anchorage Zone during VTS Line-to-Berth* status and *Anchored at Anchorage Zone during Berth-to-VTS Line* status. This is one area that Xiamen Port can seek improvements.

The third time efficiency assessment performed in this study focuses on the *VTS Line-to-Berth* time (VBT) and the *Berth-to-VTS Line* time (BVT). Table 5 shows the statistics of time per kilometer spent at the *VTS Line-to-Berth* status and the *Berth-to-VTS Line* status for container, cargo, tanker, and passenger ships in Shanghai Yangshan Port and Xiamen Port. Fig. 8 illustrates the distributions of VBT and BVT for the four types of ships in Shanghai Yangshan Port and Xiamen Port.

Several patterns are observed from comparisons of *VTS Line-to-Berth* time (VBT) and the *Berth-to-VTS Line* time (BVT). First of all, the mean, median, SD, and CV of VBT are always greater than or equal to those of VBT across all four types of ships in each of the two ports (see Table 5). This indicates that it usually takes longer for ships to travel from the VTS line to a berth than from a berth to the VTS line in both ports. This observation is not surprising because incoming traffic usually needs to wait for available berths and/or other instructions from the port authority. Second, Xiamen Port has more concentrated distribution patterns on both VBT and BVT across all four types of ship than those of Shanghai Yangshan Port (see Fig. 8). This leads to a smaller mean and median of both VBT and BVT for all four types of ships in Xiamen Port than those in Shanghai Yangshan Port (see Table 5), which suggests that it takes less time to move between the VTS line and a berth in Xiamen Port than in Shanghai Yangshan Port. In the meantime, Shanghai Yangshan Port has a smaller CV than Xiamen Port except for passenger ships. This indicates that Shanghai Yangshan Port has more consistent time efficiency performance in both VBT and BVT for container, cargo, and tanker ships, but not for passenger ships.

The analysis results presented in this section indicate that we can use the space-time trajectories derived from AIS data to assess time efficiency at the *Moored at Berth* status, the *Anchored at Anchorage Zone during VTS Line-to-Berth* status, the *Anchored at Anchorage Zone during Berth-to-VTS Line* status, the *VTS Line-to-Berth* status, and the *Berth-to-VTS Line* status for different types of ships across different ports. This allows us to assess time efficiency in different geographic zones in a port and gain deeper insight on potential operation improvements for different types of ships in different geographic zones of a port. It also provides a method of comparing time efficiency across different ports.

4.3. Time efficiency analysis based on categories of ship size

Since ship size could have impacts on time efficiency especially at the *Moored at Berth* status to unload/load goods, this section further assesses the effects of ship size (based on ship length and draught) on time efficiency at the *Moored at Berth* status. Ships that do not have information about their size are removed from this assessment. The remaining ships are grouped into four categories based on their size:

Table 5
Statistics of *VTS Line-to-Berth* time (VBT) and *Berth-to-VTS Line* time (BVT) of container, cargo, tanker, and passenger ships in Yangshan Port and Xiamen Port (unit: hour/km).

Port	Min	Median	Mean	Max	SD	CV	CI_1	CI_2
Part I: VBT of container ships								
Yangshan	0.08	0.13	0.14	0.26	0.04	30.06	0.09	0.20
Xiamen	0.04	0.05	0.07	0.27	0.04	59.38	0.04	0.12
Part II: BVT of container ships								
Yangshan	0.05	0.09	0.10	0.23	0.03	28.85	0.07	0.14
Xiamen	0.03	0.04	0.04	0.27	0.01	33.03	0.04	0.05
Part III: VBT of cargo ships								
Yangshan	0.05	0.13	0.14	0.28	0.06	41.26	0.07	0.23
Xiamen	0.04	0.07	0.10	0.27	0.05	53.65	0.06	0.20
Part IV: BVT of cargo ships								
Yangshan	0.05	0.09	0.10	0.27	0.03	36.84	0.06	0.14
Xiamen	0.04	0.06	0.07	0.27	0.03	43.43	0.05	0.10
Part V: VBT of tanker ships								
Yangshan	0.07	0.15	0.16	0.27	0.07	43.40	0.09	0.26
Xiamen	0.03	0.06	0.07	0.28	0.05	58.04	0.03	0.12
Part VI: BVT of tanker ships								
Yangshan	0.06	0.10	0.13	0.27	0.05	44.86	0.08	0.22
Xiamen	0.03	0.05	0.06	0.22	0.03	53.34	0.03	0.10
Part VII: VBT of passenger ships								
Yangshan	0.03	0.08	0.09	0.23	0.04	49.57	0.06	0.16
Xiamen	0.01	0.03	0.03	0.10	0.01	41.95	0.02	0.04
Part VIII: BVT of passenger ships								
Yangshan	0.03	0.07	0.08	0.23	0.04	51.52	0.06	0.08
Xiamen	0.01	0.03	0.03	0.10	0.01	38.35	0.02	0.03

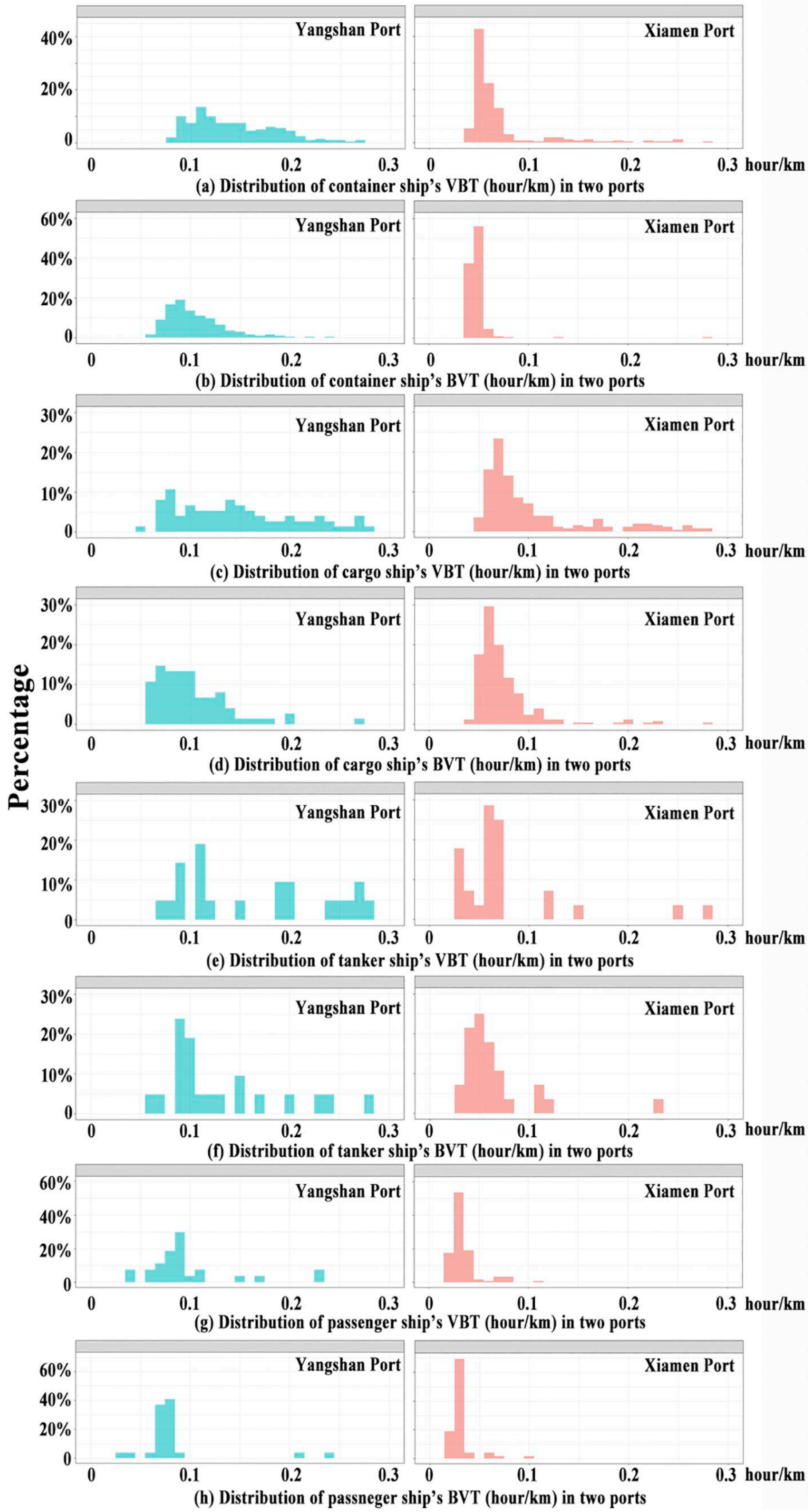

Fig. 8. Distribution of BVT and VBT in Yangshan Port and Xiamen Port.

Table 6
Statistics of time spent at the *Moored at Berth* status for container, cargo, tanker, and passenger ships based on ship length in Yangshan Port and Xiamen Port (unit: hour).

Port	Min	Median	Mean	Max	SD	CV	CI1	CI2	Length	Count
Part I: container ships										
Yangshan port	NA	NA	NA	NA	NA	NA	NA	NA	(0,100]	1
	7.10	12.64	13.82	21.26	4.66	33.72	9.40	19.63	(100,200]	9
	5.75	12.95	14.49	28.99	5.56	38.38	9.42	23.41	(200,300]	84
	9.32	22.70	21.94	46.02	8.12	36.99	12.39	35.05	(300, + ∞)	105
Xiamen port	NA	NA	NA	NA	NA	NA	NA	NA	(0,100]	0
	4.07	9.79	11.69	38.42	5.81	49.70	6.51	18.13	(100,200]	104
	3.02	11.04	12.28	48.26	6.26	51.00	7.01	18.92	(200,300]	109
	1.62	13.39	14.09	26.97	6.01	42.66	7.36	22.10	(300, + ∞)	51
Part II: cargo ships										
Yangshan port	1.55	10.80	12.71	32.16	8.48	66.71	2.55	24.16	(0,100]	53
	6.60	15.24	20.00	62.35	13.04	65.21	8.81	34.12	(100,200]	22
	NA	NA	NA	NA	NA	NA	NA	NA	(200,300]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	0
Xiamen port	1.50	10.83	17.96	148.11	23.71	132.01	2.61	41.50	(0,100]	149
	1.51	21.60	32.70	154.22	32.49	99.37	5.51	73.40	(100,200]	89
	6.26	66.29	59.57	134.14	43.87	73.64	7.97	99.77	(200,300]	9
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	0
Part III: tanker ships										
Yangshan port	3.44	6.79	11.29	47.84	11.33	100.34	4.01	19.12	(0,100]	15
	3.45	14.28	16.09	27.37	8.95	55.61	7.67	26.33	(100,200]	6
	NA	NA	NA	NA	NA	NA	NA	NA	(200,300]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	0
Xiamen port	2.05	2.39	8.54	46.86	12.07	141.33	2.12	21.62	(0,100]	17
	1.59	18.35	28.83	137.89	39.21	135.99	4.04	37.98	(100,200]	10
	NA	NA	NA	NA	NA	NA	NA	NA	(200,300]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	1
Part IV: passenger ships										
Yangshan port	2.26	16.22	16.01	20.14	3.01	18.80	15.68	18.54	(0,100]	27
	NA	NA	NA	NA	NA	NA	NA	NA	(100,200]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(200,300]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	0
Xiamen port	1.52	8.01	11.31	44.97	11.90	105.27	1.88	18.08	(0,100]	120
	NA	NA	NA	NA	NA	NA	NA	NA	(100,200]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(200,300]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(300, + ∞)	0

(0,100] m, (100,200] m, (200,300] m, and (300, + ∞) m in length as well as (0,5] m, (5, 10] m, (10,15] m, and (15, + ∞) m in draught, respectively. Table 6 lists the statistics of time spent at the *Moored at Berth* status based on the four categories of ship length for all four types of ships in Shanghai Yangshan Port and Xiamen Port, while Table 7 shows the same statistics based on the four categories of ship draught.

Tables 6 and 7 show that the mean and median of time spent at the *Moored at Berth* status in general increases with either ship length or draught for all types of ships. In other words, as ship size gets bigger, it takes longer to unload/load goods at berth. However, due to either a very small sample size or no data in some categories of ship length or draught for cargo, tanker, and passenger ships, it is not feasible to compare these ship types between Shanghai Yangshan Port and Xiamen Port. Time efficiency assessment in this section therefore focuses on container ships only.

It is clear that Xiamen Port consistently has a smaller mean and median of time spent at the *Moored at Berth* status across different categories of ship length (Table 6) and across different categories of draught (Table 7) than those of Shanghai Yangshan Port. In the meantime, Shanghai Yangshan Port has a smaller CV of time spent at the *Moored at Berth* status across different categories of ship length (Table 6) and across different categories of draught (Table 7) than those of Shanghai Yangshan Port, except for the category of (15,+ ∞) m in draught that has a very small sample size. These results are in agreement with the findings in Section 4.2 (see Table 3). However, one interesting observation is that the category of (200,300] m in ship length and the category of (10,15] m in draught has the largest CV than other categories of ship size in both Shanghai Yangshan Port and Xiamen Port. In other words, container ships of (200,300] m in length or (10,15] m in draught tend to have a larger variation of time efficiency at the *Moored at Berth* status than container ships of other sizes in both ports. This is an observation worthy further investigation in a future study.

5. Conclusion and future work

This study develops a framework and related methods for assessing time efficiency of ship activities within different geographic zones of a port based on space-time trajectories derived from automatic identification system (AIS) data. AIS data are routinely used and collected for vessel traffic services (VTS). This study applies the space-time path concept from time geography to generate space-time trajectories from AIS data. This proposed time efficiency assessment framework based on time geography and AIS data enables researchers and port authorities to analyze time efficiency of various types of ships (e.g., container, cargo, tanker, and passenger ships) at various statuses in a port such as the *VTS Line-to-Berth* status, *Moored at Berth* status, *Berth-to-VTS Line* status, *Anchored at Anchorage Zone during VTS Line-to-Berth* status, and *Anchored at Anchorage Zone during Berth-to-VTS Line* status. This proposed approach also makes it easy to compare time efficiency of handling different types of ships at various statuses across different ports using a set of simple statistics. Major contributions of this study include: (1) an innovative idea of using time-geographic concepts to develop a space-time trajectory framework for assessing time efficiency performance of ship activities in a port, and (2) a set of AIS-based time efficiency indicators to assess the operational performance of various

Table 7

Statistics of time spent at the *Moored at Berth* status for container, cargo, tanker, and passenger ships based on draught in Yangshan Port and Xiamen Port (unit: hour).

Port	Min	Median	Mean	Max	SD	CV	CI_1	CI_2	Draught	Count
Part I: container ships										
Yangshan port	12.73	12.73	12.73	12.73	NA	NA	12.73	12.73	(0,5]	1
	6.11	14.01	16.19	38.93	6.78	41.89	9.68	24.40	(5,10]	33
	5.75	16.06	18.85	46.02	8.11	43.03	10.10	28.33	(10,15]	161
	12.38	17.41	19.07	29.07	7.83	41.06	12.66	26.80	(15, + ∞)	4
Xiamen port	NA	NA	NA	NA	NA	NA	NA	NA	(0,5]	0
	4.07	11.04	11.92	38.42	5.70	47.80	6.85	18.37	(5,10]	121
	3.02	11.57	12.95	48.26	6.22	48.08	7.09	20.52	(10,15]	137
	13.31	13.69	17.01	24.04	6.08	35.77	13.38	21.97	(15, + ∞)	3
Part II: cargo ships										
Yangshan port	1.55	12.29	15.26	62.35	10.79	70.68	3.24	28.31	(0,5]	63
	5.55	23.12	19.70	26.19	8.40	42.65	10.81	25.70	(5,10]	51
	NA	NA	NA	NA	NA	NA	NA	NA	(10,15]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(15, + ∞)	0
Xiamen port	1.50	11.26	15.37	148.11	17.25	112.24	2.78	25.29	(0,5]	125
	1.51	18.69	30.84	140.38	28.70	93.04	5.71	70.63	(5,10]	86
	1.50	26.16	51.07	154.22	50.84	99.54	6.46	136.99	(10,15]	23
	6.26	8.40	23.23	55.03	27.56	118.60	6.69	45.71	(15, + ∞)	3
Part III: tanker ships										
Yangshan port	3.44	7.00	11.39	47.84	10.62	93.31	3.92	17.75	(0,5]	17
	15.86	21.61	21.61	27.37	8.13	37.65	17.01	26.22	(5,10]	2
	3.87	14.58	14.58	25.29	15.15	103.88	6.01	23.15	(10,15]	2
	NA	NA	NA	NA	NA	NA	NA	NA	(15, + ∞)	0
Xiamen port	1.59	13.29	23.81	137.89	38.28	160.74	2.07	44.47	(0,5]	12
	4.31	17.24	18.49	26.87	7.85	42.49	10.67	26.68	(5,10]	7
	14.88	14.88	14.88	14.88	NA	NA	14.88	14.88	(10,15]	1
	2.09	2.34	2.30	2.46	0.13	5.66	2.12	2.41	(15, + ∞)	8
Part IV: passenger ships										
Yangshan port	2.26	16.22	16.01	20.14	3.01	18.80	15.68	18.54	(0,5]	27
	NA	NA	NA	NA	NA	NA	NA	NA	(5,10]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(10,15]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(15, + ∞)	0
Xiamen port	1.52	12.79	11.78	44.97	12.03	102.14	1.88	18.10	(0,5]	114
	NA	NA	NA	NA	NA	NA	NA	NA	(5,10]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(10,15]	0
	NA	NA	NA	NA	NA	NA	NA	NA	(15, + ∞)	0

types of ship within different zones of a port as well as their performance between different ports to enable useful analyses and applications of AIS data.

A case study using AIS data collected at two major ports in China, which are Shanghai Yangshan Port and Xiamen Port, is conduced to illustrate how the proposed framework and methods can help us quantitatively assess time efficiency as various types of ships moving through different areas of a port from the time they enter the VTS line to the time they leave the VTS line of a port. For example, this case study identifies some useful results from time efficiency assessments based on the AIS data.

1) Xiamen Port is more time efficient in handling container ships and passenger ships in terms of the average time spent at the *Moored at Berth* status than Shanghai Yangshan Port, while Shanghai Yangshan Port is more time efficient in handling cargo ships and tanker ships in terms of the average time spent at the *Moored at Berth* status than Xiamen Port.
2) Shanghai Yangshan Port has a more consistent time efficiency performance in handling container, cargo, tanker, and passenger ships in terms of time spent at the *Moored at Berth* status than Xiamen Port.
3) Only some cargo and tanker ships at Xiamen Port experienced long anchorage time, especially at the *Anchored at Anchorage Zone during VTS Line-to-Berth* status.
4) It generally takes longer for all types of ships to move from the VTS line to a berth than from a berth to the VTS line in both Shanghai Yangshan Port and Xiamen Port.
5) Time spent at the *Moored at Berth* status in general increases with either ship length or draught for all types of ships in both Shanghai Yangshan Port and Xiamen Port.
6) Xiamen Port consistently has a smaller mean and median of time spent at the *Moored at Berth* status across different categories of ship length and across different categories of draught than those of Shanghai Yangshan Port. On the other hand, Shanghai Yangshan Port generally has a smaller coefficient of variation of time spent at the *Moored at Berth* status across different categories of ship length and across different categories of draught than those of Shanghai Yangshan Port.

Findings from this case study should not be interpreted as the current situations at Shanghai Yangshan Port or Xiamen Port. Instead, they are presented to illustrate the insights that can be derived from the proposed time efficiency assessment approach using AIS data. Although the proposed time efficiency assessment framework demonstrates how it can enable researchers and port authorities to assess port efficiency in different geographic zones and across different types of ships to gain insights for potential improvements and assist port management, there are many other potential applications and some challenges of using AIS data for maritime transportation studies.

AIS is still a relatively new "big data" source for maritime transport studies. AIS data can be considered as tracking data of individual vessels like Global Positioning System (GPS) tracking data of cars, trucks, and airplanes that have been widely used to tackle a diverse range of transportation and geographic problems. Since AIS data include spatial, temporal, and other data of vessels, it is a useful data source for studying maritime transportation from a geographic perspective. This study illustrates one particular application area using AIS data. Other potential applications areas of AIS data include maritime environmental monitoring, collision warning and avoidance, maritime logistics, and many other intelligent applications. With satellite-based AIS data, study areas are no longer limited to coastal zones and can be extended to a global scale.

However, AIS data is not perfect. It often requires preprocessing of AIS data to deal with missing data and data noises. With large data volume and spatiotemporal nature of AIS data, it also requires some specific knowledge and skills to work with AIS data. Furthermore, like many other big data application areas, it sometimes is challenging to validate the patterns derived from AIS data since we may not have other better data to validate the derived patterns. For the time efficiency assessment framework proposed in this study, we also face some challenges that need to be addressed in future research. One challenge resides in the integration of AIS data with other relevant ship information (e.g., cargo volume, cargo type) and port operation data (e.g., operation schedule, loading/unloading capacity) that can further enhance the proposed framework to conduct more comprehensive efficiency assessments of port operation. In addition, when we work with "big" AIS data that cover multiple years and many ports, we need to develop more efficient data management and analysis methods to facilitate spatiotemporal efficiency analysis of maritime transport. This study is the first step of developing an approach of integrating space-time concepts in time geography with AIS data to assess time efficiency of different types of ships across different zones in a port. We hope it serves as an example to encourage more transportation researchers and geographers to pursue other exciting research topics and applications that can benefit from the spatial and temporal information embedded in AIS data.

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