MEASURING PORT EFFICIENCY INCORPORATING AIS DATA

ZHANG JING

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The Hong Kong Polytechnic University

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The Hong Kong Polytechnic University

Department of Logistics and Maritime Studies

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Port efficiency is an important issue in international trades and logistics, which has different meanings for various stakeholders. This thesis aims to have a clear understanding of port efficiency from different perspectives and measuring the port efficiency incorporating AIS data from ships' perspectives.

The first part of this research reviews the existing studies on port efficiency analysis from both port's and users' perspectives. It has been found that the users' time in port is seldom considered, and there is a lack of balance between the interests of users and that of port in the port efficiency analysis. Without consider shipowners' interests, it is difficult to distinguish the efficient port from the congested port, as port efficiency is measured by how to use minimum inputs (yard area, number of cranes, employed labor, etc.) to produce the maximum outputs, such as throughput. With intense competition among ports and terminals, the users' interests and needs become increasingly important. Therefore, it is important to consider both interests of port and users in port efficiency analysis.

The second part of this research extracts ships' berthing time in port from AIS data and examines the empirical relationship of berthing time with ship attribute, port attributes, including the scale efficiency score calculated by DEA methods. Firstly, the berthing time of all ship calls is extracted from AIS data. Secondly, port efficiency score is calculated by using DEA methods. Then, a regression method is applied to estimate the impact of port scale efficiency and other port and ship attributes on berthing time. The result shows that the rankings of port scale efficiency score and that of average berthing time are different. The attributes of port and ship can influence berthing time at different levels.

This thesis provides a comprehensive and up-to-date review of existing studies on port efficiency analysis, and a novel method to evaluate port efficiency incorporating AIS data from ships' perspective. The empirical results of this thesis can provide the basis for port authorities and policymakers to make a more appropriate method to evaluate port efficiency.

Keywords: Port efficiency analysis, ship's time in port, DEA, AIS data

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

This thesis addresses the issue of port efficiency analysis incorporating AIS data. This chapter provides the background, the research questions, and the structure of this thesis. Specifically, this chapter first describes the research background on port efficiency analysis. Then, the research questions and the structure of this thesis are presented.

1.1 Research background

Port is an important node in maritime transportation and a key determinant in trade flow. With the rapid growth of international trade and the increasing congestion events, the efficiency of ports has become a significant issue in the shipping industry.

Despite its importance, port efficiency has different meanings for various stakeholders. For port authorities and operators, it may be referred to the productivity or profitability of port. For port users, port efficiency means the turnaround time of ships and cargo. For public, port efficiency stands for the contribution of the port to trade and local economy, together with pollution generated from port production process. Due to its wide interests, port efficiency has been analyzed extensively in literature over the past 40 years. However, the majority of existing studies analyzed port operational efficiency only from port's perspective. Such research from users' perspectives is very rare.

One reason for the absence of such research is the data availability—it is very difficult, or impossible, to obtain data that can reflect users' interests when they calling at a port. In recent years, AIS data has been developed and used in maritime research. AIS data provides worldwide real-time ship information, including the dynamic position, speed, time-stamp and the static ship's information, such as MMSI, ship's capacity, etc. The development of AIS data provides the potential to analyze ship turnaround time in port. But the application of AIS data in port efficiency analysis is still in its infancy.

Thus, this thesis aims to have a clear understanding of port efficiency from different perspectives and to measure the port efficiency incorporating AIS data from both shipowners' perspectives and port's perspectives.

1.2 Research questions

Question 1: The research on port efficiency analysis has been developed from many perspectives over the past decades. What are the perspectives covered before and how to understand port efficiency comprehensively?

To answer this question, the first part of this research reviews the existing studies on port efficiency analysis from different perspectives. It has been found that the users' time in port is seldom considered, and there is a lack of balance between the interests of users and that of port in the port efficiency analysis. Without the consideration of ships' interests in port, measuring port efficiency solely based on the inputs and outputs of ports, it is difficult to distinguish the efficient port from the congested port. Some studies used the concept of environmental efficiency to analyze port efficiency with the consideration of the negative impacts of port production, such as air emissions and water pollutions. But the measured efficiency of ports is different from environmental efficiency, which should focus on the output per unit of environmental load but not the magnitude of negative environmental impacts in port production process.

Question 2: AIS data can reflect ship's status in port. How to find ship's time in port by AIS data and what affects ship's time in port?

To answer this question, the second part of this thesis first extracts the berthing time of ship from AIS data. Then, the technical efficiency score and scale efficiency score are calculated from port's perspective by using traditional DEA methods. Thirdly, to find out the impact of port scale efficiency and other port and ship attributes on berthing time, the regression models are applied and examined. The empirical results show that the rankings of port scale efficiency score and that of berthing time are different. The scale efficiency score has an overall negative impact on berthing time with the concertation of the interaction effect of ship capacity.

1.3 Structure of the thesis

This thesis is organized as follows:

Chapter 1 is the introduction of this research. In this chapter, the research background, the research questions, and the thesis structure are presented.

Chapter 2 is the literature review of this research. In this chapter, the classification of port efficiency analysis, the main methods used in port efficiency analysis, and the major factors on port efficiency are reviewed. The contribution and limitations of previous studies are also discussed in this chapter.

Chapter 3 measures port efficiency incorporating AIS data empirically. Firstly, this chapter describes the method to extract berthing time of ship in port by AIS data. Then, the scale efficiency score of 20 selected ports is evaluated based on DEA methods. Thirdly, the impact of ship attributes and port attributes on berthing time are examined by regression models.

Chapter 4 summarizes the findings and contributions of this thesis. The limitations of this research and future research directions are also concluded in this chapter.

Chapter 2: Review of existing studies on port efficiency analysis

This chapter reviews the existing studies on port efficiency from different perspectives. The classification of port efficiency analysis, the methods used in port efficiency analysis, and the major factors on port efficiency are summarized in this chapter.

2.1 Introduction

Port efficiency is an important issue in international trades and logistics, which has different meanings for various stakeholders. For port managers, port is a business whose efficiency can be regarded as productivity or profitability. For port users, such as shipping companies or cargo owners, port is an important node where efficiency means shorter turnaround time and high-quality services. With intense intra-port and inter-port competition and more attention on ship's turnaround time in port, the efficiency of port and the time ship spent in port became more important for port operators to evaluate port performance and a key factor for port users to arrange logistic schedules. Therefore, it is essential to analyze port efficiency with the consideration of the interest of both users and ports.

However, due to difficulties in integrating users' interests and the lack of data, port efficiency in the existing studies is commonly evaluated only from port perspectives using Data Envelopment Analysis (DEA) or Stochastic Frontier Analysis (SFA). These two methods measure port efficiency solely based on the output and input of ports. Thus, it is difficult to distinguish the efficient port from the congested port, which is not efficient from the perspective of port users, as it may generate long service time and poor service quality. Although there are some exceptions (Roll & Hayuth, 1993; Sánchez et al., 2003; Tongzon, 2001) that considered ships' time in port efficiency analysis using DEA, the ships' time and port inputs-output are belong to different decision-make-units (DMUs). To our best knowledge, port efficiency analysis from both port's and users' perspectives does not exist.

Besides, with growing awareness of environmental issues, the analysis of port environmental efficiency also attracts scholars' interests. It is worth noting that although some studies used the concept of environmental efficiency, the measured environmental efficiency of ports (hereinafter referred to as Environmentally Adjusted Efficiency, EAE) (Castellano et al., 2020; Chang, 2013; Chin & Low, 2010; Cui, 2017; Dong et al., 2019; Tovar & Wall, 2019) is different from Environmental Efficiency (EE). These on EAE analysis adjust the desirable outputs by the undesirable ones, such as air pollution, noise, and water pollution. However, the EE represents the output per unit of environmental load, which can be stated as the ratio between the output and environmental cost (Gong et al., 2019).

A clear understanding of port efficiency is important for scholars to adopt appropriate efficiency measures, and important for port operators and policymakers to improve port performance. Although some articles have reviewed the related articles on port efficiency (Cullinane & Wang, 2006; Khin & Yang, 2010; Park et al., 2019; Tovar & Rodríguez-Déniz, 2015), they mainly focused on port operational efficiency analysis from port's perspective. To the best of our knowledge, no existing study has provided a comprehensive review regarding the port efficiency analysis from both operational and environmental perspectives and both port' and users' perspectives. With this background, this research reviewed 213 papers on port efficiency analysis over the past 40 years to present a whole picture of present studies on port efficiency analysis.

This research first presents the review method and the structure of reviewed papers. Then follows the classification of port efficiency from different perspectives and the methods used in previous port efficiency evaluation. The key factors on port efficiency are also summarized. Finally, the limitation in existing studies and the potentials for future study are presented.

2.2 Literature review method and structure

Extensive studies exist in port efficiency analysis. After searching Google Scholar, Scopus, and JSTOR using the keywords "port efficiency" or "terminal efficiency", a total of 361 articles were found. To concentrate on port efficiency analysis in the maritime study, the articles are further narrowed with the keywords "shipping", "sea", "maritime" or "marine". 213 articles have been collected (including 186 journal articles, 23 conference papers, and 4 book chapters).

Among these articles, 110 were published in the following journals: *Maritime Economics and Logistics* (23), *Maritime Policy and Management* (21), *Transportation Research Part A* (13), *International Journal of Shipping and Transport Logistics* (10), *International Journal of Transport Economics* (10), *Asian Journal of Shipping and Logistics* (7), *Transport Policy* (7), *Transportation Research Part E* (7), *Research in Transportation Business and Management* (4), *Transport Reviews* (4), *Transportation Research Part D* (4). Table 2-1 shows these journals that have published at least 4 such articles. The time of publication has been divided into four periods with intervals of 10-11 years.

According to Table 2-1, it can be found that the study on port efficiency starts from the 1980s (Cuzán, 1983; Shoemaker, 1981; Williamson & Daunt, 1984). Since then, the research on this topic has received growing attention.

Table 2- 1 Journals for port efficiency analysis

Journal	1980-89	1990-99	2000-09	2010-20	Total
Maritime Economics and Logistics	0	0	8	15	23
Maritime Policy and Management	0	3	4	14	21
Transportation Research Part A	0	1	5	7	13
International Journal of Shipping and Transport Logistics	0	0	4	6	10
International Journal of Transport Economics	0	2	4	4	10
Asian Journal of Shipping and Logistics	0	0	0	7	7
Transport Policy	0	0	0	7	7
Transportation Research Part E	0	0	1	6	7
Research in Transportation Business and Management	0	0	0	4	4
Transport Reviews	0	0	1	3	4
Transportation Research Part D	0	0	0	4	4
Others	3	2	24	74	103
Total	3	8	51	151	213

In terms of the cited situation, Figure 2-1 and Figure 2-2 show the most cited sources and the most cited authors by their articles' citation numbers. The articles from *Transportation Research Part A*, *Maritime Policy and Management*, and *Maritime Economics and Logistics* have the highest citation numbers. Tongzon, L., Wang, T. F., and Cullinane, K. are the most cited authors. These journals and authors have the highest influences in this research area.

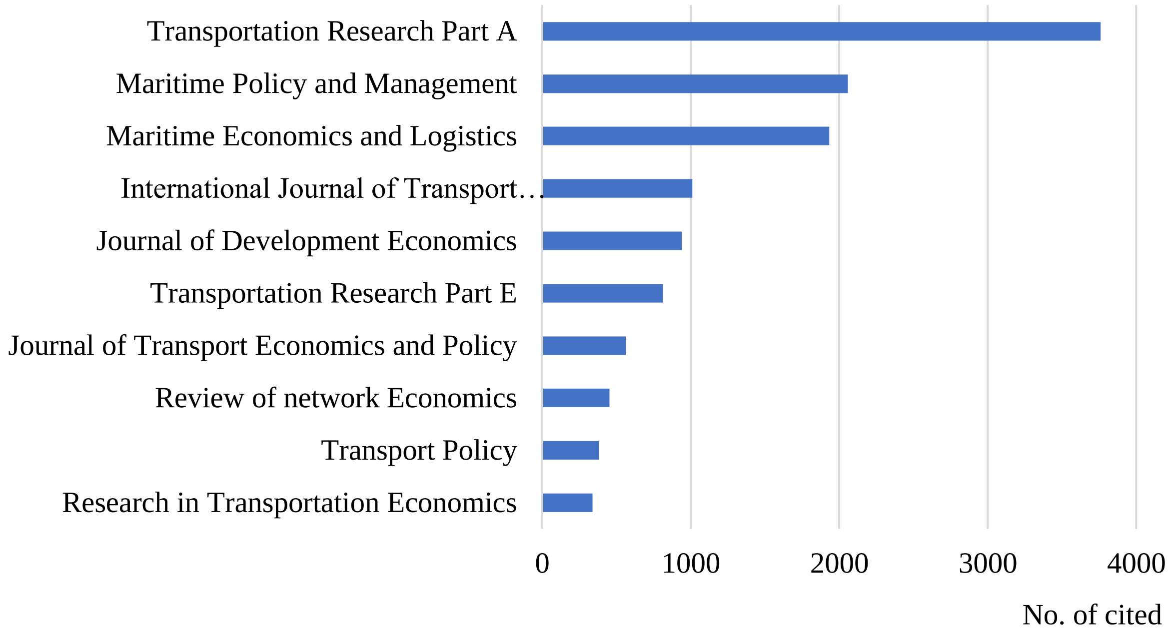

Figure 2- 1 Top 10 cited sources by citation number

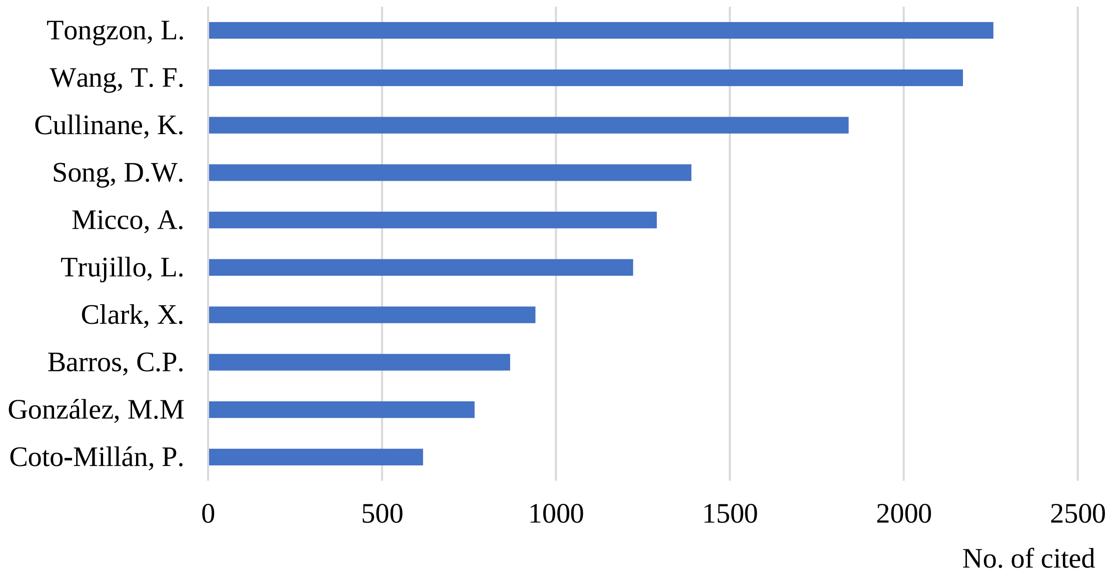

Figure 2- 2 Top 10 cited authors by citation number

Based on the perspectives and concepts used by previous studies, the literature on port efficiency can be classified into two groups. One group is composed of *port operation efficiency analysis*, which considered desirable outputs in port operations, and *port EAE analysis*, which considered undesirable outputs in port-related activities. The other group includes *port efficiency analysis from port's perspective*, which measuring port efficiency from the perspectives of port operators, owners, and managers, and *port efficiency analysis from users' perspective*, which measuring port efficiency from the standpoint of port users.

With regard to the analysis from different perspectives, DEA (Data Envelopment Analysis) and SFA (Stochastic Frontier Analysis) methods are the most common methods adopted by literature to analyze port efficiency from port perspectives. And the indicators-based methods, such as scale method, differences analysis are used by some scholars to capture users' perceptions in port efficiency analysis (Brooks & Schellinck, 2013, 2015; Vaggelas, 2019).

Classifying papers by different perspectives and methods, the distribution of the 213 articles is depicted in Figure 2-3. Among the 213 articles, 182 papers analyze port operation efficiency from port's perspectives, 13 papers analyzed port operation efficiency from users' perspectives, 4 papers evaluated port EAE based on port activities, and 11 papers measured port EAE based on ships' activities in port. And it can be found that the DEA and SFA methods are adopted by 185 papers, with DEA methods (125), SFA methods (37), and both DEA and SFA (23). The indicator-based methods were employed in 17 papers. During the review process, we found that some studies are conducted with the aim to examine the major factors' impact on port efficiency. To reflect these research objectives and provide references for the second study of this thesis, this research also identified and summarized the factors. It has been found that the input factors, organization factors, regulation factors, and transport factors are commonly considered in existing studies.

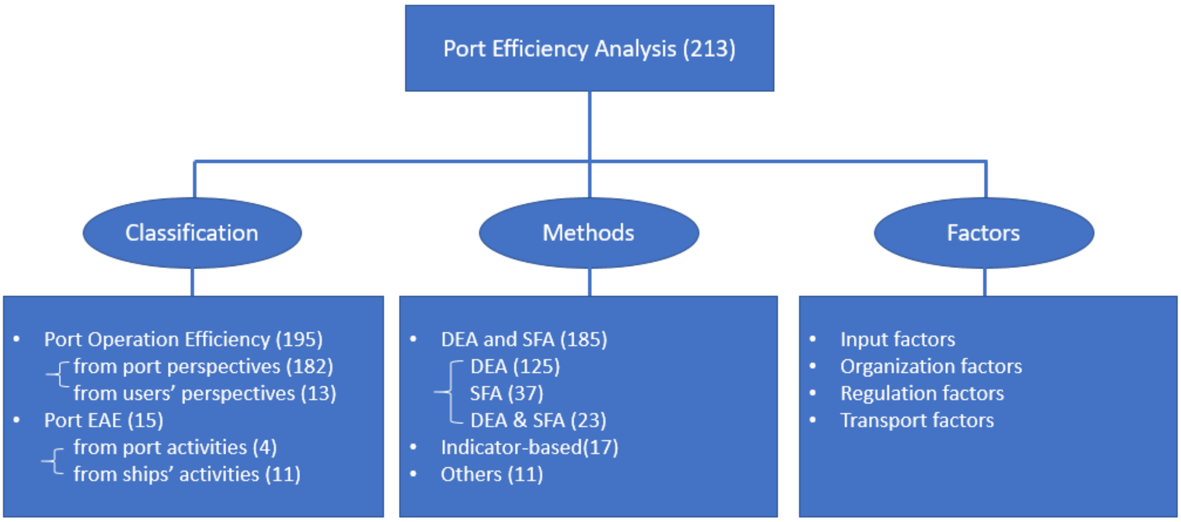

Figure 2- 3 Structure of reviewed papers

2.3 Classification of port efficiency

Efficiency is always considered as relative productivity, which comprises two notions (Barros & Sampaio, 2004). One notion is technical efficiency, which measures the extent to which a decision-making unit (DMU) is able to produce a maximum level of output for given inputs, or which a given output is produced at minimum inputs (Farrell, 1957). Based on this notion, the technical efficiency of port has been analyzed as the production possibility by using ports' input (e.g. labor, berth) to achieve its outputs (e.g. cargo throughputs) in some studies (Barros, 2003b; Cullinane & Song, 2006; Schøyen & Odeck, 2013; Tovar & Wall, 2015). The other notion is allocative efficiency, which refers to optimal combinations of inputs and outputs in light of prevailing inputs and products' prices (Lovell, 1993). According to this notion, the allocative efficiency of port has been measured as the cost possibility of port to select prices of input to achieve its maximal productivity by some scholars (Banos-Pino et al., 1999; Zheng & Yin, 2015). Both technical efficiency and allocative efficiency mainly concern the operational issues and desirable outputs of port.

With the growing awareness of the environmental issue, more scholars noticed the environmental impacts in port operations. Some studies treat the negative environmental impacts, such as air pollution conducted by crane and wastewater released by ships as undesirable outputs, and adjusted the desirable outputs in the efficiency analysis (Castellano et al., 2020; Chin & Low, 2010; Cui, 2017; Lee et al., 2014; Park et al., 2019; Tovar & Wall, 2019). However, although these studies used the term of port EE, they are actually doing port EAE analysis as they are conducted based on input-output ratio, but not the output-environmental cost ratio.

In addition to the classification of port efficiency from operational and environmental perspectives, port efficiency can also be classified from the view of different stakeholders. From port's perspective, port efficiency is more oriented toward the needs and interests of ports. Therefore, it is mostly determined by the amount of cargo handled, ships called, or earnings (Bichou, 2011; Cullinane et al., 2004; Cullinane & Wang, 2006; Ding & Xu, 2014; Elsayed

& Shabaan Khalil, 2017; González & Trujillo, 2009; Jang et al., 2016; Ju & Liu, 2015; Julien et al., 2020; Khin & Yang, 2010; Liu & Medda, 2009; Notteboom et al., 2000; Polyzos & Niavis, 2013; Zahran et al., 2017). However, from users' perspectives, efficiency means the quality of port service, time spent in port, and users' satisfaction levels (Brooks & Schellinck, 2013, 2015; Vaggelas, 2019).

Following the classifications of port efficiency mentioned above, the sections of 2.3.1 and 2.3.2 review port operation efficiency and port EAE from port's perspective and users' perspective.

2.3.1 Port operation efficiency

Port operation efficiency, which only concerns desirable outputs in port operations, has been analyzed in many studies. The desirable outputs reflect the objectives of port, such as cargo throughput, profits, users' visits, etc.

Most of the previous studies were originated directly from the needs and interests of port, referring to productivity and profitability, which can be classified as the port operation efficiency analysis from port's perspective. For instance, Cullinane and Wang (2006, 2010) stated that container throughput is the most relevant, most appropriate, and analytically most tractable variable for port output in port efficiency analysis. Based on this output, they examined the world's top 30 leading container ports in 2001 and found that 9 and 22 out of the 57 terminals of these ports are efficient in the measurement by DEA-CCR and DEA-BCC. Coto-

Millán et al. (2016) considered the cargo as the most immediate and important source of revenue for the port authority and used the amount of solid bulk, liquid bulk, containerized general cargo, non-containerized general cargo, and passengers as the outputs. Using the panel data of 26 Spanish port authorities from 1986 to 2012, they found that inefficiency is significantly presented in these ports. Such studies that stand at port's perspectives, regarding the amount of cargo traffic, passenger traffic, and ship traffic as the outputs without the consideration of how quick they moved and turnaround, accounted for about 92% of the total reviewed papers.

In addition to the above studies, some noticed the importance of users' needs and interests and attempted to evaluate port efficiency through using the indicators, such as the time spent by users, quality of port service, and users' satisfaction. Due to the data accessibility and conventional understanding of port efficiency, some limitations existed in these studies. For instance, Roll and Hayuth (1993) used cargo throughput and the number of ships' calls to reflect the operation efficiency from port's perspectives, and used the ratio of handling time to the total time of ships stay in port and the users' satisfaction level to reflect port operation efficiency from users' perspective. The result of their study shows that when considering port efficiency more from users' perspective, ports may gain different results on efficiency rankings. Unfortunately, their research is conducted based on hypothetical data. Tongzon (2001) used the total number of containers loaded and unloaded to reflect the efficiency of cargo-related facilities and services from port perspective, and the number of containers moved per working hour per ship to represent the efficiency of moving cargos off and onto ships from ships' and cargo owners' perspectives. His study first used the actual data of 16 international container ports from both views of port and users in efficiency analysis. But the number of containers moved per working hour per ship is the time ships spend in berth to handle cargos, which should not be mixed with the inputs of port. Sánchez et al. (2003) measured the port efficiency by using the survey data, such as the average waiting time of ships in congestion period and normal period, the average number of containers per vessel handled in port, port annual congestion time, port loading, and unloading rate, and the average time of ship stay in port. Their research supplement the study of Tongzon (2001) by using the indicator method. But it is hard to conduct for more ports due to the survey coverage and the data quantity.

Suárez-Alemán et al. (2014) proposed the direct utilization of time ship stays in ports in analyzing port efficiency in Short Sea Shipping and stated that AIS data could be used as the basis for future research. Due to difficulty in obtaining the time data of ship, they used the cargo movements in ports as the quantity indicator and movements per hour as the time indicator. Based on the time indicator of cargo, they found that ports may obtain a higher score when just considering the volume of cargo movements in ports as the outputs rather than the inclusion of movements per hour in a DEA empirical example of African ports. Slack et al. (2018) used the average vessel turnaround times (ATTs) drawn from Lloyds intelligence unit to analyze the efficiency of 70 ports. Their study suggested that the lack of associations between ATTs and container throughput. Michaelides et al. (2019) used the vessel and berth scheduling information from the database of Port Community System (PCS) to evaluate the efficiency of the Port of Limassol. They found that a significant fraction of cargo ships spent several hours waiting for berth and the required time was different based on the type of vessels, origin of vessels, and the scheduling of agents. But their study only measured the time the ship spends in port without the consideration of the traffic amount or the correlation of ships' time in port and productive aspects of port.

From the number of published articles, it is obvious that the majority of studies analyzed port operation efficiency only from port's perspectives, and the research from users' perspectives is relatively few. And although the latest studies noticed the importance of users' interests and ships' time in port in port efficiency analysis, few of them combined the indicators from both users' and port's aspects in the evaluation.

2.3.2 Port environmentally adjusted efficiency

Different from port operation efficiency analysis that only considers desirable outputs, port EAE analysis also considers the undesirable outputs, such as air emissions and water pollutions, in efficiency analysis. As these undesirable outputs are usually from the energy consumption of port equipment and ships, the literature on port EAE analysis could be divided into environmental impacts from port activities, or that from ships' activities.

Based on port activities, most studies adopted the energy consumption of port and the amounts of air emissions, such as $CO_2, SO_2, NO_x, PM_{2.5}$ in the port EAE analysis. For example, Chang (2013) evaluated the EAE of ports in Korea, using the energy consumption, labor, and capital at ports as major inputs, cargo volume and vessel number as desirable outputs, and CO_2 emissions as undesirable outputs. The results of the study show that these Korea ports are inefficient in operation efficiency, but relatively efficient in overall EAE. Similarly, Cui (2017) considered the CO_2 emissions as undesirable outputs and measure the CO_2 emissions through converting the energy consumption of ports in the evaluation of 10 Chinese ports' EAE. His study found that the high competition of production among ports may lead to a decrease in EAE because ports put top priority on the benefit rather than environment. Sun et al. (2017) selected the NO_x emission as the undesirable outputs to analyse the efficiency of Chinese ports. The results show that the port efficiency is significantly lower when put more weight to undesirable output. Castellano et al. (2020) evaluated the EAE of 24 Italy ports with the consideration of greenhouse gas emissions caused by port activity. The result of their study suggested that efficiency converges to the optimal target when ports feature a high pro-environmental attitude by implementing proactive green policies.

Based on ships' activities, most scholars compute air emissions from ships in the port area. For example, Chin and Low (2010) measured the EAE of 13 major East Asian ports' efficiency by adjusting a major environmental load based on the exhaust emission of ships. Lee et al. (2014) calculated the EAE for 11 ports using a slack-based DEA model with CO_2, SO_2, NO_x emissions from ships at berth as the undesirable output variables. Tovar and Wall (2019) also evaluated port EAE by measuring emissions from ships in port. These studies estimated air emissions based on ships' fuel consumption using some general established specific emission factors. However, the quantity of energy consumption and ship's emissions are different due to various engine types, sailing speed, ship size of ships. The difference may lead to a divergence in EAE analysis. Representing the ship-by-ship and real-time data through the sophisticated spatial and temporal activity of ships, AIS data is used to obtain accurate estimates of ship emissions in port EAE analysis by some scholars (Song, 2014; Tichavska & Tovar, 2015).

With the increasing concerns on global warming and pollution issues, more studies investigated the environmental issues in the port sector and the number of published articles related to port EAE analysis grow gradually in recent years. Distinguishing desirable outputs and undesirable outputs, some studies try to explore how efficiency rankings are influenced with and without the consideration of environmental issues. For instance, Chin and Low (2010) used the frequency of shipping services and bilateral trade flow as inputs, container capacity flows as desirable output, and emissions released by ships as undesirable output. They found that using a smaller number of larger ships with higher ship loadings instead of a larger number of small vessels, the volume of shipping services decreases thus allowing for advantages of scale economics and a decrease of fuel consumption per unit of cargo transported. Therefore, their study implies that the operation efficiency may be consistent with EAE when considering ships' utilization and ships' capacity in port efficiency analysis. However, when considering the energy consumption and emission based on port' activity, ports are likely to show high EAE but relatively low productive efficiency (Chang, 2013; Cui, 2017; Sun et al., 2017). Cui (2017) and Sun et al. (2017) also found that expanded port scale may contribute to high operation efficiency rankings due to scale economy, but it is not necessarily beneficial for EAE. Therefore, the relationship between operation efficiency and EAE is complex and related to the utilization of resources.

2.3.3 Summary and discussion

From the reviewed literature, we can find a trend that while considering the economic benefits of port, scholars have a growing awareness of port's environmental impacts and considered negative environmental impact as the undesirable output in port efficiency analysis. With intense competition among ports and terminals, the users' interests and needs, such as the users' time in port, quality of port service also become important in port efficiency analysis. Considering the interests of both port and users, the real efficient ports should have not only high capacity utilization but also short turnaround time for ships and cargo.

However, without considering users' interest, measuring port efficiency solely based on the outputs and inputs of ports, it is difficult to distinguish the efficient port from the congested port, which is not efficient from the perspective of port users. Even some studies considered ship's time in port efficiency analysis using DEA, the ships' time and port inputs-outputs belong to different DMUs. And there exist difficulties in collecting data of actual users' interests. Some studies pointed out that the time data of ships, such as AIS data and ATTs data could be used to reflect ships' time in port. But they analyzed ships' time in port without the consideration of port productive indicators. How to balance the needs and interests of both users and port could be investigated in the future.

2.4 Method of port efficiency analysis

The methods used in port efficiency analysis can be categorized as input-output based methods and indicators based methods. The input-output based methods measuring the efficiency with different combinations of inputs and outputs, are represented by DEA and SFA. The indicator based methods use the differences, criteria, or indicators to evaluate port efficiency.

As the input-output based methods enable the evaluation of efficiency on the comparison of observed values of outputs and inputs, these methods are mainly employed by scholars to analyze port efficiency from port's perspectives. The indicators based methods, capturing the users' interests through the scales in the survey or the differences in time metrics, are mainly used to analyze port efficiency from users' perspectives. The other methods, such as Principal component analysis (PCA), Ordinary Least Squares (OLS) estimations, Analytic hierarchy process (AHP), Directional distance function (DDF), and Multi-agent-based simulation model are also adopted together with the input-output based or indicator based methods by some scholars in port efficiency analysis.

Table 2- 2 Methods used in port efficiency analysis

	Methods	No. of papers	Examples
Input-output Based (185)	DEA	125	Roll and Hayuth (1993)
	SFA	37	Z. Liu (1995)
	DEA & SFA	23	Cullinane et al. (2006)
Indicators-Based (17)	Descriptive analysis	9	Michaelides et al. (2019)
	Multi-criteria analysis	6	Tongzon and Ganesalingam (1994)

According to Table 2-2, it can be found that the DEA and SFA are the most popular methods used by scholars in port efficiency analysis. As the details of the methods have been reviewed in several articles (Barros, 2006; González & Trujillo, 2009; Merkel & Holmgren, 2017; Panayides et al., 2009; Tovar &

Rodríguez-Déniz, 2015), this section will only briefly review the literature with most up-to-date studies.

2.4.1 DEA methods

DEA is a non-parametric method to evaluate efficiency based on the ratio of output to input. For applications, Roll and Hayuth (1993) first introduced this method into the port sector, generating the efficiency rankings of 20 ports by adopting cross-sectional hypothetical data. Further, Martinez-Budria et al. (1999) examined the efficiency of 26 Spanish ports by applying DEA-BCC models with the panel data from 1993-1997. After that, both DEA-CCR and DEA-Additive models are employed in the research of Tongzon (2001) to evaluate the efficiency of 4 Australian ports and 12 international container ports in 1996. The combinations of different models of DEA have also been employed in studies to analyze port efficiency. For example, Cullinane et al. (2004), Cullinane, Song, et al. (2005), and Schøyen and Odeck (2013) calculated the efficiency scores obtained from DEA-CCR and DEA-BCC with panel data and used the indicator derived from DEA-CCR and DEA-BBC models to measure the scale efficiency of ports. Elsayed and Shabaan Khalil (2017) adopted radial-output oriented DEA models (DEA-CCR and DEA-BCC) models and non-radial DEA model (DEA-SBM) to measure the comparative efficiency of Safaga port. Mustafa et al. (2020) compare the efficiency of ports in South Asia and Middle Eastern with those in East Asia through the DEA-CCR and DEA-BCC models. From the results of these studies, it can be found that the score differences are not significant or consistent in DEA-CCR and DEA-BCC model applications.

To meet some specific needs in practice application, DEA methods have been developed and extended. Malmquist Productive Index (MPI) is used with the DEA method to measure port efficiency changes by some studies (Ding et al., 2015; Julien et al., 2020; Yuen et al., 2013). Bootstrapped DEA method is an advanced and popular choice for researchers to avoid the sensitivity of standard DEA to the number of random variables in port efficiency analysis (Gil Ropero et al., 2019; Le & Nguyen, 2020; Nguyen et al., 2016). The Imprecise DEA (IDEA) method is also used in some studies when meeting imprecise and missing data problems in port efficiency analysis (Zahran et al., 2020). Considering the possible imprecision in the data set, the Fuzzy DEA model is another developed and popular method to evaluate the efficiency of ports based on uncertain input and output in studies (Bray et al., 2015; Castellano et al., 2019; Wang & Han, 2018; Wanke et al., 2018). The development of models enriches the methods in port efficiency analysis and overcomes some limitations of traditional DEA models.

2.4.2 SFA method

SFA is another widely used method in port efficiency analysis based on a production function with the assumptions imposed over the error term. Different from DEA, SFA is a parametric method. For applications of SFA in port efficiency analysis, Z. Liu (1995) first adopted it to evaluate the efficiency of UK ports with the data from 1983-1990. Coto-Millán et al. (2000) further employed this method with a translog cost function to measure the relationship of port size and port efficiency of 27 Spanish ports. Lots of following studies employed this method to analyze the efficiency of port under different conditions (Coto-Millán et al., 2016; Estache et al., 2002; Liu & Medda, 2009; Pagano et al., 2013; Serebrisky et al., 2016; Suárez-Alemán et al., 2016; Tongzon & Heng, 2005).

As DEA and SFA have different advantages in port efficiency analysis and stand for parametric and non-parametric methods respectively, some studies try to find the difference between these two methods. In principle, the treatment of random noise and sensitivity to specification are the main differences existed between DEA and SFA method (Merkel & Holmgren, 2017). In empirical studies, researchers identified the difference by comparing the evaluation results of these two methods. For example, Cullinane et al. (2006), Bergantino et al. (2013), and Jiang et al. (2017) have conducted the port efficiency analysis by both DEA and SFA method and compared the results of these two methods. The results from their studies indicated that the SFA method tends to produce higher efficiency scores than the DEA method.

2.4.3 Summary and discussion

From the applications of these methods in existing studies, it can be found that DEA and SFA are the most popular methods used in analyzing port efficiency. And for those studies which used the same method, the main differences are the selection of inputs and outputs, the type of data, and the DMUs. The advantage of these two methods, allowing models with multiple inputs and outputs without the requirement of the same units, makes them suit to be used in port efficiency analysis. And as the DEA and SFA models have some constraints and the combination of different models can enhance the empirical analysis, there is a trend of combining different models in port efficiency analysis.

However, some limitations of these methods in analyzing port efficiency have not been eliminated. In recent years, congestion events occur irregularly and port trade changes occasionally, more ports and shipping companies concern the real-time changes in a specific port. Although some existing studies used the panel data to capture the variations of efficiency over time, this kind of time-series data is always from annual surveys (Cullinane, Ji, et al., 2005; Cullinane et al., 2004), which cannot reflect the real-time random changes in port efficiency.

2.5 Major factors on port efficiency

With the development of port efficiency studies, different factors and their impacts on port efficiency have been addressed and examined in the literature.

As port operation and production heavily rely on labor, facilities, investment capitals, etc., some studies investigated port efficiency changes with these input factors. The organization and policy changes in the port sector arise the researchers' interest in examining the impact of some factors, such as port ownership, port competition, pricing policy, and legal restrictions, on port efficiency. The connectivity and accessibility of transport systems of ports are also considered as factors that influencing port efficiency. In this research, the major factors are divided into four categories, including inputs, organization factors, regulation factors, and transport factors.

Table 2- 3 Major factors considered in previous studies

Factors	**Detailed**
Inputs	Labor
	Capital
	Facilities
	Land
Organization factors	Port ownership
	Port competition
Regulation factors	Pricing policy
	Legal restriction
Transport factors	Connectivity and accessibility

2.5.1 Inputs

The most common inputs considered in previous studies are labor, capital, facilities, and land. Although the analysis aspects of factors are similar, the indicators used for the same factor are various in different studies.

Labor. Previous studies preferred to use the number of employees or the related expense to identify the labor input. For example, Roll and Hayuth (1993), Banos-Pino et al. (1999), Tongzon (2001), Estache et al. (2002), and Barros (2003a, 2003b) used the annual average number of employees in the port to define the labor input. Z. Liu (1995), Martinez-Budria et al. (1999), and Yuen et al. (2013) adopted the wage payment as the representation of labor input. In addition to analysis of labor input quantity, the structure of manpower input is also identified as the key factor. The study conducted by Ding et al. (2015) suggested that professional talent can enhance the efficiency of port management and production.

Capital. The indicators used to define capital could be divided into two groups. One used the net value of fixed capital, including the berths, cranes, tugs, and other port infrastructures to represent the capital input of the port (Z. Liu, 1995; Tongzon, 2001). Others define capital as the invested capital, or the depreciation expenditures in ports in a period Barros (2003a); Martinez-Budria et al. (1999). The general conclusion from these studies shows that capital input has no significant impact on port efficiency. But Banos-Pino et al. (1999) found the overcapitalization existed in the Spanish port sector.

Facilities. The number of berth, gantry cranes, tugs, and yard equipment are the most popular indicators used by scholars (Bichou, 2011; Cullinane & Wang, 2006; Güner, 2018; Kutin et al., 2017). Meanwhile, the equipment utilization and occupancy, such as the container handling capacity, container loading rate, crane move per hour are also used in some studies (Bichou, 2013; Sánchez et al., 2003). With the development of technologies and information, an interesting study conducted by Castellano et al. (2019) pointed out that the input of digital and communication technologies should be considered in the equipment measurement and stated that the adoption with advanced infrastructure could improve the port efficiency.

Land. Terminal area and yard area are often considered as proxies for land resources in some studies (Bray et al., 2015; Chang et al., 2018; Hung et al., 2010; Serebrisky et al., 2016; Wanke & Barros, 2015). The port size and port scale are also considered as related indicators by some scholars (González & Trujillo, 2009; Martinez-Budria et al., 1999; Notteboom et al., 2000; Pérez et al., 2020; Tetteh et al., 2016). For the relationship between port scale and port efficiency, some researchers stated that the larger ports performed better than the smaller ones in terms of port efficiency, while others' opinions are conflicting.

2.5.2 Organization factors

***Ownership*.** The ownership of port could be classified into three categories: pure public, in which ownerships and all operations are owned by the public sector; mixed, in which the public sector is a landowner and private sector owns the operations functions; pure private, in which ownership and all functions are owned by the private sector. Studies on the relationship of port ownership and port efficiency are mostly inspired by port reforms (Cheon et al., 2010; Cullinane, Ji, et al., 2005; Estache et al., 2004; Estache et al., 2002; González & Trujillo, 2008; Nwanosike et al., 2016; Pagano et al., 2013; Tongzon & Heng, 2005). The representative study is conducted by Tongzon and Heng (2005), which suggested that the port reform from the public to private is useful for improving port operation efficiency, but the relationship between port efficiency and port privatization is not linear. Some studies focused on the impact of private participants in port operation, such as the involving number of global terminal operators and shipping companies in ports or terminals. But the results of these studies show divergence in the relationship between private participants and port efficiency. For example, Yeo (2015) examines the influences of the participation of global terminal operators and the restructuring of ports on the efficiency of 260 terminals located in China, Japan, and Korea. He found that both of these two factors could increase port efficiency. However, the research conducted by Ding et al. (2015) indicated that the increase of terminal operators may hurt port efficiency in the case of 21 coastal small and medium sized-port container terminals in China.

Competition. The rapid development of ports and maritime transportation drives the changes of port market structure from monopoly to competition in many parts of the world. Following this trend, some papers examined the impact of competition and found that that intra- and inter-port competition may enhance port efficiency (Coto-Millán et al., 2019; Pérez et al., 2016; Wang et al., 2005; Yuen et al., 2013; Zheng & Negenborn, 2014). Figueiredo De Oliveira and Cariou (2015) measured the degree of inter-port competition via the Herfindhal-Hischman Index (HHI) and investigated the impact of competition on port efficiency. With an investigation of 200 container ports, they found that the port efficiency decreases with competition at the regional level but the competition effect is not significant at the local or global level.

2.5.3 Regulation factors

The regulation factors analyzed by previous studies include pricing policy and legal restrictions related to port operations. These factors directly affect users' choice of port call and consequentially impact port efficiency.

Pricing policy. Price determinates the cost efficiency of users and users' demand for port service. The pricing policy can be classified as cost-based pricing, cost recovery pricing, congestion pricing, and strategic port pricing. Tongzon (1993) and Strandenes and Marlow (2000) found that pricing policy charged on ship-based, such as the congestion pricing can decrease the ship and cargo turnaround time, and subsequently improve the port efficiency.

Legal restrictions. Legal restrictions and customs requirements influence the procedures of cargo flow and ship transportation, which can affect port efficiency to a certain extent. Clark et al. (2004) find that the cargo handling restriction and mandatory port services are two legal restrictions that existed in ports, which have negative effects on port efficiency. Other legal restriction factors, such as inspection procedure (Barros, 2003a), security policy (Yeo et al., 2013), environmental regulations on controlling SOx and NOx emissions from ships (Chang et al., 2018), are also proved as the influencing factors on the port efficiency.

2.5.4 Transport factors

The boosted amount of cargo and traffic volume puts pressure on the connecting corridors and intermodal transportation systems of the port. The accessibility and connectivity of ports to other transportation nodes have been recognized as influencing factors on port efficiency.

Multimodal transport. Multi-transportation is useful in improving port transit efficiency. Onyemechi (2013) suggested that the formation of a waterfront sport system linked by feeder vessels and hinterland rail could improve port efficiency. Wan et al. (2014) analyzed the impacts of hinterland accessibility on the efficiency of US container ports and found that unobstructed roads connecting to the ports may largely improve port efficiency. The study conducted by Suárez-Alemán et al. (2016) indicated that the connectivity improvements of liner shipping and the multimodal links can increase the level of port efficiency in developing regions. Schøyen et al. (2018) also suggested that a high level of logistics quality and competence could promote port efficiency.

2.5.5 Summary and discussion

From previous studies, it can be found that there are many factors had been considered in port efficiency analysis and their impacts on port efficiency are different. However, there is a lack of consensus on the impact of each factor on port efficiency. This may result from different DMUs or different variables used in different studies.

Also, in existing studies, the latest development in port facilities has not been incorporated. For example, the construction of automated terminals removed the need for manpower in port operation and improved port handling efficiency. The automated equipment may have a larger impact on port efficiency than the traditional equipment and become a more important factor. Besides, better benefits can enhance the workers' efficiency and prevent strikes. However, the existed studies only focused on workers' number or the expenditure on workers' wage without the consideration of the benefits of port workers. The latest development should be considered in future studies.

2.6 Current issues and further research opportunities

Despite the contribution of exiting studies, the limitations in port efficiency analysis should be aware in further research. First, due to the data limitation and rare awareness of users' interest, there is a lack of research to balance the benefits of users and ports in port efficiency analysis. Without the consideration of ships' time in port, measuring port efficiency solely based on the inputs and outputs of ports, it is hard to distinguish the efficient ports from the congested ones. Second, although the relative efficiency ranking within a group of ports or terminals and the efficiency changes of an individual port in a continuous time have been examined, the random real-time changes, such as the congestion and strike events are difficult to be identified. Third, some latest changes on factors, such as the automated facilities used in port operation, the benefits of port workers, are not considered in existing studies. These particular issues compromise the existed studies, but also provide potentials for researchers to enhance the research. The relevant suggestions are listed below.

(1) Incorporating AIS data to capture ship's time in port with existed productive variables to analyze the overall port efficiency from both views of port and users. AIS data could provide worldwide real-time ship information from time and space perspectives continually. Incorporating AIS data is helpful to capture ships' time in port from shipowners' perspective and to overcome the constraints of existed methods in the reflection of random real-time changes on port efficiency.

(2) Considering the latest changes, such as the workers' benefits and equipment atomization in efficiency analysis. The mechanism of welfare's impact on worker efficiency has been proven by many studies (Katz, 1986; Leibenstein, 1966). These studies provide the reference to consider welfare as an input factor in efficiency analysis. Besides, the equipment atomization not only influences the port efficiency by itself but also influences the human resource structure of the port. The percentage of port equipment atomization, the investment of port atomization, and the related talent changes in human recourses can also be considered as inputs in further study.

2.7 Chapter summary

This research reviewed 213 papers over the past 40 years in port operation efficiency analysis and EAE analysis from both port's perspective and users' perspective.

After reviewing the literature, it can be found that the majority of studies measured port efficiency only from port's perspectives, and the research from users' perspectives is relatively few. And there is a lack of research that balances the interests of users and ports in the port efficiency analysis. In terms of methods, DEA and SFA methods are the most common methods adopted by literature to analyze port efficiency from port perspectives. But due to the difficulty of collecting the data in users' aspects and port' aspects with standard, there are limitations for studies to analyze the port efficiency from both users' perspective and port perspective. And the real-time changes in port efficiency are difficult to be identified. Moreover, the major factors on port efficiency are summarized, including inputs, organization factors, regulation factors, transport factors. But the latest developments on factors are ignored by existed studies.

Port efficiency, as an important indicator for port operators and policymakers to evaluate port performance and for users to make transportation choices, should be understood and analyzed in a comprehensive and up-to-date way. This review may be helpful to future researchers in the analysis perspective, the selection of methods, and the exploring of factors.

Chapter 3: Measuring port efficiency incorporating AIS data

The turn-around-time (TAT) of a ship in a port can reflect the efficiency of the port from shipowners' perspective. TAT includes waiting time and berthing time. Waiting time is required if the port processing rate is lower than the ship arrival rate. Therefore, the ship has to wait for an available berth. Berthing time is the time required for the port to load/unload the cargoes. As the first step, this research attempts to study the important factors on ships' berthing time and their impacts. The method to extract ships' berthing time in port from AIS data is proposed. The empirical relationship of berthing time with ship attributes, port attributes, including the scale efficiency score calculated by DEA methods is explored.

3.1 Introduction

In the shipping community systems, port efficiency can be interpreted differently by different stakeholders. For port authorities and operators, port efficiency refers to port productivity or profitability. For shipping companies, port efficiency means how long a ship has to stay in each port and the quality of port service. Although the time of ship spends in port is relatively less than that voyages in the sea, it is an important indicator for shipping companies to arrange shipping schedules, manage the revenue, and select port to call (Slack et al., 2018).

However, traditional port efficiency analysis only focused on the inputs/output of the port, not that from the ships. Therefore, port efficiency is always evaluated only from port's perspectives in previous literature. Although there are some exceptions in recent years (Michaelides et al., 2019; Slack et al., 2018), they used the time metric of the ship without the consideration of port productive aspects.

Automatic Identification System (AIS) data have been widely employed in maritime research, such as maritime data mining, navigation safety, ship behavior analysis, environmental evaluation, trade analysis, and ship and port performance (Yang et al., 2019). Providing direct ship information in space and time perspectives continually, AIS data provide potentials for obtaining the detailed time information of ships in port. But the application of AIS data in port efficiency analysis is still in its infancy.

To fulfil this gap, this research uses a three-stage procedure to evaluate port efficiency from different perspectives and explore the relationship between them. In the first stage, the berthing time of ships is extracted from AIS data. In the second stage, the technical and scale efficiency score is calculated from port's perspectives using DEA methods. Then, to find out the impact of port scale efficiency score and other factors on berthing time, the regression model is applied in the third stage.

This research makes two important contributions. First, it is a novel attempt to use AIS data in port efficiency analysis by capturing ships berthing time in port. By using this method, the berthing time of each ship call can be calculated and estimated. Second, this research correlates the port efficiency analysis from the view of both ports and ships with empirical results, which provides the basis for port authorities and policymakers to balance the interests of both port and port users.

3.2 Methodology

3.2.1 Extracting the berthing time of each ship call

AIS data, recording ship's information, such as ships' time stamps and positions, provides opportunities to determine the time of ships stay in berth. This research employed the AIS data of ships in 2019 drawn from the IHS database. As each AIS data records only one timestamp, location, speed, and other dynamic information of ships, the AIS data need to be processed to determine the berthing time of the ship.

The data is processed with the following steps.

Step 1. Identifying the berth geographic area

The berth geographic area should be identified as the basis to determine whether the ship's position is in the berth. To draw the geographical area of berth for each port, the berth latitudes and longitudes, and the berth length are collected from IHS Sea-web and Alphaliner. Then, the berth boundaries can be draw based on the maximum and minimum latitudes and longitudes. With closed boundaries, the berth geographic area can be defined as geographic polygons.

Note: the latitudes and longitudes of the located points are collected from *IHS Sea-web* and *Alphainler*; the polygons are drawn by *Google Earth* based on these located points.

Figure 3- 1 Berth Boundary of Hong Kong Port

Step 2. Collecting the first and last signal of each ship call

The first and last signal of ships' AIS data in the berth geographic area records the first timestamp and last timestamp of each ship call in the berth area. Based on the position information of the berth geographic area and the position information of ships' AIS data, we can determine that whether the ship is located in the berth area. Collecting all the ships' AIS data within the berth area and sorting these collected AIS data by time series, the first and the last timestamps in the berth area of each ship call can be obtained.

Step 3. Calculating the berthing time of each ship call

The time when that ship stays in berth can be considered as the berthing time of the ship for loading and unloading cargo. And the first and last signal of each ship call stands for the arrival time and the departure time of each ship call in berth. Using the time stamp of the last signal minus that of the first signal of each ship call in the berth area, we can obtain the berthing time of each ship call.

Focusing on container ports, this research selects the Top 20 ports from *Lloyd's List One Hundred Ports 2020* except the port of Long Beach (ranked 21) and Yingkou (ranked 27). *Lloyd's List One Hundred Ports 2020* rank the ports by container throughputs. These selected ports are the major hub ports in Asia, North Europe, and North America with certain market shares, container throughputs, facilities, and scale.

As the database of AIS is so large, this research collected the AIS data in 2019 of containership calls in the selected 20 ports. After processing the AIS data with ports' selection and data integration, a total of 112,204 ships calls' records of these 20 ports with berth arrival time and berth departure time are obtained. The distribution of berthing time and ship capacity for each ship call in each port is represented in Figure 3-2. It can be found that different ports performed differently in berthing time and ships in different capacities also spent different berthing time in port.

It should be noticed that the collected data is not completed. There may exist some missing AIS signals and abnormal signals due to the limited AIS providers, the error of AIS signals receivers, etc. These missing signals and abnormal signals are excluded in this research.

Table 3- 1 Selected ports

Port	Global Ranking		Located Region	Regional Market Share
	2020	2019		
Antwerp	13	13	Europe	7.969%
Busan	6	6	Asia	4.985%
Dalian	19	16	Asia	2.248%
Guangzhou	5	5	Asia	5.045%
Hamburg	17	19	Europe	6.268%
Hong Kong	8	7	Asia	4.509%
Kaohsiung	15	15	Asia	2.404%
Laem Chabang	20	21	Asia	1.857%
Long Beach	21	20	North America	11.784%
Los Angeles	16	17	North America	13.776%
Ningbo-Zhoushan	3	3	Asia	6.064%
Qingdao	7	8	Asia	4.445%
Rotterdam	10	11	North Europe	10.419%
Shanghai	1	1	Asia	9.667%
Shenzhen	4	4	Asia	5.923%
Singapore	2	2	Asia	8.422%
Tanjung Pelepas	18	18	Asia	2.062%
Tianjin	9	9	Asia	3.675%
Xiamen	14	14	Asia	2.463%
Yingkou	27	26	Asia	1.493%

Note: *Lloyd's List One Hundred Ports* ranks the port by container throughput; the regional market share is the ratio of port throughput to regional container activity reported by *Drewry Maritime Research*.

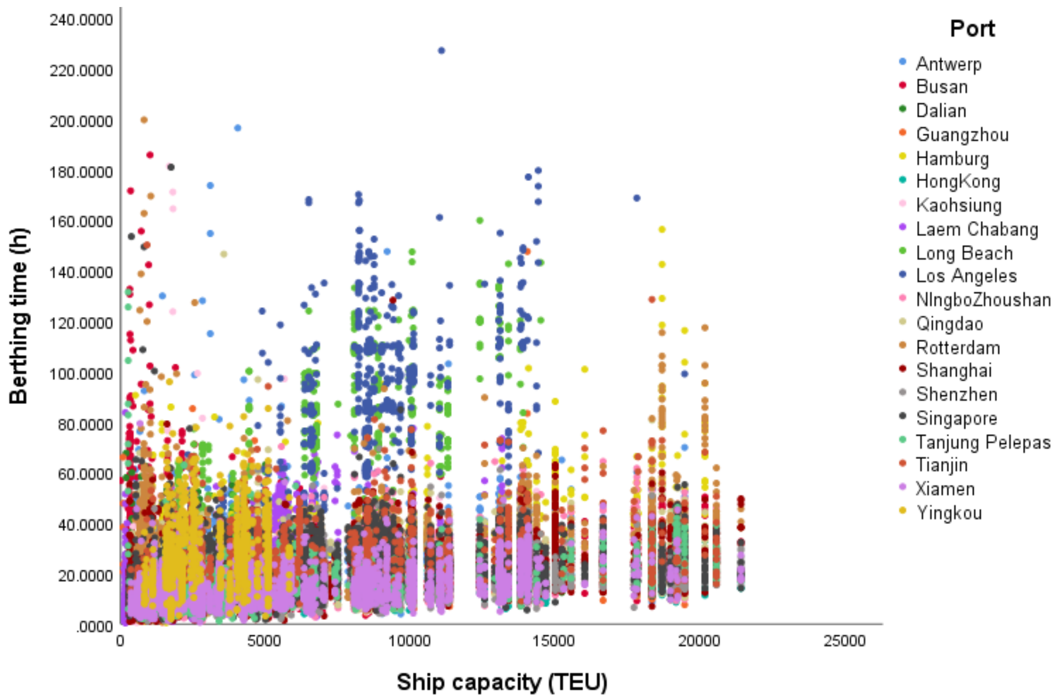

Figure 3- 2 Distribution of berthing time and ship capacity for each port

3.2.2 Measuring port efficiency from port's perspectives

After reviewing the existed articles, it has been known that DEA and SFA are the most common methods used in port efficiency analysis from port's perspectives. DEA measures the efficiency based on the best practice frontiers and SFA evaluates efficiency based on the assumed functional form. With a particular functional form, the SFA models may drawback by involving the cost of imposing a particular functional form and making particular distribution assumptions for the one-sided error term associated with the technical efficiency (Odeck & Bråthen, 2012).

DEA is the non-parametric method to analyze the relative efficiency for a group of DMUs by using a weighted measure of multiples inputs and outputs. And with multiple inputs or outputs, DEA does not need detailed functions and, therefore, can avoid the effects of different measurement units. This advantage of DEA makes the measurement and comparison of port efficiency possible. Therefore, this research employs DEA to measure the efficiency of selected ports.

And for port operators, owners, and managers, the port is a long-term investment and fixed asset, and the efficiency of the port is difficult to be evaluated based on short-term changes in inputs and the results in outputs (Wanke & Barros, 2015). Thus, this research measures port efficiency by output-oriented models.

Considering different frontier types, there are two traditional measurement methods based on the DEA model. One is the DEA-CCR model, which is also known as Constant Return to Scale (CRS) (Charnes et al., 1978). The Other one is the DEA-BCC model, which is also known as Varying Returns to Scale (VRS) (Banker et al., 1984). Let $x_k = (x_{1k}, x_{2k}, \dots, x_{mk}) \in R_+^M$ denote inputs, and $y_k = (y_{1k}, y_{2k}, \dots, y_{nk}) \in R_+^N$ denote outputs. The row vectors x_k and y_k form the kth rows of data matrices X and Y. Let $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_k) \in R_+^K$ denote the non-negative vector of the linear combinations of the K DMUs and $e = (1, 1, \dots, 1)$ denote a suitable dimensioned vector of unity values.

Then, the DEA-CCR and DEA-BCC models can be written as a series of K linear programming envelopment problems with the combination of Equations from (3-1) through (3-4) and (3-1) through (3-5) respectively.

$$\max_{U,\lambda} U \tag{3-1}$$

Subject to

$$Uy'_k - Y'_k \leq 0 \tag{3-2}$$

$$X'\lambda - x'_k \leq 0 \tag{3-3}$$

$$\lambda \geq 0 \text{ (DEA-CCR)} \tag{3-4}$$

$$e\lambda' = 1 \text{ (DEA-BCC)} \tag{3-5}$$

And based on the models, the output-oriented measure of technical efficiency and scale efficiency of the jth DMUs can be calculated as Equation (3-6) and (3-7).

$$TechE_j = \frac{1}{U_j} \tag{3-6}$$

$$ScalE_j = \frac{U_{CCR\_j}}{U_{BBC\_j}} \tag{3-7}$$

where $TechE_j$ denotes the technical efficiency of port j; $ScalE_j$ denotes the scale efficiency of port j; U_{CCR_j} and U_{BBC_j} denote the technical efficiency score of port j derived from DEA-CCR and DEA-BCC models respectively.

$ScalE_j = 1$ indicates the port j is scale efficient and $ScalE_j < 1$ indicates the port j is scale inefficient. The result of scale efficiency also suggests that if $ScalE_j = 1$, the outputs of scale efficient port cannot be further expanded without a corresponding increase in inputs and further increase throughput may result in congestion.

The ports used in DEA applications are also the 20 ports stated in Table 3-1 covering the year 2019. These selected ports, with the highest container throughputs in the world and the ability to handle large amounts of ships and containers, can be considered as homogeneous hub ports.

And as this research focuses on container ports, the inputs used for each port are related to container facilities and inputs, such as the total length of berth (km), maximal depth of berth (m), number of container terminals, number of cranes, and container handling capacity (million twenty-foot equivalents). And the outputs used for each port are container throughputs. The data used for inputs and outputs are compiled from various sources, including *IHS*, *Alphaliner*, *Lloyd's list*, *Chinese Ports Yearbook*, company annual reports and websites, and statistical yearbooks from different countries.

Table 3- 2 Summary statistics of inputs and outputs

Variables		Min	Max	Mean	Std. dev.
Inputs	Total length of berth (km)	3.65	169.00	42.79	39.32
	Maximal depth of berth (m)	14.50	24.80	18.74	3.70
	Number of container terminals	1.00	13.00	6.65	3.67
	Number of cranes	46.00	416.00	173.90	102.75
	Container handling capacity (mteu)	2.25	27.90	14.64	6.82
Outputs	Container throughputs (mteu)	6.49	42.01	16.77	9.91

Note: km represents kilometres; m represents metres; mteu represents million TEU.

3.2.3 The important factors on berthing time

In the third stage, this research explores the relationship between berthing time and port scale efficiency score. As there may exist other factors on berthing time, such as the volume of cargo ship loads or unloads in port, the peak season or off-season of port, these factors are also considered in the multiple regression model.

For the regression model, we considered the berthing time of each ship call as an observation. Each berthing time BT_{ijn} of ship i in port j has been obtained in the first stage of this research. The explanatory variables are as follows.

(1) Containership capacity

The berthing time is influenced by the volume of cargo ship loads or unloads in the berth and the cargo handling operation of the berth (Kamble et al., 2010; Tongzon & Ganesalingam, 1994). In this view, the containership carries to load/unload in the berth impacts the berthing time of the containership to a large extent. Unfortunately, there is no available data on the actual volume of containers handled at each ship call. To solve this question, Ducruet et al. (2014) employ the gross registered tonnage of the ship to replace the cargo amount of each ship. In this research, we use the capacity of each containership to reflect the container handled volume of each ship call and assume that each ship loads/unloads containers at the weight of its capacity.

And as we observed a decrease in the growth of berthing time on containership capacity, after using the linear regression to examine the basic relationship between ship capacity and berthing time, we further expanded the regression as a quadratic model to detect the relationship.

(2) Scale efficiency score of port

For some ports with a higher scale efficiency score, it may serve the ships quickly with sufficient berth and crane in a shorter berthing time. But for some efficient ports whose scale efficiency score equals 1, the maximum throughput is researched and further increase of throughput may result in congestion. In this research, we consider the port scale efficiency score as an explanatory variable, which has been obtained in the second stage of this research.

(3) Regional market share of port

Some literature has found that the competition among ports can enhance port efficiency (Coto-Millán et al., 2019; Pérez et al., 2016; Wang et al., 2005; Yuen et al., 2013; Zheng & Negenborn, 2014). These studies mainly exam the effect of competition on port efficiency from port’s perspectives. To consider the competition power of each port, this research uses the regional market share of each port and examines its impact on ships’ berthing time.

(4) Peak-season or off-season

In the peak season, the cargo volume is large and the working load for the port may higher. Thus, there may exist differences for ships’ berthing time in port between peak-season and off-season. In this research, we use the median monthly throughput of each port as a threshold to determine whether the month is in the peak season of this port.

(5) Alternative specific

The port chosen by the ship to call may also impact the berthing time of the ship. Excluding market share and scale efficiency, each port has its unique feature and will impact its operation on ship’s container handling and berthing arrangement. To examine the alternative specific impact of each port, this research further uses the dummy variables in the third regression models.

(6) Interaction terms

In addition, there may exist interaction effects among the explanatory variables. For instance, for the ship with the same capacity and same volume of the container to be handled, it may need less berthing time in a more scale efficient port. And for the port with a large market share, it may have high bargain power, put less attention on ships' interests, and provide longer berthing time for ships. Thus, the market share may also influence the efficiency score and ships’ berthing time in port.

To consider the interaction effect among explanatory variables, the interaction items are also considered in this research.

The basic multiple regression model can be represented as Equation (3-8).

$$BT_{ijn} = \alpha + \beta_1 S_i + \beta_2 E_j + \beta_3 M_j + \beta_4 D_{peakijn} + \beta_5 S_i E_j + \beta_6 S_i M_j + \beta_7 E_j M_j + \varepsilon_{ijn} \qquad (3\text{-}8)$$

where BT_{ijn} denotes the n_{th} berthing time of each observation of ship i in port j; S_i denotes the capacity of container ship i; E_j denotes the scale efficiency score of port *j* obtained in the second stage of this research; M_j denotes the regional market share of port j;$D_{peakijn}$ denotes whether the observation is in the peak season of port j; α is the intercept and ε_{ijn} is the error term.

To fit the relationship between berthing time and ship capacity, the regression model stated in Equation (3-8) can be extended as Equation (3-9).

$$BT_{ijn} = \alpha + \beta_1 S_i + \beta_2 {S_i}^2 + \beta_3 E_j + \beta_4 M_j + \beta_5 D_{peakijn} + \beta_6 S_i E_j + \beta_7 S_i M_j + \beta_6 E_j M_j + \varepsilon_{ijn} \quad (3\text{-}9)$$

Then, to examine the alternative specific impact on berthing time, dummy variables are used in Equation (3-10). We can treat ports as 20 dummy variables to replace the constant item. As the alternative specific of ports is reflected in the dummy variables, the explanatory variable from the port side, namely port scale efficiency score and regional market share of port, are excluded in the equation to avoid multicollinearity. The regression model can be further stated as follows.

$$BT_{ijn} = \alpha_j P_j + \beta_1 S_i + \beta_2 {S_i}^2 + \beta_3 D_{peakijn} + \beta_4 S_i E_j + \beta_5 S_i M_j + \varepsilon_{ijn} \quad (3\text{-}10)$$

3.3 Empirical Results

This section presents the results of our three-stage analysis on port efficiency. In the measurement of berthing time, Kaohsiung Port, Hong Kong Port, Xiamen Port, Shenzhen Port, and Guangzhou Port are most efficient as they handle ship call for a shorter time, while in the measurement of scale efficiency, Guangzhou port, Laem Chabang Port, Shanghai Port, Singapore port and Yingkou port are most efficient as they produced maximal container throughput by certain input. The difference between these two measurement rankings can be explained by different perspectives and different concerns in these two methods.

Later, the factors and their impacts on berthing time are examined. The results suggested that port scale efficiency scores have an overall negative relationship with berthing time. The ship capacity plays an important role in both berthing time and port scale efficiency score. And the port-specific also affects berthing time significantly.

3.3.1 Berthing time of ship calls

In the first stage, the berthing time of each ship call is extracted based on AIS data. The average berthing time for each selected port and each ship capacity are summarized in Table 3-3. And the distribution of berthing time and ship capacity in each port shows from Figure 3-3 to Figure 3-22.

Table 3- 3 Summary statistics of berthing time and ship calls

Port	Berthing Time (h)		
	Mean	Std. Deviation	Ship calls
Antwerp	23.1884	12.4609	3610
Busan	15.7807	9.3590	11111
Dalian	17.2307	8.4634	2191
Guangzhou	14.9872	8.1547	3483
Hamburg	17.8311	14.0686	4146
Hong Kong	12.0622	4.5470	8158
Kaohsiung	11.1214	7.1943	8271
Laem Chabang	15.9906	11.9877	3332
Long Beach	57.3792	35.3562	764
Los Angeles	71.3779	36.7959	819
Ningbo-Zhoushan	15.4050	7.8198	7596
Qingdao	17.3388	8.0992	5276
Rotterdam	16.2503	12.8611	9108
Shanghai	15.0438	7.4993	11966
Shenzhen	14.3845	6.3833	8692
Singapore	18.5779	7.7338	12931
Tanjung Pelepas	16.2657	8.1450	2700
Tianjin	21.5126	10.7131	2892
Xiamen	13.2298	6.6990	4144
Yingkou	27.5679	12.7168	1015
Total	16.5733	11.7757	112204

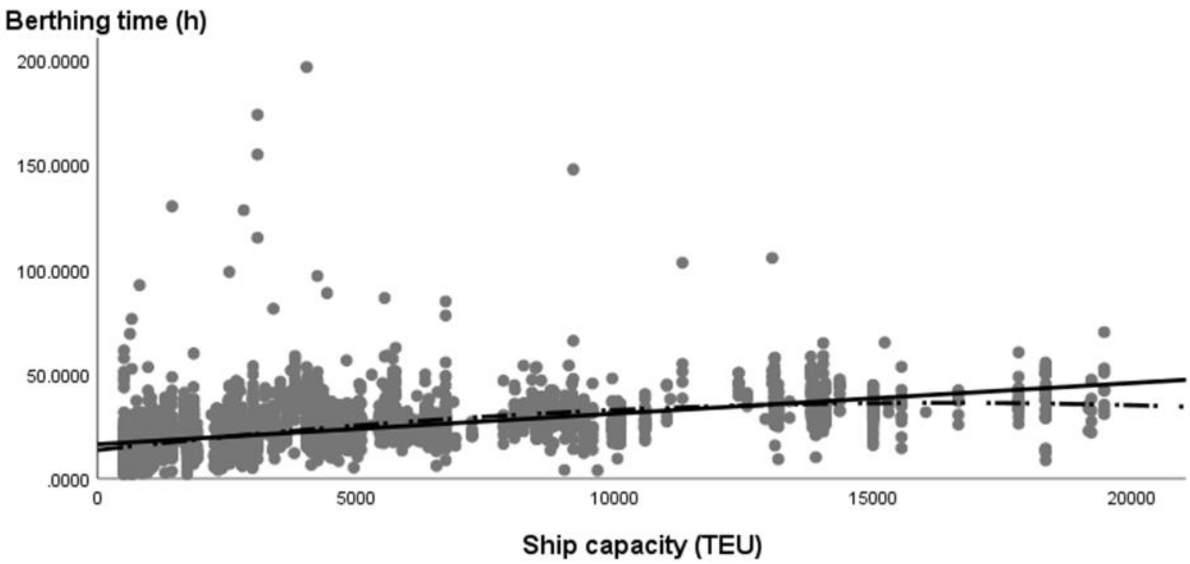

Figure 3- 3 The distribution of berthing time and ship capacity in Antwerp Port

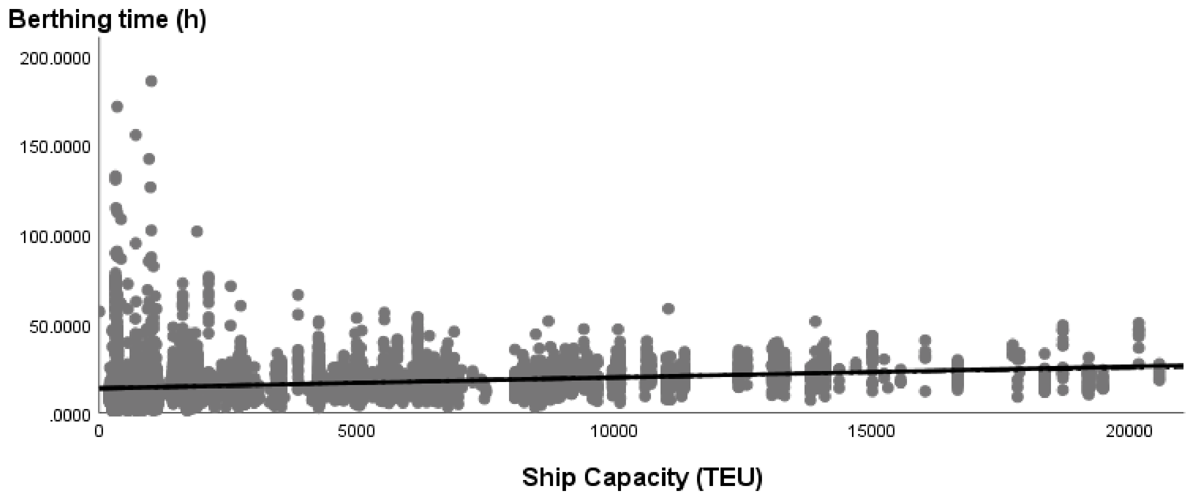

Figure 3- 4 The distribution of berthing time and ship capacity in Busan Port

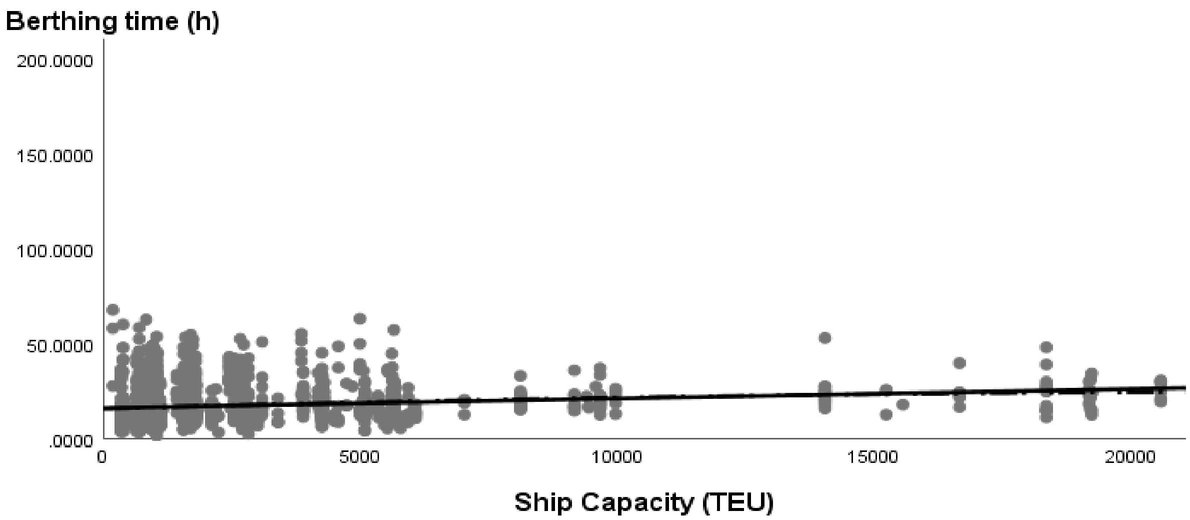

Figure 3- 5 The distribution of berthing time and ship capacity in Dalian Port

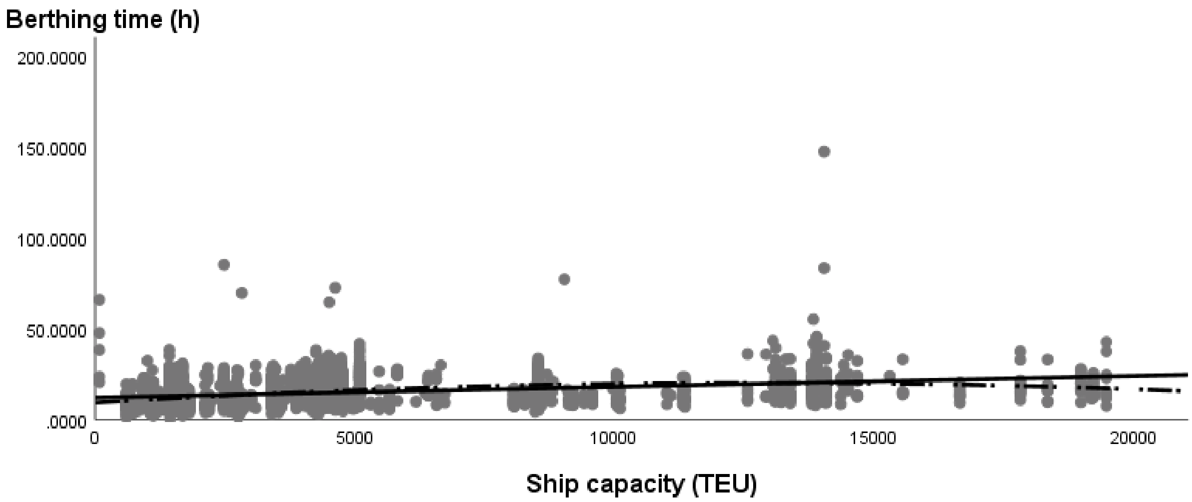

Figure 3- 6 The distribution of berthing time and ship capacity in Guangzhou Port

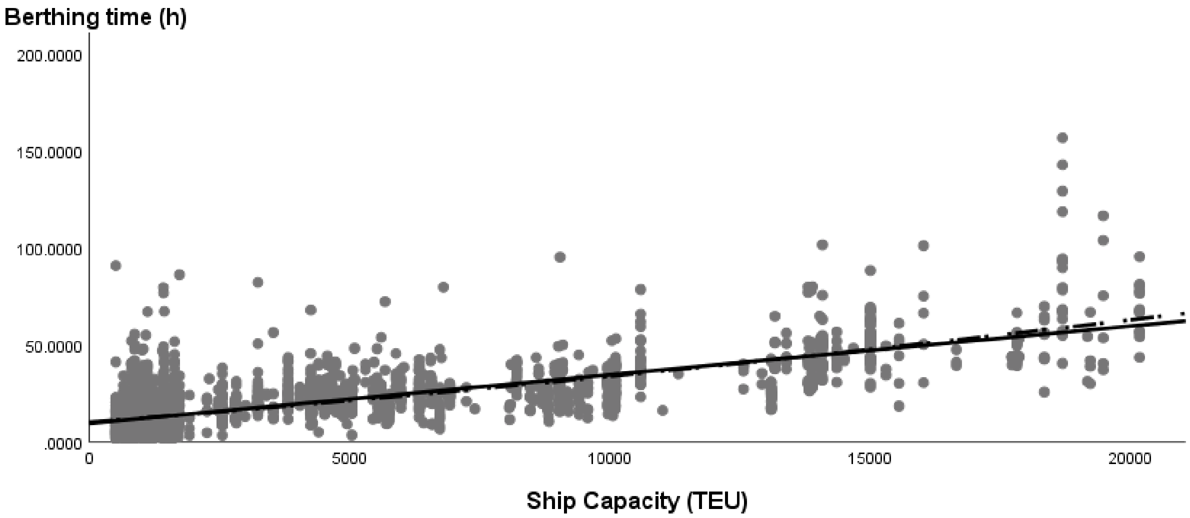

Figure 3- 7 The distribution of berthing time and ship capacity in Hamburg Port

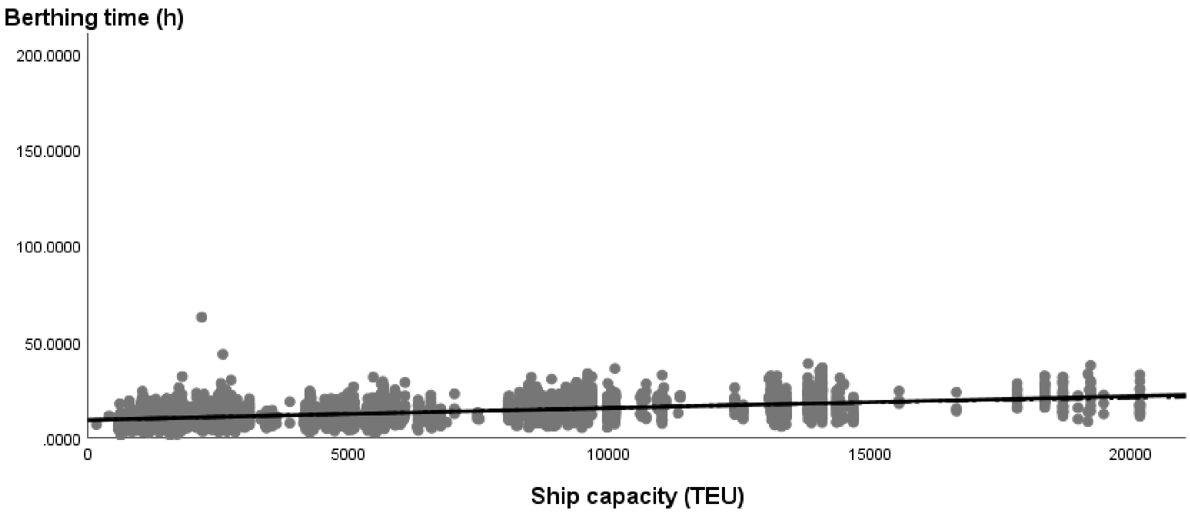

Figure 3- 8 The distribution of berthing time and ship capacity in Hong Kong Port

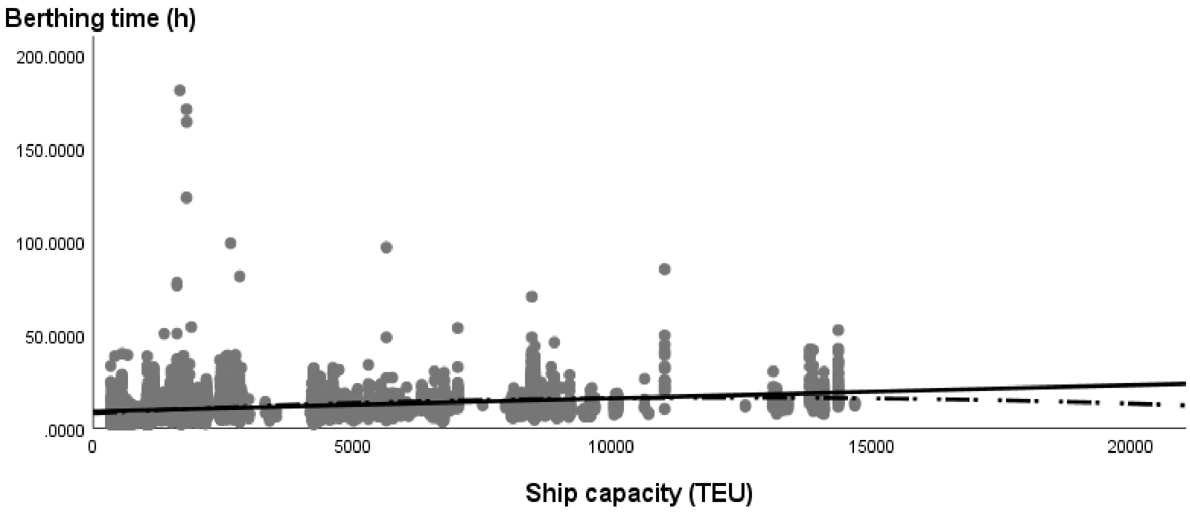

Figure 3- 9 The distribution of berthing time and ship capacity in Kaohsiung Port

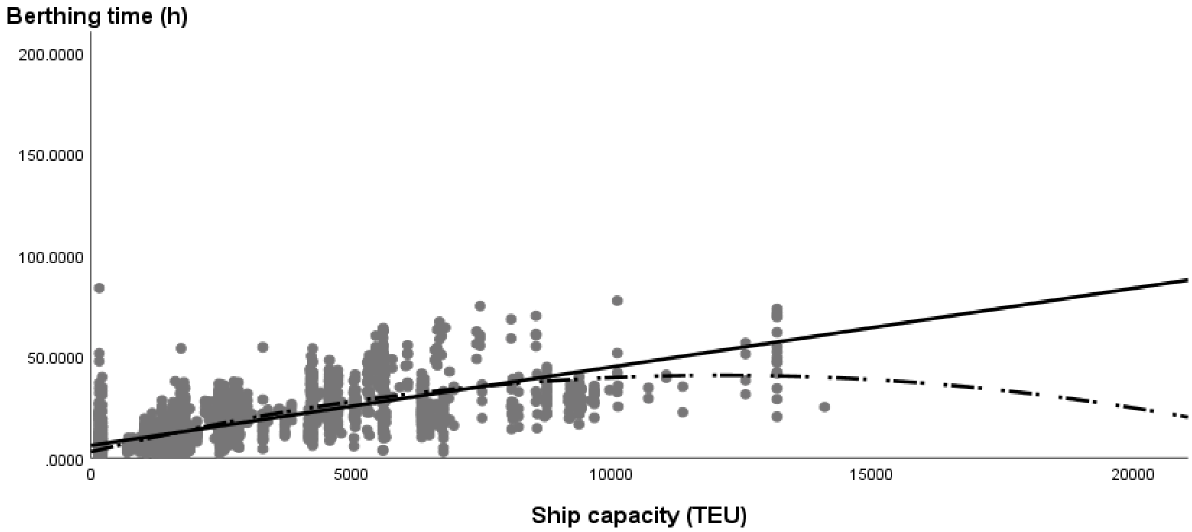

Figure 3- 10 The distribution of berthing time and ship capacity in Laem Chabang Port

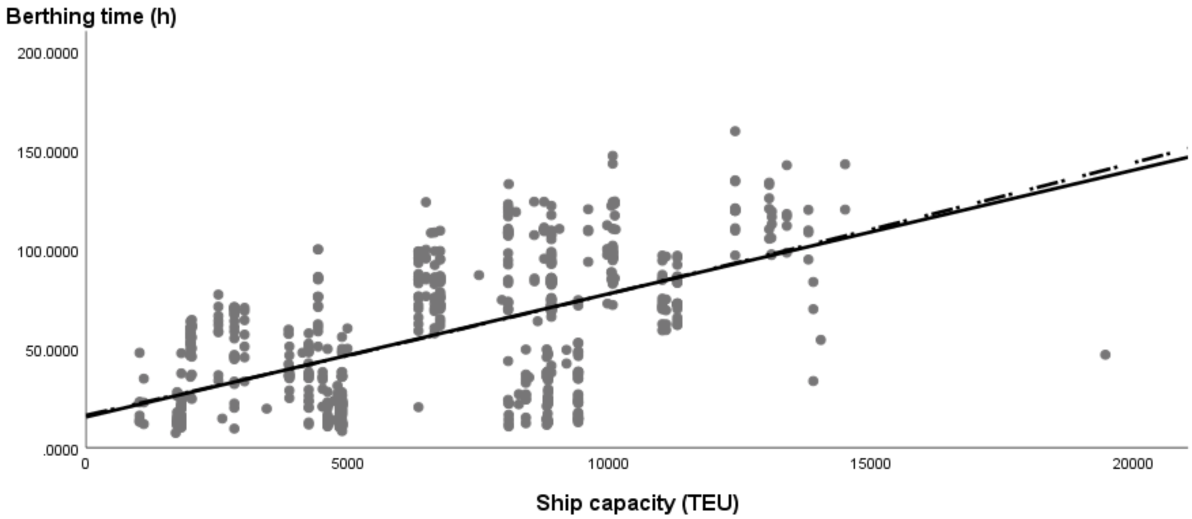

Figure 3- 11 The distribution of berthing time and ship capacity in Long Beach Port

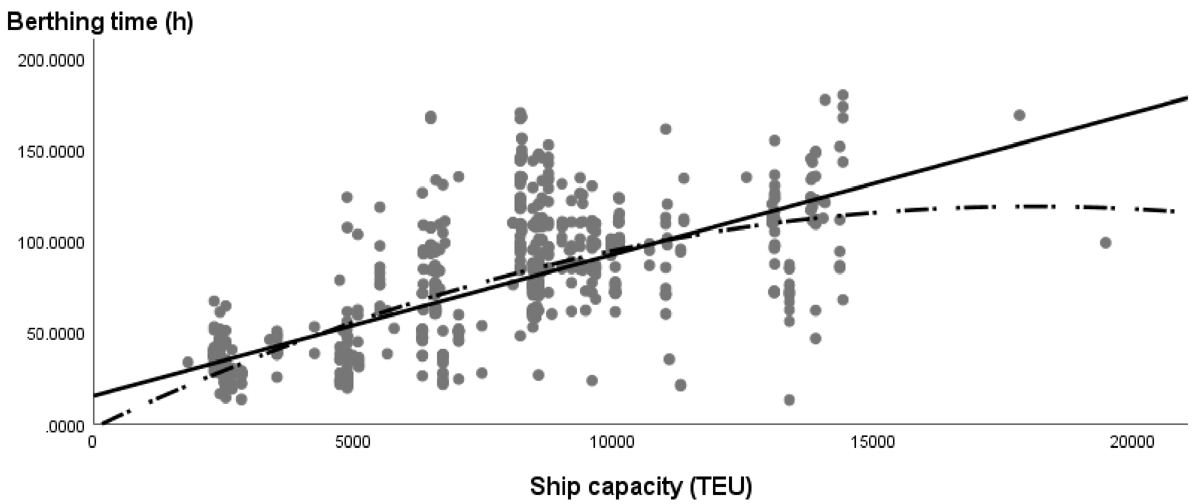

Figure 3- 12 The distribution of berthing time and ship capacity in Los Angeles Port

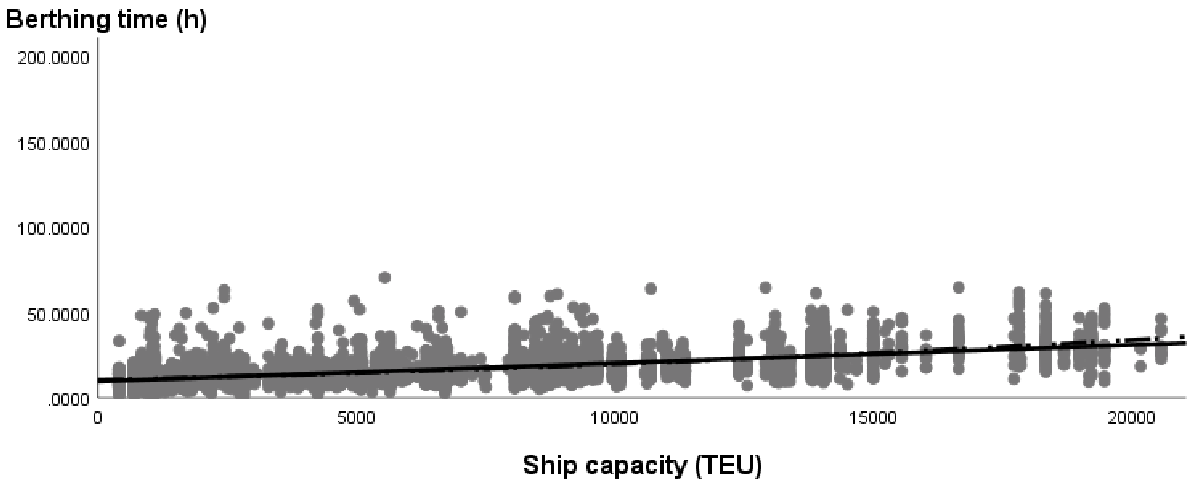

Figure 3- 13 The distribution of berthing time and ship capacity in Ningbo-Zhoushan Port

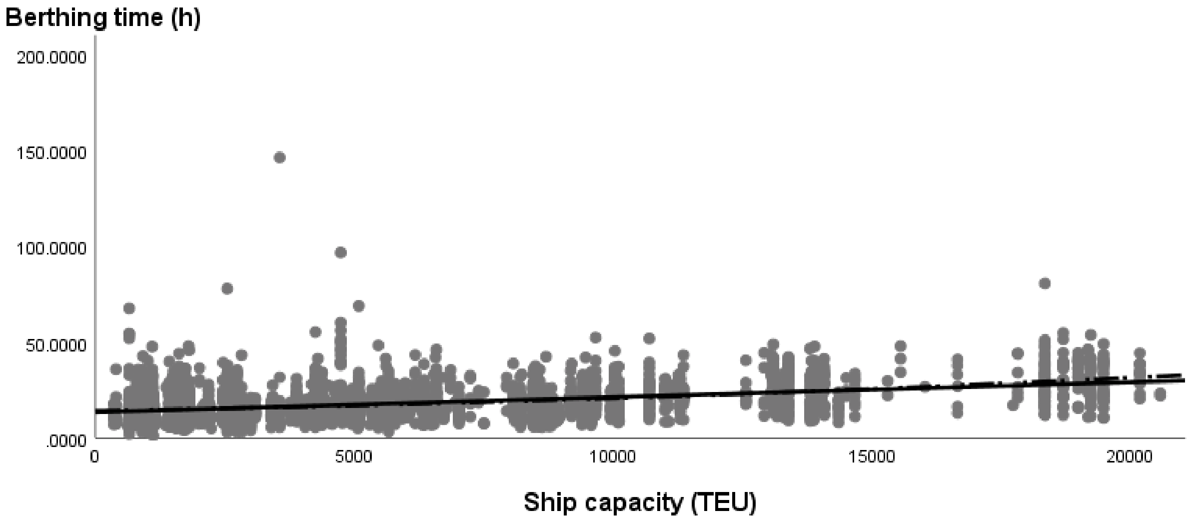

Figure 3- 14 The distribution of berthing time and ship capacity in Qingdao Port

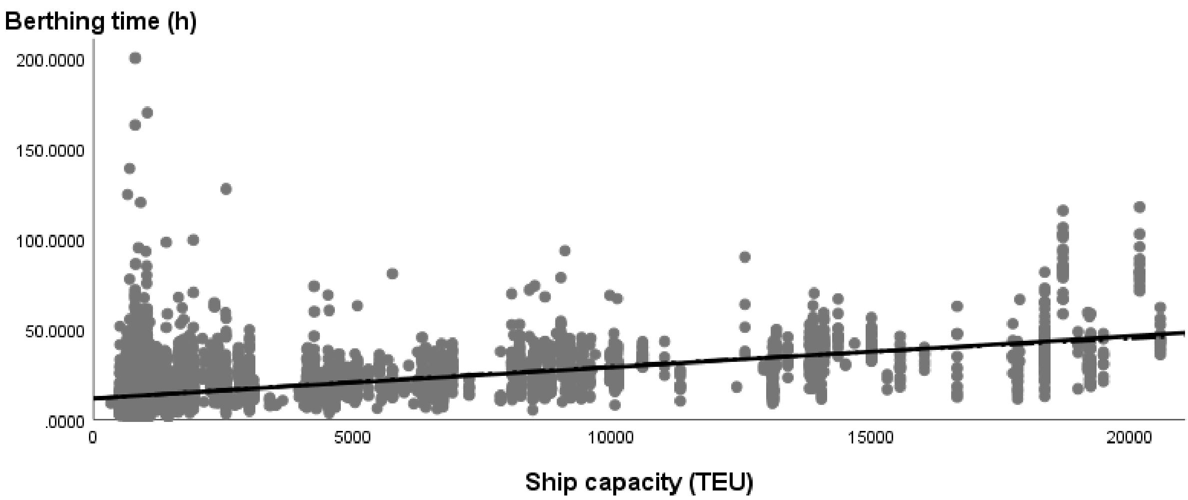

Figure 3- 15 The distribution of berthing time and ship capacity in Rotterdam Port

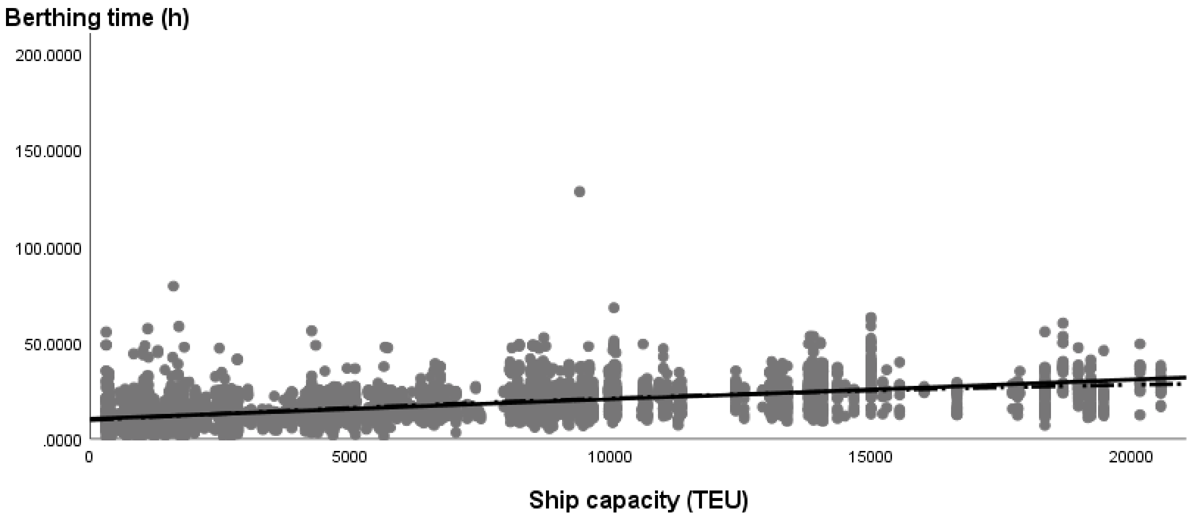

Figure 3- 16 The distribution of berthing time and ship capacity in Shanghai Port

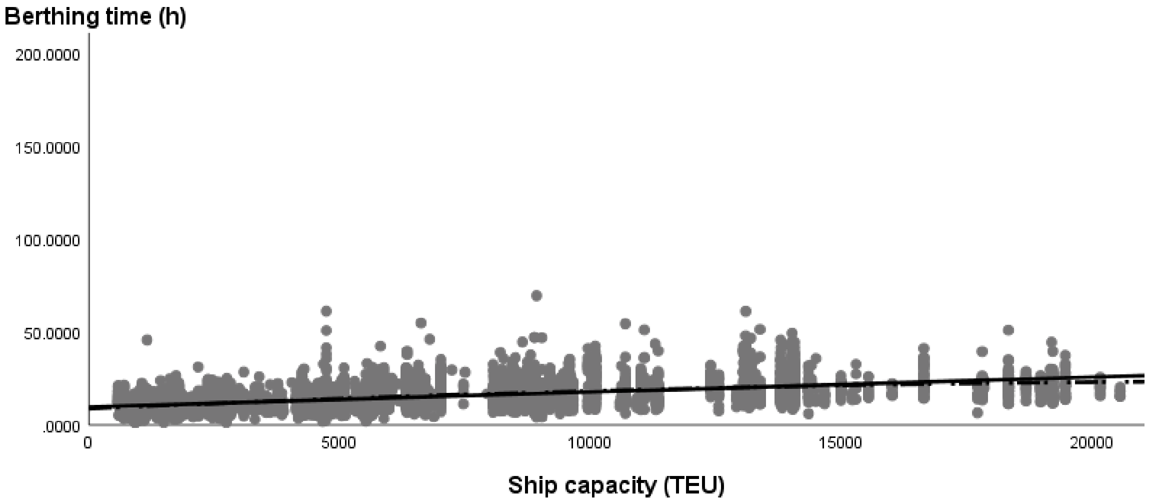

Figure 3- 17 The distribution of berthing time and ship capacity in Shenzhen Port

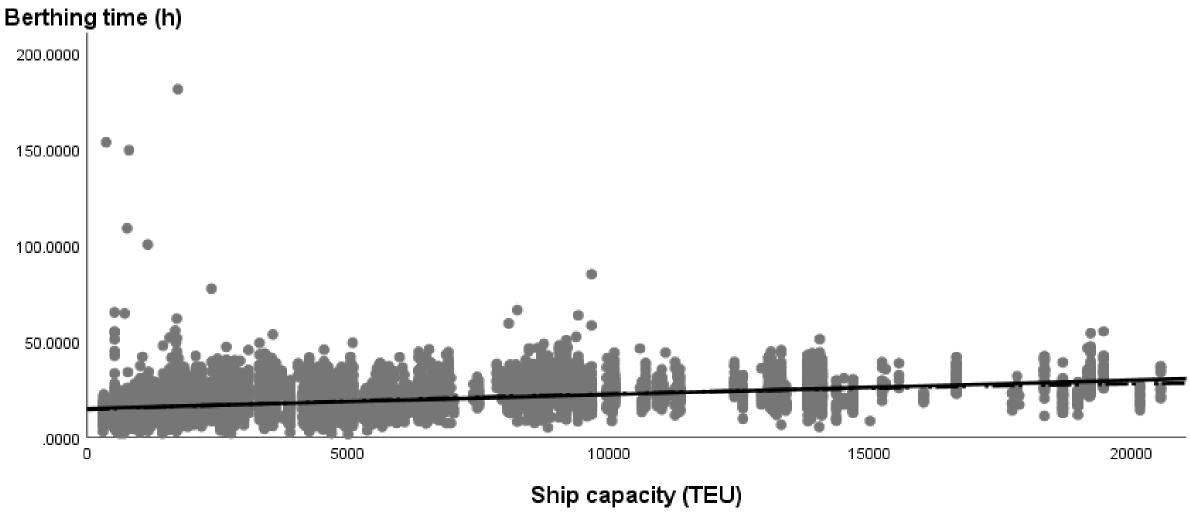

Figure 3- 18 The distribution of berthing time and ship capacity in Singapore Port

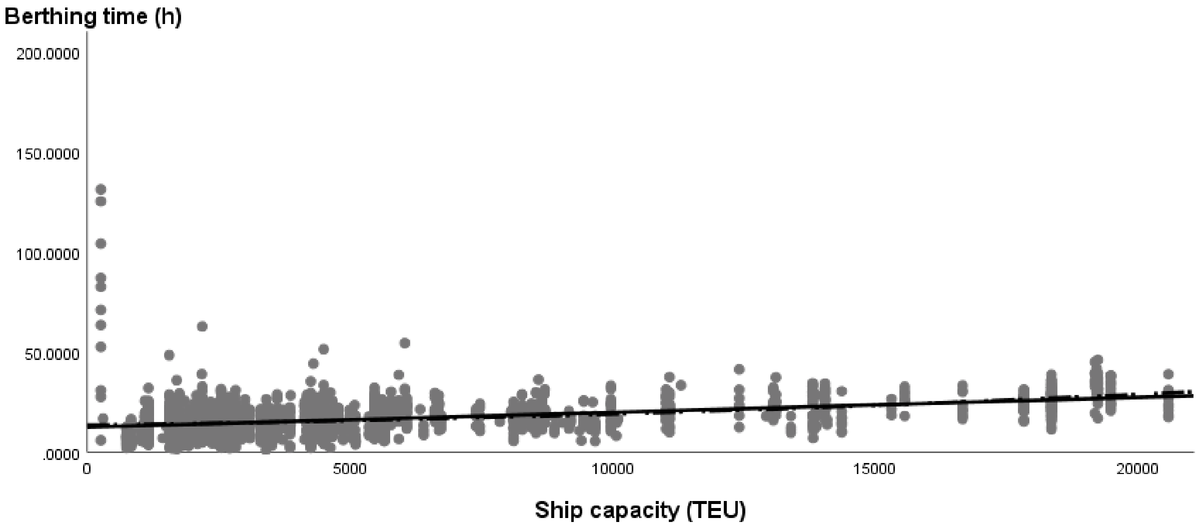

Figure 3- 19 The distribution of berthing time and ship capacity in Tanjung Pelepas Port

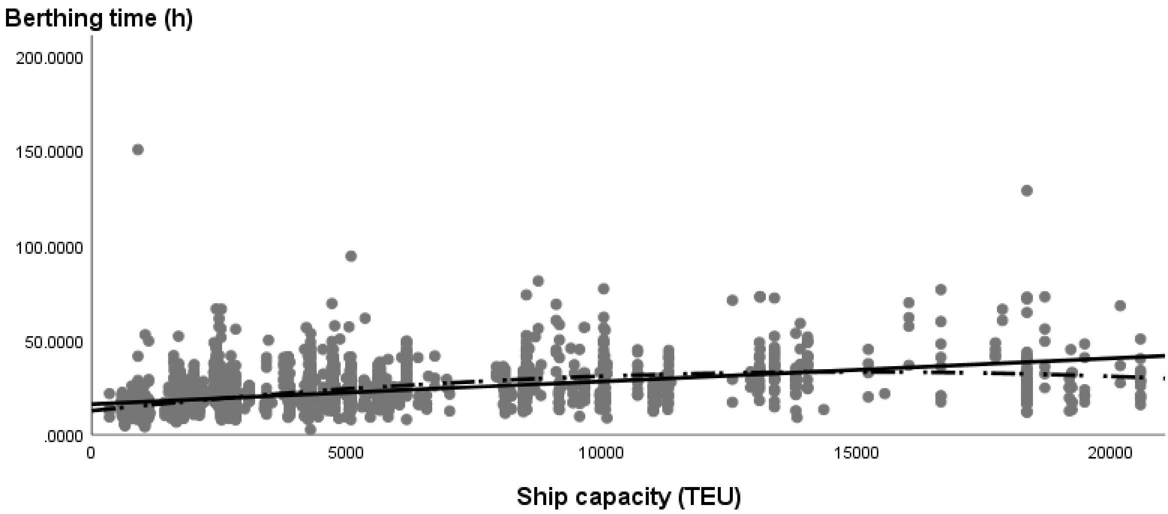

Figure 3- 20 The distribution of berthing time and ship capacity in Tianjin Port

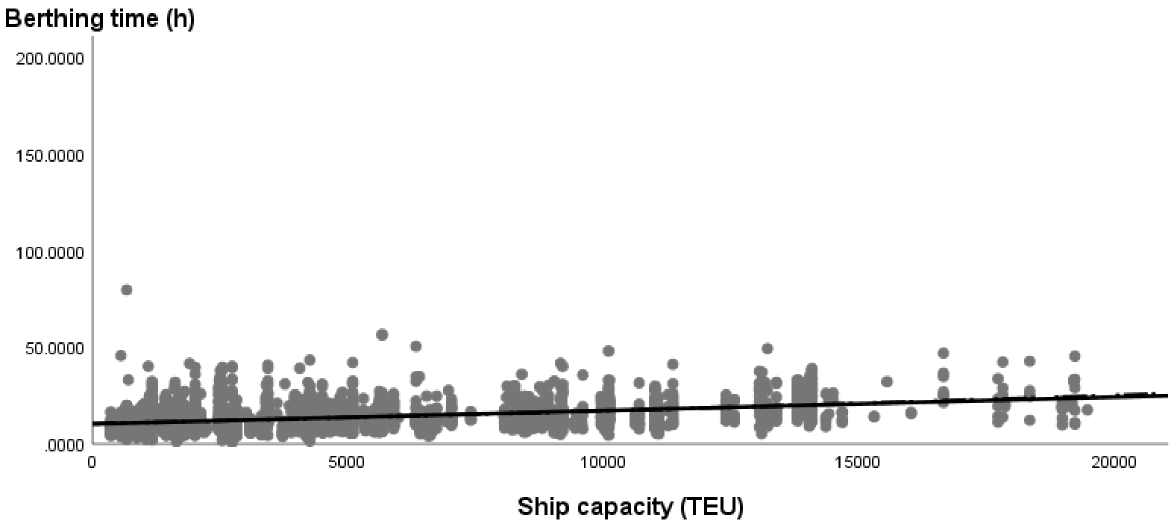

Figure 3- 21 The distribution of berthing time and ship capacity in Xiamen Port

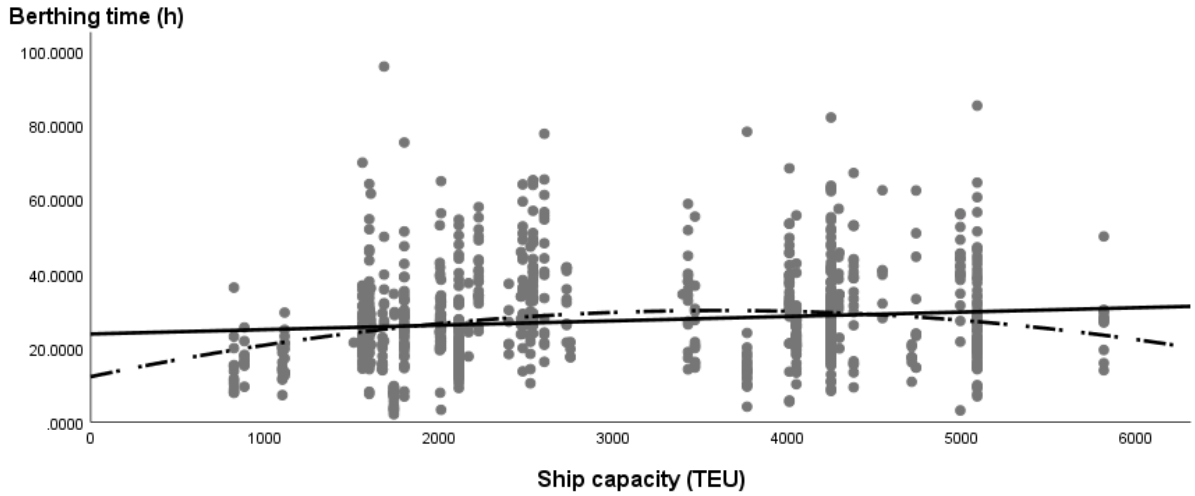

Figure 3- 22 The distribution of berthing time and ship capacity in Yingkou Port

Based on the average berthing time of ship calls in each selected port, it can be found that the Asian ports, representing by Kaohsiung Port, Hong Kong Port, Xiamen Port, Shenzhen Port, and Guangzhou Port, are time-saving ports with the range of 10-15 hours of berthing time for each ship call. But the North American ports, representing by the port of Long Beach and Los Angeles are time-consuming. The ship may need to spend more than 50 hours for a port call.

The differences in berthing time of these ports may contribute to the different working patterns. For example, the berths in Asian ports are generally working 168 hours a week. But in the Port of Los Angeles and Port of Long Beach, the berths work 16 hours a day, which means only 112 hours a week, and the terminal gates only work 88 hours a week (JOC, 2021). Besides, the differences in berthing time may also cause by the function and the role of ports in the shipping service network. For example, the hub ports in America are Los Angeles and Long Beach, but the hub ports in Asia include Busan, Shanghai, Ningbo-Zhoushan, Guangzhou, Shenzhen, Hong Kong, Singapore, etc. The multiple choices of Asia hub port will lead to the diversion of cargo, so as to the less amount of handled container and less berthing time of each ship call in Asia port.

To further analyze the relationship between ship capacity and berthing time, this research categorized ship capacity into five groups: 0-4999 TEU, 5000-9999TEU, 10000-14999TEU, 15000-19999TEU, and on or above 20000 TEU. The average berthing time for each ship capacity group in each port is stated in Table 3-4. It can be found that larger ship generally needs a longer time to berth although the increase of berthing time for different ship capacity categories are not consistent. This suggested that the relationship between ship capacity and berthing time may be positive but not so linear. To test this phenomenon, we run a quadratic model as Model 2 in the third stage.

Table 3- 4 Average berthing time in each port categorizing by ship capacity

(unit: hour)

Port	Ship capacity category (,000 TEU)				
	0~5	5-10	10-15	15-20	>20
Antwerp	19.7414	28.4232	34.1804	35.5590	-
Busan	14.7052	17.9904	22.3910	23.0633	33.3426
Dalian	16.8953	18.1664	24.8737	23.5233	25.9198
Guangzhou	13.9683	17.2536	20.0240	18.1889	-
Hamburg	13.6161	25.7714	37.9360	56.3251	68.5893
HongKong	10.7855	14.4188	16.8553	21.3094	18.1712
Kaohsiung	10.2667	14.2969	16.9390	-	-
Laem Chabang	13.0680	32.7568	44.8161	-	-
Long Beach	32.1491	68.2879	96.0347	46.9433	-
Los Angeles	33.4386	84.2256	100.2700	133.9101	-
Ningbo-Zhoushan	11.9541	17.0545	22.3528	30.5200	29.6349
Qingdao	15.3943	17.9939	23.7988	29.8417	31.5504
Rotterdam	13.8175	25.3795	32.1360	39.8702	60.0844
Shanghai	12.1312	18.6528	23.4400	26.2011	31.4582
Shenzhen	11.4520	15.9641	21.0487	21.0984	21.5061
Singapore	16.7254	20.7104	24.3603	28.1194	22.6489
Tanjung Pelepas	14.6602	17.1854	22.0750	26.9187	26.8648
Tianjin	18.8242	26.1193	30.5451	33.5099	31.6931
Xiamen	11.7425	14.5509	19.0564	23.2592	20.4433
Yingkou	27.5995	27.2474	-	-	-

Note: - represents no ship call has been extracted in the category.

3.3.2 Port efficiency scores

In the second stage, the technical and scale efficiency score of selected ports based on DEA methods is measured. The technical efficiency score and scale efficiency score of these 20 ports can be found in Table 3-5.

Table 3- 5 Efficiency scores of selected ports based on DEA methods

	CRS-TechE	VRS-TechE	VRS-ScalE
Antwerp	0.3710	0.9450	0.3920
Busan	0.7850	1	0.7850
Dalian	0.8920	1	0.8920
Guangzhou	1	1	1
Hamburg	0.4430	1	0.4430
Hong Kong	1	1	1
Kaohsiuing	0.6990	1	0.6990
Laem Chabang	1	1	1
Long Beach	0.6860	0.9510	0.7210
Los Angeles	0.5530	0.9600	0.5760
Ningbo-Zhoushan	0.9230	0.9750	0.9470
Qingdao	0.9840	1	0.9840
Rotterdam	0.4150	0.6620	0.6270
Shanghai	1	1	1
Shenzhen	0.7980	1	0.7890
Singapore	1	1	1
Tanjung Pelepas	0.9980	1	0.9980
Tianjin	0.7660	0.7930	0.9910
Xiamen	0.5870	0.9320	0.6300
Yingkou	1	1	1
Mean	0.7950	0.9600	0.8240

According to the result by DEA methods, it can be found that the ranking of ports from technical efficiency score and scale efficiency score is similar. Asian ports, such as Guangzhou Port, Hong Kong Port, Shanghai Port, Singapore Port, and Yingkou Port are the efficient ports, while the European ports, such as Antwerp Port and Hamburg port are the inefficient ports. The efficient ports with technical and scale efficiency scores equal to 1, have achieved the maximal throughput and may have congestion issues without the increase of inputs. But for the inefficient ports whose technical and scale efficiency score is less than 1, they have not fully used their capacity.

In practice, the utilization of port container handling capacity, referring to the ratio of port actual container throughput to port designed container handling capacity, is used to determine whether the productivity of port is fully used. Considering this indicator, we also found a consistent in the distribution of port container handling capacity utilization and that of port scale efficiency score (Figure 3-4). The main reason for this consistent is that both scale efficiency score and port container handling capacity utilization are calculated based on an input-output ratio. As mentioned before, the DEA methods are linear programs based on the ratio of inputs to outputs and the port container handling capacity utilization is obtained from the ratio of port throughput to port container handling capacity. Port container handling capacity can be considered as a combination of port inputs although there is no correlation between the port inputs used in this research.

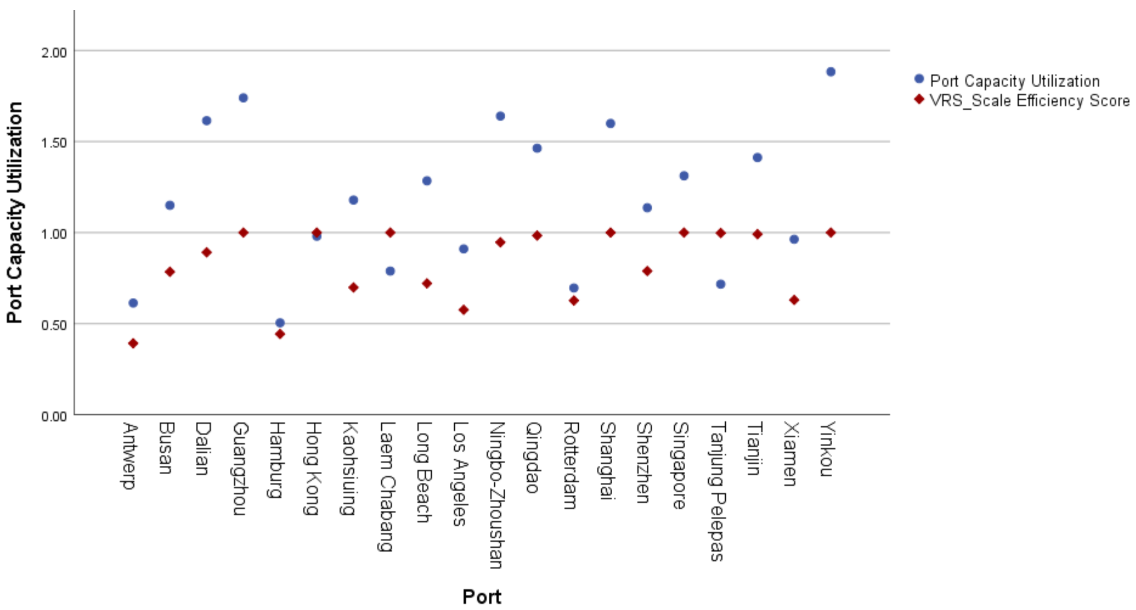

Figure 3- 23 The distribution of port capacity utilization and scale efficiency scores

3.3.3 The important factors on berthing time

In the third stage, we run regression models based on Equation (3-8), (3-9), and (3-10). The results of regression models are stated in Table 3-6.

Table 3- 6 Results of regression models

		Model 1 Linear model for ship capacity		Model 2 Quadratic model for ship capacity		Model 3 20 dummy variables for each port	
		Coefficients	Std. Error	Coefficients	Std. Error	Coefficients	Std. Error
Constant		-10.082***	0.366	-11.077***	0.367	-	-
Port	-Antwerp	-	-	-	-	0.124***	0.170
	-Busan	-	-	-	-	0.178***	0.095
	-Dalian	-	-	-	-	0.099***	0.191
	-Guangzhou	-	-	-	-	0.093***	0.158
	-Hamburg	-	-	-	-	0.111***	0.149
	-Hong Kong	-	-	-	-	0.109***	0.110
	-Kaohsiung	-	-	-	-	0.091***	0.106
	-Laem Chabang	-	-	-	-	0.115***	0.156
	-Long Beach	-	-	-	-	0.194***	0.325
	-Los Angeles	-	-	-	-	0.249***	0.324
	-NingboZhoushan	-	-	-	-	0.130***	0.113
	-Qingdao	-	-	-	-	0.137***	0.133
	-Rotterdam	-	-	-	-	0.169***	0.100
	-Shanghai	-	-	-	-	0.175***	0.093
	-Shenzhen	-	-	-	-	0.099***	0.108
	-Singapore	-	-	-	-	0.231***	0.105
	-Tanjung Pelepas	-	-	-	-	0.090***	0.178
	-Tianjin	-	-	-	-	0.138***	0.172
	-Xiamen	-	-	-	-	0.062***	0.150
	-Yingkou	-	-	-	-	0.115***	0.280
Ship capacity		1.019***	0.000	1.206***	0.000	0.780***	0.000
$\boldsymbol{Ship\ capacity^2}$		-	-	-0.224***	0.000	-0.055***	0.000
Port scale efficiency		0.362***	0.417	0.358***	0.416	-	-
Port market share		1.055***	1.924	1.087***	1.922	-	-
Peak-season or off-season		0.009**	0.061	0.009**	0.061	0.004**	0.052
Ship capacity and port scale efficiency		-0.787***	0.000	-0.754***	0.000	-0.435***	0.000
Ship capacity and port market share		0.180***	0.000	0.173***	0.000	0.019***	0.000
Port scale efficiency and market share		-1.043***	2.206	-1.071***	2.202	-	-
R square		0.246		0.251		0.814	

Note: ** represents 5% significant; *** represents 1% significant

First, we consider the linear regression model with the explanatory variable of ship capacity, port scale efficiency score, port regional market share, peak season, and the interaction items. The results are represented under Model 1 in Table 3-6. It suggests that ship capacity, port scale efficiency score, and port market share have positive main effects on berthing time. And the interaction effects of these three factors are also significant at 1 percent level.

Ship capacity has a large main positive effect on berthing time. For each unit (TEU) increase of ship capacity, the berthing time will increase by 1.019 hours. But this main effect of ship capacity on berthing time is influenced by the port scale efficiency score and port market share. The interaction effect of port scale efficiency score and market share on ship capacity is stated in Equation (3-11).

$$\frac{\partial BT_{ij}}{\partial S_i} = \beta_1 + \beta_5 E_j + \beta_6 M_j = 1.019 - 0.787 E_j + 0.180 M_j \qquad (3\text{-}11)$$

For a ship with the same capacity, the port with higher scale efficiency provides a shorter berthing time, while the port with more market share will hold a longer berthing time. The port with a higher scale efficiency score means it can handle more containers with given equipment and labor. Thus, for the same volume of containers, a port with higher scale efficiency needs less working time. But for the port with a large market share, the volume of containers in port to be handled is huge and the operation of the container handling process may be congested. And the port with a higher market share has strong bargaining power in the market, may put less attention on users' perception. Both the congestion of port operation and less attention on users' interests will lead to longer berthing time of the ship.

Port scale efficiency score shows an overall negative effect on berthing time. Although the port scale efficiency score has a positive main effect on berthing time at 0.362, it should be noticed that the port scale efficiency is a variable in the range of 0-1 and the ship capacity is a variable in the range of 200-22000, the positive effect can be largely affected by the interact effect of ship capacity (-0.787). Besides, the market share also has a negative interact effect on port scale efficiency at -1.043. Higher market share refers to a large container throughput, which is the output in port scale efficiency measurement. For the port having the same scale efficiency score, the input and output ratios are the same. Thus, a higher market share for ports with the same scale efficiency score refers to a higher handling capacity of the port, which will decrease the handling time for ships.

$$\frac{\partial BT_{ij}}{\partial E_j} = \beta_2 + \beta_5 S_i + \beta_7 M_j = 0.362 - 0.787 S_i - 1.043 M_j \qquad (3\text{-}12)$$

Peak season is another influencing factor on ships' berthing time in port. In peak season, the berthing time of the ship will longer than that in the off-season for 0.009 hours. As this research measures the peak season by monthly throughput data, it is hard to reflect the most peak time of ports when congestion occurs. But this result suggests that the more ships calls and container throughputs in peak season, the larger berthing time is needed for a ship call.

Secondly, we consider a quadratic model on the variable of ship capacity. The results show in Model 2 of Table 3-6. It can be found that the coefficient for a linear item of ship capacity is positive but for the quadratic item is negative. And Model 2 has an increase in R square by 0.05 over Model 1, which suggested that the quadratic model may fit the relationship between ship capacity and berthing time better. For some large ships in ports, although the volume of containers they carried is more than that carried by small ships, they may just handle part of carried containers in each ship call.

Lastly, we considered the alternative specific impact of each port. Without constant items in Model 3, each port is represented by a dummy variable and stands for a component of berthing time. In ports with smaller coefficients, such as Tianjin port and Tanjung Pelepas port, the ship with a certain capacity may spend less berthing time than in the port with a larger coefficient. It can be also found that the coefficients of other explanatory variables are still significant and similar to the results of Model 1. And considering each port's effect, the R square of Model 3 increases to 0.814, which implies that Model 3 can better explain the relationship between factors and berthing time.

3.4 Chapter conclusion

This chapter proposed the method to extract ships' berthing time in port from AIS data and study the factors on ships' berthing time and their impacts. The empirical relationship of berthing time with ship attributes, port attributes, including the scale efficiency score calculated by DEA methods is explored.

The empirical results of this research show that when measuring berthing time from ships' perspectives, Kaohsiung Port, Hong Kong Port, Xiamen Port, Shenzhen Port, and Guangzhou Port are efficient for time-saving and American ports, including Los Angeles and Long Beach are inefficient for time-consuming. When measuring port efficiency from port's perspective by traditional DEA methods, Guangzhou port, Laem Chabang port, Shanghai port, Singapore port and Yingkou port are efficient and European ports, represented by the port of Antwerp, Hamburg, and Rotterdam are inefficient. The rankings of ports by these two measurements are not consistent.

Moreover, there are some interesting findings in this research. Firstly, we find that ship's capacity, which can stand for the container handling volume of each ship call, has a significant positive impact on berthing time. The larger ship may need longer berthing time as there are more containers to be handled in the port. But the impact of ship capacity on berthing time can be reduced by the increase of port scale efficiency and be enhanced by the increase of port market share.

Secondly, the port scale efficiency score has an overall negative impact on berthing time when considering the ship operated in port and the market share of the port, which suggested that the scale efficient port may provide shorter berthing time. Besides, we also found that the increase of market share and the port in peak season will lead to longer berthing time. These empirical results imply that the scale efficiency of the port is not equal to the short turnaround time for ships. Ship attributes play an important role in the berthing time, which should be considered by different shipping companies and port operators in schedule arrangement and operation.

To enhance the competitiveness of port and attract more ship calls, port authorities, port operators, and policymakers should consider shipping companies' interests and make a more appropriate method to evaluate port efficiency and arrange port production. In the scale efficient port with a large number of ship calls, port authorities and operators could invest more facilities or arrange more cranes or labor in deep-water berths to speed up the load/unload operation of large ships, so as to reduce the overall turnaround time of ships. In the scale inefficient port which has not achieved maximal throughputs, port operators should improve the working rate of the berth so as to increase the scale efficiency and reduce the time ship spend in port. It should be noticed that port authorities and operators should not only focus on the increase of port market share or productivity. The increase of market share may lead to the decrease of efficiency and the growth of berthing time, and subsequently more congestions in port and less ship arrangement of shipping companies in the future. Thus, considering the shipping companies' interests and ships' time in port is essential in practice.

Chapter 4 Contributions and Limitations

4.1 Conclusions

In this thesis, we analyzed port efficiency from different perspectives and measured port efficiency incorporating AIS data. This research attempts to answer three questions: how to understand port efficiency from different perspectives, how to measure the port efficiency incorporating AIS data, and what affects ship's time in port?

The first part of this research reviewed 213 articles in port efficiency analysis and found that the majority of studies measured port efficiency only from port's perspective, the research from users' perspective is relatively few. There is a lack of balance between the interests of users and that of ports in the port efficiency analysis. In terms of methods, DEA (Data Envelopment Analysis) and SFA (Stochastic Frontier Analysis) methods are the most common methods adopted by literature to analyze port efficiency from port perspectives. With the increase of congestion events and the changing of port trade, more ports and shipping companies concern the real-time changes in a specific port. But due to the accessibility and measurability of real-time data, there are limitations for existed studies to identify the real-time changes in port efficiency analysis. Moreover, we summarized the major factors in port efficiency analysis. It has been found that some latest developments in port operation, such as the automated facilities and the benefits of port workers, are not considered in existing studies.

The second part of this research proposed a method to extract ships' berthing time from AIS data and study the factors on ships' berthing time and their impacts. The empirical results show that larger ships may need longer berthing time and the port scale efficiency score has an overall negative impact on berthing time when considering the ship operated in port and the market share of the port. Besides, we also found that the increase of market share and the port in peak season will lead to longer berthing time. These empirical results imply that the scale efficiency of the port is not equal to the short turnaround time for ships. Ship attributes play an important role in the berthing time, which should be considered by different shipping companies and port operators in schedule arrangement and operation.

4.2 Contributions

This thesis contributes to the research on port efficiency in several ways.

The first part of this thesis provides a comprehensive and up-to-date review with an emphasis on both interests and needs of ports and users in port efficiency analysis. It has been well recognized that the efficiency measurement is critically important for the port sector, which could provide information for port managers to improve port performance and support users to optimize their shipment schedule. However, the lack of research from both port's perspective and users' perspective is rarely noticed by the previous studies. This research emphasizes the interests of both ports and users in port efficiency analysis, providing a more comprehensive understanding of port efficiency analysis. Besides, with the discussion of limitations, the review of existing studies can contribute to future researchers in the analysis perspective, the selection of methods, and the exploring of influencing factors.

The second part of this research provides a novel method to extract ships' berthing time in port from AIS data. By using AIS data, the time ship spends in port can be calculated and estimated. This research also correlates the traditional port efficiency analysis with the berthing time of ships by empirical regression models. The results suggest that the scale efficiency does not mean a short turnaround time for ships. Considering shipping companies' interests and port competitiveness, port authorities, port operators and policymakers should make a more appropriate method to evaluate port efficiency.

4.3 Limitation and future studies

Firstly, this thesis uses the berthing time of ships to reflect the ships' time in port. The waiting time of ships in port has not been extracted and considered in this research. However, the TAT of a ship in a port, including both berthing time and waiting time. The analysis of port efficiency from ships' time metrics can be extended with deeper mining of AIS data.

Secondly, this research considered only several attributes of ships and ports when exploring the factors and their impact on berthing time. Some factors related to port and ship have not been captured and analyzed in this research. And the regression models have been examined by a large amount of AIS data. The factors may only have minor impacts on berthing time but show high significance in regression analysis. Using a large amount of dataset, the machine learning method can be considered and used in future studies to identify the factors and their impacts.

Finally, this thesis measured the port efficiency from the port perspective and the users' perspective separately. The question of how to balance users' interests and ports' interests in port efficiency is not answered. Considering both the interests of ports and users, comprehensively measuring port efficiency should be considered in the future.

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