The Role of Reliability in Container Shipping Networks

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Abstract

Container transportation has a pivotal role in global supply chains and thus the quality of high reliability container shipping services is of critical importance. The literature shows that the word “reliability” has often appeared in different aspects of maritime transportation, accompanied by a variety of interpretations. Few studies have investigated reliability in container shipping networks in any systematic way. Therefore, this research seeks to address this gap by providing a detailed understanding of such reliability and a comprehensive approach to assess it, and investigates four research questions: (RQ1) How is reliability best understood in the context of container shipping networks? (RQ2) What factors influence the network reliability? (RQ3) How can the impact of these factors on container shipping networks be measured? (RQ4) Would there be a more comprehensive approach to assess the reliability?

A mixed-methods approach was adopted comprising: (i) a systematic literature review and semi-structured interviews which contribute to the elaboration of a holistic definition of reliability, encompassing different influencing factors; (ii) a review and classification of existing metrics and measuring methods across a variety of fields; and (iii) network analysis and simulation of the shipping network between Asia and Europe to assess the network reliability. The selected network comprises 115 strings operated by five shipping companies, among which 89 nodes from 38 countries are involved. More specifically, the AIS data of 86 ships within the network in the period of 1 November 2021 – 31 January 2022 was captured to analyse the network performance. This necessitated observing the different AIS position and movement signals of each of the 86 sample ships every day over the three-month period. As well as detailing specific characteristics of the selected network, the research led to the development of a systematic framework comprising three themes (infrastructure reliability, network configuration reliability, and connectivity reliability) for understanding reliability in the context of container shipping networks. The output of the research contributes to helping stakeholders identify – for any container shipping network – the key nodes and links, sources of risks and vulnerable elements, and then decide what actions are necessary to avoid and mitigate disruptions, and to ensure networks become more resilient.

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List of Abbreviations

AIS	Automatic Identification System
APL	American President Lines
APL	Average Path Length
ATB	Actual Berth
CASP	Critical Appraisal Skills Program
CAx	Container Availability index
CMA CGM	Compagnie Maritime d'Affrètement - Compagnie Générale Maritime
CO_2	Carbon dioxide
COFCO	China Oil and Foodstuffs Corporation
COSCO	China Ocean Shipping Company
COVID	Coronavirus Disease
CPCI	Container Port Connectivity Index
CSN	Container Shipping Network
ETB	Estimate Berth
GCSP	Global Carrier Schedule Performance index
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLP	Global Liner Performance
GTCDIT	Global Transport Costs Dataset for International Trade
HITS	Hyperlink Induced Topic Search
IMO	International Maritime Organization
ITF	International Transport Forum
LPI	Logistics Performance Index
LSCI	Liner Shipping Connectivity Index
MSC	Mediterranean Shipping Company
OD	Origin-Destination
PCSN	Performance Container Shipping Network
PLSCI	Port Liner Shipping Connectivity Index
RQ	Research Question
SD	Standard Deviation
SLR	Systematic Literature Review
TEU	Twenty-Foot Equivalent Unit
UNCTAD	United Nations Conference on Trade and Development

Chapter 1. Introduction

1.1 Introduction

The purpose of this research project is to understand what reliability in the context of container shipping (i.e., liner) networks means, what are the influencing factors and how can such reliability be measured. It provides a comprehensive analysis of different perspectives of reliability in the context of container shipping networks. This chapter provides an overview of the thesis.

1.2 Background to the research

Container transportation has contributed significantly to the development of international trade and global supply chain and now accounts for more than 60% of world seaborne trade value, by means of its unique convenience, reliability and safety. Figure 1.1 illustrates the remarkable growth in container TEUs that took place since the mid-1990s. Despite the decrease in maritime trade caused by the impact of COVID-19, the container trade volume was not significantly affected, and it rebounded by the end of 2020 (UNCTAD, 2021). The large scale of container shipping contributes significantly to the development of international trade and global supply chains (Feng *et al.*, 2020). At the same time, the competition of managing global container distribution and the complexity of making profit and providing reliable service in the international market increased. Container transportation plays a pivotal role in global supply chains and thus, the quality of high reliability container shipping services is of critical importance.

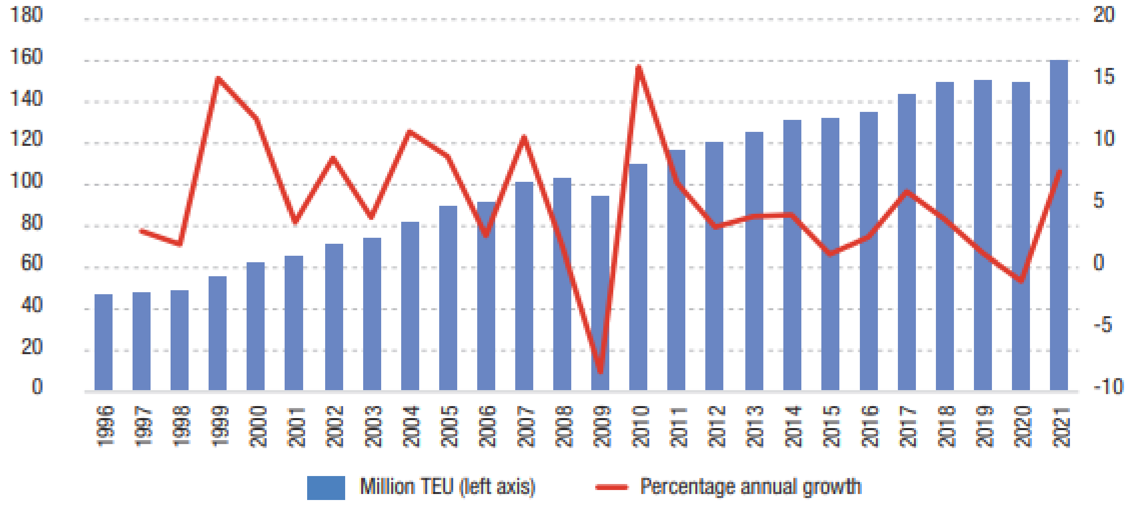

Figure 1.1: Global container trade since 1996-2021 (million TEU and percentage annual change) (Source: UNCTAD, 2021)

However, container shipping is sensitive to many influencing factors and unexpected disruptions. A wide range of barriers still persist – thus, reducing its reliability – the most obvious being the recent impact of the Covid-19 pandemic. Each disruption triggers different ramifications and tests networks' vulnerability and resilience, the Covid-19 pandemic, in particular, presents new and unprecedented impacts on global container shipping networks and the port industry (Zhou *et al.*, 2022). For example, in May 2021, the port of Yantian in China, closed for a month due to the pandemic restrictions, with port congestion and container handling delays emerging. Port operations and supply chain management experienced interference to varying degrees. At the same time, liner companies cancelled port calls and certain services in severely affected areas, resulting in a diminished mobility of maritime trade and a consequential impact on global maritime freight flows. The Covid-19 pandemic presented challenges to established norms in various domains, such as the direction of trade flows, the stability of global financial institutions, sustainable economic growth and the efficacy of applied logistics concepts e.g. on-time rates.

The maritime sector also faces other disruptions, e.g., the blockage of the Suez Canal in March 2021 by the containership *Ever Given*, had a major impact on global freight flows. Meanwhile, as an important sign of container shipping reliability, containership schedule reliability dropped to 35.6% in July 2022, a massive 39.7% down compared with 2021 (75.3%), according to the analysis from Sea-Intelligence Maritime Analysis. It has been estimated that each additional day of delay before a shipment sails to its foreign destination will reduce the possibility of it being traded by 1% (6% when it is time-sensitive), and this reduces its value by 0.8% (Djankov *et al.*, 2010). Such delays also made trade movements erratic and unpredictable (Haralambides, 2019).

If the risk or disruption happens in one part of the container shipping network e.g., the port, it will lead to delay or cancellation of the shipping routes and the operation of containerised international trade will be affected, which will cause damage and additional costs to the stakeholders. Moreover, when disruption happens in one part of the container shipping network, it can have a knock-on effect elsewhere in the network. These influencing factors can significantly undermine the efficiency and overall reliability of the shipping network and supply chains. In this context, improving reliability is increasingly regarded as an important and fundamental topic in maritime transport, both to mitigate and overcome potential barriers and support the operation of transport networks (AbuAlhaol *et al.*, 2018).

1.3 Research purpose

Reliability has long been a question of great interest in a wide range of fields. According to the Oxford Dictionary, reliability refers to "the quality of being trustworthy or of performing consistently well". In the transport network field, Soza-Parra *et al.* (2019) defined reliability as the variability of service level when making the same trip on different days. More specifically, there is a framework agreed upon by many researchers for understanding reliability in the context of transport networks which is based on three domains: connectivity reliability, time reliability and capacity reliability (Sánchez-Silva *et al.*, 2005; Heydecker *et al.*, 2007; Chen *et al.*, 2011) – however, such categorisation cannot be applied directly to the shipping network, as it will become apparent in this research project, this framework is less applicable in the context of shipping networks.

The literature shows that the word "reliability" has often appeared in different aspects of maritime transportation, and it is explained by giving it a variety of meanings. The commercial indices that are currently used to analyse the reliability of container shipping networks are mainly focused on schedule reliability, e.g., the Global Liner Performance (GLP) report developed by Sea-Intelligence Maritime Analysis. Schedule reliability is one of the most widely used definitions for shipping companies and customers (Wu *et al.*, 2009; Tierney *et al.*, 2019), and it is also a key measure in transportation reliability analysis which has been widely studied in passenger transport. Another topic of increasing interest in the context of shipping reliability is from the perspective of network structure, which is concerned with investigating the failure of different components of the network related to infrastructure and operations (Stathopoulos and Tsekeris, 2003). Prabhu Gaonkar *et al.* (2011) has also shed light on network reliability, explaining reliability as the measure of safety within the maritime transportation system, taking into account risk, ambiguity and imprecision associated with its operations. Mokashi *et al.* (2002) defined reliability as the maintenance function of maritime transportation. Furthermore, some transport agendas also offer a different understanding of the concept of reliability. UNCTAD (2019) for example highlighted different aspects and interpretations of reliability in the context of container shipping, including reliable direct connections to foreign markets, infrastructure reliability, and reliable shipping services by enhancing the protection of ports, port efficiency, geopolitical flashpoints, trade protection, etc.

While various explanations and interpretations of reliability are provided in different fields, few studies have investigated reliability in any systematic way especially in the context of container shipping networks. This research project therefore set out to address this gap by providing a systematic understanding of reliability in the context of container shipping networks and comprehensive approaches to assessing it.

1.4 Research design

This research project focuses on understanding and assessing reliability in the context of container shipping networks. From the perspective of analysing shipping networks, the container shipping network is composed of nodes, which refer to ports, and links which refer to the shipping lines that directly connect each port as the geographic area (Barabasi, 2014; Ducruet, 2017). With the development of the global economy, integration of logistics services and advances in information technology, international container shipping is actually expanding its services from its core container maritime transportation to “door-to-door,” namely the supplier to consumer, embracing combined transport (Mukherjee and Brownrigg, 2013; Guerrero and Rodrigue, 2014; Paridaens and Notteboom, 2022; Gülmez *et al.,* 2023). Therefore, the term reliability in the context of container shipping networks in this research is regarded as **the quality of liner performance under uncertainty from consignor to consignee.**

According to the research gap identified in the systematic literature review (Chapter 2), the research problems addressed in this research project were defined as follows: little research is available on reliability in the context of container shipping networks, and the research about shipping network reliability mainly refers to one perspective of reliability. There is evidence in the literature that there are factors from different perspectives that affect the reliability of container shipping networks, and few studies have investigated reliability in any systematic and comprehensive way. There is indeed a need to provide a comprehensive analysis to explore the influencing factors of reliability in the context of container shipping networks and provide approaches that can assess reliability. In line with the research problems, two research objectives were stated: (1) to investigate the relationship between reliability and container shipping networks, and (2) to determine the best approach for comprehensively assessing the reliability of container shipping networks. Each research objective encompassed two research questions. Mixed methods were used to answer the research questions quantitatively and qualitatively. Table 1.1 summarises the research design.

Research Objective	Phase	Research Question	Methods	Chapter
To investigate the relationship between reliability and container shipping networks.	Year 1	RQ1: How is reliability best understood in the context of container shipping networks?	Systematic literature review Interviews	2 4
	Year 2	RQ2: What factors influence the network reliability?		
To determine the best approach for comprehensively assessing the reliability of container shipping networks.	Year 2	RQ3: How can the impact of these factors on container shipping networks be measured?	Review and classification of measures	5
	Year 3	RQ4: Would there be a more comprehensive approach to assess the reliability?	Network analysis Simulation	6, 7, 9 8

Table 1.1 Overall research design

In this research project, we consider the container shipping network in multi-scale hierarchical sub-networks, governed by the spatial extent and operation linkages. These different sub-networks interact with each other, creating a complex and interconnected shipping system (Verschuur *et al.*, 2022). This research comprises a systematic literature review (Chapter 2) as well as empirical research (Chapter 4) – which includes in-depth interviews with relevant stakeholders in the container shipping market – and aims to investigate a comprehensive definition of reliability in the context of container shipping networks encompassing different influencing factors. Identified sub-networks gave insight into the different theoretical perspectives on reliability, and a framework for analysing reliability is formulated by comprising infrastructure reliability, network configuration reliability and connectivity reliability. In light of the framework retrieved in the literature review, this research proposes that reliability is influenced by determinants from different themes, and the inter-dependency between these determinants should be taken into account when assessing reliability. Indeed, container transportation can be affected by different factors at the same time. Therefore, instead of considering only one dimension of the network, this research suggests that reliability should be understood systematically and comprehensively.

After defining reliability and identifying the influencing factors, the research analyses the existing metrics and measuring methods for assessing network reliability (Chapter 5). The result of the methodology review and the suitability of the metrics further prove that there are different methods for calculating network reliability, but from different perspectives. There is a need for an approach that can specifically and comprehensively assess container shipping networks' reliability.

In response to this need, network analysis is used to develop a more comprehensive approach to assess reliability (Chapters 6, 7, 8 and 9), based on the framework identified in the previous analysis. Network analysis, which is consistent with graph theory and complex network theory, combines different influencing factors identified from the literature review and empirical research. The approach intends to build the container shipping network consisting of ports and shipping routes. It aims to identify the role of ports within the network, simulate the impact of risks in the network and find out the weak points and areas within the network. This research focuses on container transportation between Asia and Europe, encompassing 89 ports across 38 countries.

1.5 Contribution and dissemination

The contribution of the research project can be summarised as follows:

- Contribution to the definition of reliability in the context of container shipping networks, and development of a systematic framework for comprehensively understanding reliability based on three themes;
- A comprehensive review and classification of existing metrics and methods that are used to assess reliability;
- Proposing a more comprehensive network analysis model by considering network vulnerability, resilience, port performance and propagation effects;
- Identification of important nodes and links, risks and vulnerable elements within the network so that decision-makers and industry stakeholders can improve the reliability of the shipping networks.

The contents of the research were presented at several conferences: e-Logistics Research Network Conference – LRN (Web conference, 2020), RGS (with IBG) Annual International Conference (United Kingdom, 2022) and the International Association of Maritime Economists Conference (Long Beach, California, 2023). Meanwhile, the systematic literature review, titled "A framework for understanding reliability in container shipping networks", carried out in this thesis has been accepted for publication in the journal Maritime Economics & Logistics (accepted in September 2023).

1.6 Overview

The thesis is structured as follows: Chapter 1 introduces the background and motivation of this research project and presents the overall research design. Chapter 2 uses a systematic literature review to explore the topic of container shipping networks' reliability and analyses the research gap of this research. Chapter 3 presents the research design including the research philosophy, theoretical framework and research methods that are used in this research project, as well as the research plan. Moving forward, Chapter 4 further explores the understanding of reliability and influencing factors from the industry perspective by using semi-structured interviews. After analysing the definition of reliability, Chapter 5 explores the available indices, metrics and methods that are used to assess the reliability of the container shipping network according to the different themes identified in the literature review and interviews. The following chapters (Chapters 6 to 9) present a more comprehensive approach based on network analysis and simulation, building upon the results of the previous review, and assessing the reliability of the container shipping network between Asia and Europe. More specifically, Chapter 6 describes the data selection procedures and research design for network analysis. Chapter 7 focuses on the connectivity of the shipping network and the role of ports within the network in the assessment of connectivity reliability. Chapter 8 conducts simulations to evaluate network vulnerability and resilience under disruptions, thus, assessing the reliability of network configuration. Chapter 9 investigates the infrastructure performance of ports in line with the analysis of infrastructure reliability. Finally, Chapter 10 presents the conclusion of this research project.

1.7 Conclusion

This chapter provided the background of the research and the need for enhancing network reliability in the context of container shipping networks. It also offered an overview of the thesis and outlined the contribution of the research. The next chapter will present the results of the systematic literature review.

Chapter 2. Systematic literature review

2.1 Introduction

Reliability has long been a question of great interest in a wide range of fields. Based on the method of Ducruet (2020), this research counted the total number of network reliability-related publications in different transport modes between 1950 and 2020 by Google Scholar (Table 2.1). The search was conducted using the words: “reliability” and different transport networks. The results provide concrete evidence of the research trends, showing that shipping network reliability-related analysis has still remained in the shadow of other transport networks (4.2% of total publications). However, due to the availability of the maritime data and the development of the research methods, the number of publications achieved the highest growth in the last decade. To summarise, when considering the analysis of transport network reliability, shipping network reliability is still far away from other networks.

Type of network reliability	*1950-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-1999*	*2000-2009*	*2010-2020*
Airline/ air	7	23	60	94	238	748	2240
Maritime/shipping	1	0	4	13	35	302	1560
Rail/ railway	15	85	256	498	1320	5830	16400
Road/ highway	31	163	562	1130	3720	15200	16900
Total	54	271	882	1735	5313	22080	37100
%Maritime/shipping of Total	1.9	0	0.45	0.75	0.66	1.37	4.2

Table 2.1 Number of publications on transport network reliability, 1950-2020
(Source: Own elaboration based on Google Scholar)

As discussed in Chapter 1, the term “reliability” has often appeared in different aspects of maritime transportation, and it is explained with a variety of meanings. This is to say that the definition of reliability is not absolute; it is related to the characteristics of the research field and its determinants. While various explanations and interpretations of reliability have been provided in different fields, few studies have investigated reliability in any systematic way in the context of container shipping networks. Therefore, the purpose of this systematic literature review in this research project is to investigate the understanding of reliability in the context of container shipping networks. In particular, (1) to explore and understand the definition of reliability in the context of container shipping networks, (2) to identify the determinant factors that may influence the degree of reliability in container shipping networks, and (3) to establish a suitable conceptual framework for reliability in the context of container shipping networks.

In order to achieve this purpose, Chapter 2 is going to explore reliability in container shipping networks in relevant research areas through a systematic literature review. Section 2.2 presents the methods employed and outlines the initial outcomes of the search. Section 2.3 explains and analyses the specific results in each field. Finally, Section 2.4 discusses and summarises the findings and research gaps revealed by the systematic literature review.

2.2 Systematic literature review: methodology and results

To comprehensively explore the concept of reliability in the context of container shipping networks, the systematic literature review (SLR) technique was applied. An SLR is different from a traditional literature review – which might be influenced by the preferences of the reviewer (Calatayud *et al.*, 2016) – it allows the researcher to analyse and interpret the comprehensive literature in a thorough and unbiased manner, enabling the researcher to explore and summarise the body of knowledge from different perspectives on the topic (Tranfield *et al.*, 2003; Wang and Notteboom, 2014).

An SLR is deemed appropriate to search the topic from different perspectives across a broad range of studies, summarise and analyse the framework of the knowledge concerning the aim of the research and find out the existing research gap according to the analysing results. Therefore, a comprehensive SLR is essential to the aim of this research project. In this research project, reliability in the context of container shipping networks is explored comprehensively through a wide review of papers. The result will be able to summarise the body of knowledge and develop a more comprehensive understanding towards reliability and container shipping networks, explore the different perspectives and fields of reliability to the container shipping networks and develop a framework concerning the concept, and develop influencing factors in each perspective and discover the existing gaps.

According to Denyer and Tranfield (2009), the SLR involves **five stages:** (I) formulate questions; (II) exhaustive literature research; (III) choose and evaluate the studies; (IV) research analysis and synthesis; (V) report the results. This research project strictly follows the five stages of the systematic review methodology and presents an explicit research process.

Stage I is to frame the research question. The question addressed in this SLR is, according to a variety of knowledge and study about reliability, how to understand and define reliability in the context of container shipping networks and what are the influencing factors. The research question for the systematic literature review aligns with RQ1 and RQ2 of the overall research project.

In **stage II**, the literature was researched by querying the dataset Scopus, one of the largest repositories of academic papers. The literature research in the second stage comprised *four distinct phases* as illustrated in Figure 2.1.

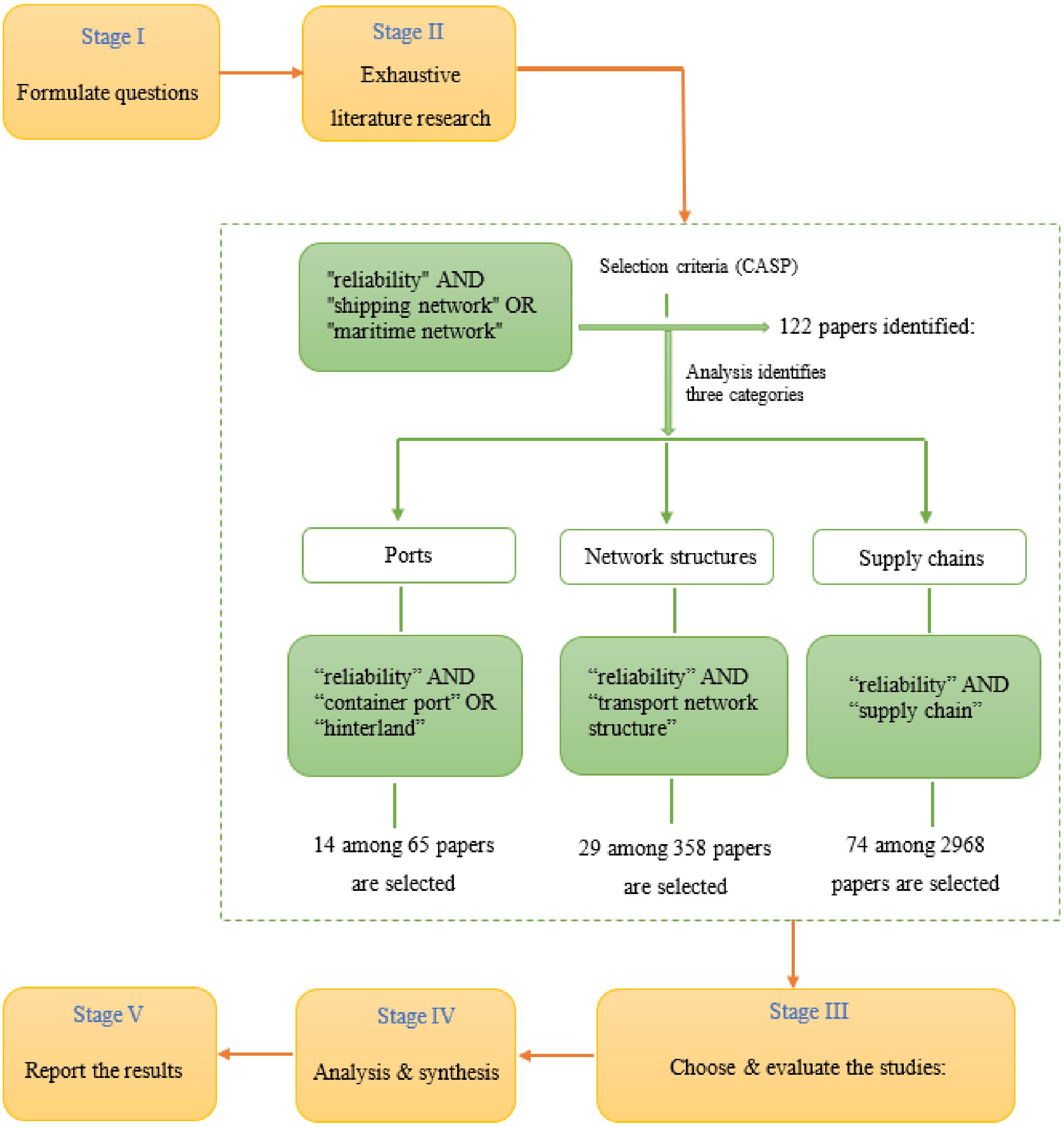

Figure 2.1 Flow of the systematic review

Phase 1: *Using the keywords ("reliability") AND ("shipping network" OR "maritime network")*

A keyword search was performed in papers and conference proceedings published between 1998 – the earliest available year in the dataset – and 2020. The first phase of the literature research resulted in 122 papers. As the focus of this research project was to investigate the reliability in the context of container shipping networks, so the first phase of the literature research intended to use the keyword container (liner) specifically at first. However, the words ("reliability") AND ("container shipping network" OR "container maritime network") resulted in 6 papers only, while ("reliability") AND ("liner shipping network" OR "liner maritime network") resulted in 3 papers. The results showed that the number of papers was not enough to extract information and support the subsequent analysis which also proved there is little research considering reliability in the context of container shipping networks specifically. In any event these papers were already included in the 122 papers. Based on these reasons, the result of the first phase was shown as 122 papers.

Phase 2: *Papers were chosen and evaluated.*

The 122 articles were first evaluated according to their relevance to the research questions based on their abstract and keywords. Then studies were chosen and evaluated according to the relevance to the project and the quality of the study. According to the studies of Wang and Notteboom (2014) and Calatayud *et al.* (2016), the Critical Appraisal Skills Program (CASP) checklist was used as the criteria to evaluate the quality of these studies (Appendix 1). The first phase of the literature research resulted in 122 articles, then the 122 articles were evaluated according to the relevance and quality criteria (CASP checklist) in phase 2, which resulted in 19 relevant studies. Table 2.2 contains the 19 papers identified as being relevant to the project. According to the relevance to the research project and the quality of the study, the earliest article identified was published in 1998 and the most recent was in 2020, with academic interest in a topic of publications growing rapidly since 2014.

No.	Category	Author	Title	Year
1	Ports	Jiang *et al*.	Strategic port competition in multimodal network development considering shippers' choice	2020
2	Network structures	Wan *et al*.	Risk-based resilience analysis of maritime container transport networks	2020
3	Network structures	Tierney *et al*.	Liner shipping single service design problem with arrival time service levels	2019
4	Supply chains	Salleh *et al*.	A framework proposal for evaluating the organizational reliability and capability of a liner shipping operator in a fuzzy context	2019
5	Network structures	Wu *et al*.	Resilience assessment of maritime container shipping networks-A case of the Maritime Silk Road	2019
6	Network structures	Xing *et al*.	Connectivity reliability of container shipping network of the 21st century maritime silk road.	2018
7	Supply chains	Nguyen and Wang	Prioritizing operational risks in container shipping systems by using cognitive assessment technique	2018
8	Ports	Asadabadi and Miller-Hooks	Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach	2018
9	Network structures	Yang and Chen	Robust optimisation of liner shipping network on Yangtze River with considering weather influences	2017
10	Port	Chen *et al*.	Developing a model for measuring the resilience of a port-hinterland container transportation network	2017
11	Supply chains	Wanzala and Zhihong	Integration of the extended gateway concept in Supply Chain disruptions Management in East Africa-Conceptual paper	2016
12	Network structures	Kepaptsoglou *et al*.	Weather impact on containership routing in closed seas: A chance-constraint optimization approach	2015
13	Supply chains	Doll *et al*.	The vulnerability of transport logistics to extreme weather events	2014
14	Network structures	Wu *et al*.	Research on time reliability of container liner shipping network	2009
15	Supply chains	Yang *et al*.	Evaluating key logistics service capabilities for Taiwanese liner shipping firms	2008
16	Supply chains	McGee *et al*.	Simulating transportation practices in Multi-Indenture Multi-Echelon (MIME) systems	2004
17	Ports	Cohen *et al*.	Airport infrastructure spillovers in a network system	2003
18	Network structures	Cheung *et al*.	Strategic service network design for DHL Hong Kong	2001
19	Ports	Dill *et al*.	Material handling robot system for flow through storage applications	1998

Table 2.2 Papers that satisfied the quality criteria (CASP) (1998-2020)

The aim of this research project is to explore reliability in the context of container shipping networks, however, the definition of the shipping network varies according to the research fields. For example merchant trading routes (maritime history), maritime tactical networks (naval strategy), alliance networks between shipping lines (maritime economics), port networks of ocean carriers (maritime geography) and so on (Ducruet, 2020). From the perspective of network analysis, the shipping network is composed of nodes which refer to ports and links which refer to the shipping routes that directly connect ports (Barabasi, 2014; Ducruet, 2017). As introduced in Chapter 1, container shipping networks have expanded their services to logistics networks. In agreement with the broad concept of the shipping network and the aim of understanding reliability systematically, it is appropriate to analyse multi-scale hierarchical networks comprehensively by classifying **sub-networks** within the entire shipping network. Through the preliminary analysis, information synthesis of the selected papers and the definition of the shipping network, the relevant studies could be divided into three sub-networks:

- Ports: with critical infrastructure assets located in the port domain.
- Network structures: which schematised as ports (nodes) and shipping lines (links).
- Supply chains: which covers the transport networks that are used to connect consignors and consignees.

The combination of these three sub-networks is hereafter regarded as the container shipping network (Verschuur *et al.*, 2022). These three sub-networks made up the basis for the research project and were then used to further query the database, searching for papers relevant to the research questions and the aim of the project.

Phase 3 & Phase 4: Searching and evaluating in the three sub-networks.

The selected 19 papers were preliminarily analysed to extract information and divided into different aspects. Based on the preliminary analysis result, the Scopus database was further queried using different keywords related to these three different sub-networks (ports, network structures and supply chains) in phase 3. Papers were then evaluated and selected based on their relevance to the research and to the selection criteria (CASP) approach (employed previously in Phase 2). The use of the keywords ("reliability") AND ("container port" OR "hinterland") to select in the ports category, resulted in 65 documents, among which 14 articles were selected. Then, using the keywords ("reliability") AND ("transport network structure"), resulted in 358 articles, among which 29 satisfied the selection criteria. Finally, using the keywords ("reliability") AND ("supply chain") to do the selection, resulted in 2698 articles, among which 74 were selected.

In **the third stage**, after the *four phases* of the literature research, according to the quality criteria and the relevance to the research project, a total of 136 articles were ultimately selected. The overall structure of the systematic literature review process is graphically illustrated in Figure 2.1.

2.3 Analysis of results

The next stage (**stage 4**) of the systematic literature review is the analysis of the selected papers after literature research (stage 2) and selection (stage 3). The analysis of the articles selected above gives insights that the understanding of reliability in the context of container shipping networks refers to different themes. The definition of reliability in each theme may be different.

2.3.1 Integrative framework

Following the implementation of literature selection and evaluation, the relevant information was extracted and integrated through synthesis. In this research, thematic analysis was used to review the selected papers on the basis of the topics and contents (Denyer and Tranfield, 2009). **Thematic Analysis** is often regarded as a general approach to analysing qualitative data (Saunders, 2015). Thematic analysis is used to identify the themes or patterns according to the research questions, classify and analyse the dataset with regard to the observed themes. This approach provides a systematic and logical way of analysing the qualitative data. Initially, the container shipping network was divided into three sub-networks: ports, network structures and supply chains (Section 2.2). Thematic analysis of the literature selected from the three sub-networks gave insights into the general definition and different research domains of understanding reliability in the context of container shipping networks.

In line with the results of thematic analysis, reliability in the context of container shipping networks could be generally defined as the quality of liner performance under uncertainty from consignor to consignee. Additionally, the three *sub-networks* are now reconceptualised in our analysis as three **themes**: (1) Infrastructure reliability: reliability was defined as the availability, capacity and efficiency of infrastructure among shipping networks (discussed further in Section 2.3.2 below); (2) Network configuration reliability: reliability here refers to whether the network could be affected by disruptions or risks and the ability of the network to perform well even when parts of the network have failed (Section 2.3.3); (3) Connectivity reliability: reliability was defined according to the probability of the components in the network being connected and the integration of different stakeholders along supply chains (Section 2.3.4).

Figure 2.2 is a graphical representation of the identified themes, forming a framework for understanding reliability in the context of container shipping networks. The bubbles in the figure refer to the identified themes and the bullet points refer to the influencing factors that could affect the reliability within each theme, which will lead to the further discussion. The overlapping areas of the bubbles indicate that some of the literature analysis was multi-disciplinary – one factor could affect the reliability of more than one theme, but from different perspectives, or else the determinants could be classified according to more than one field. For example, papers under the themes infrastructure reliability and connectivity reliability both pointed to hinterland and multimodal-related issues; however, one analysed it from the perspective of construction while the other analysed it from the perspective of connecting different transport modes.

Few papers, however, provided a systematic analysis of reliability from the perspective of more than one theme, and our framework sought to comprehensively and systematically address this deficit. To summarise, in this research project, the analysis results could be classified into three themes: infrastructure reliability, network configuration reliability and connectivity reliability. The understanding of reliability in the context of container shipping networks in each theme refers to different performances and it is influenced by different determinant factors. The systematic literature review in the following sections is going to investigate the comprehensive definition of reliability in each theme that relates to container shipping networks and explore the influencing factors that determine network reliability.

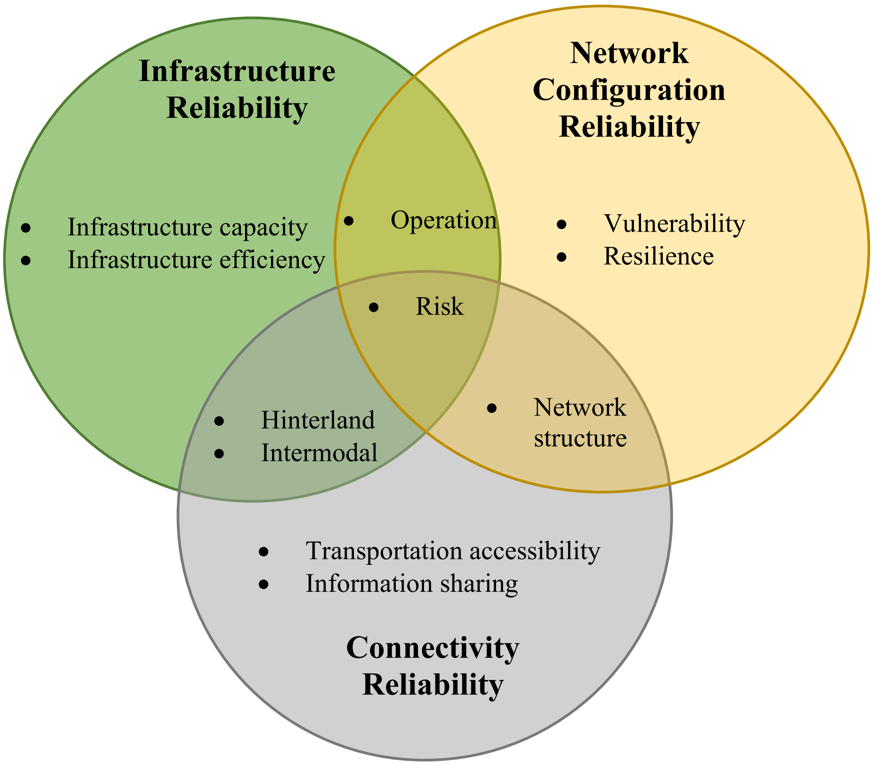

Figure 2.2 A framework of reliability in the context of container shipping networks. (Source: author elaboration based on thematic analysis results)

2.3.2 Infrastructure reliability

There is extensive literature where container shipping network reliability is defined according to infrastructure availability and capacity, focusing on the physical properties of the network. The available literature has applied this concept to investigate the effects of reliability, under a given infrastructure construction, which could have an impact on transport time, cost and competitiveness (Sánchez-Silva *et al.*, 2005).

2.3.2.1 Availability and efficiency of infrastructures

In container transportation, reliability can be defined according to the availability, efficiency and capacity of the infrastructures and service ability that container shipping networks provide. Literature on this theme has usually relied on the analysis of reliability in accordance with port time and container shipping schedules (Notteboom, 2006; Sun *et al.*, 2018), as turnaround time and on-time rate are the most commonly used indicators to assess the performance of container shipping. Ship turnaround time in port is defined as a summation of all waiting times, idle times and container handling times at ports (Moon and Woo, 2014). The Review of Maritime Transport (2019) showed that the median time that dry bulk carriers spent was 2.05 days, while container ships spent 0.7 days. A shorter time in port is a positive indicator for container trade compared with other transport modes, making time reliability an important aspect for the container transport industry. Stakeholders also look forward to shorter turnaround time, which leads to less cost and enhanced timetable reliability. However, the planning of efficient and reliable liner shipping services is challenging. According to the research of Notteboom (2006), only 20% to 30% of the ships showed schedule reliability, and nearly 70% to 80% of the ships experienced late arrivals in at least one port during a round-trip voyage.

In the studies related to in port time, reliability is defined according to how long a ship needs to wait. Delays usually occur when a ship has to wait for a berth that is currently occupied by another ship and infrastructure occupancy rates pass 50% (Gidado, 2015; Balliauw *et al.*, 2019). Some papers point to the role of port capacity and infrastructure occupancy (Dekker *et al.*, 2011; Novaes *et al.*, 2012). Although there are many other influencing factors that can lead to longer port times (Wu *et al.*, 2009; Tierney *et al.*, 2019), in the long run, the reliability of the container shipping network is still driven by structural factors (UNCTAD, 2021) including infrastructure, service and trade facilitation. According to the dataset "Global Transport Costs Dataset for International Trade" (GTCDIT), these significant structural improvements could reduce maritime transport costs by around four per cent.

For example, with the anticipated growth of the throughput, port expansion is one of the methods of solving long in port time. Expanding facilities, such as more berths, cranes, docks, terminals and also interrelated elements in ports, help reduce congestion and waiting time in ports (Novaes *et al.*, 2012). Obviously, if a port is equipped with abundant facilities, the quality of service will increase and the probability of congestion will decrease (Chen. *et al.*, 2016). The demand for a port's expansion highly depends on the level of congestion, which depends, in turn, on the utilisation rate of the port's infrastructure (Dekker *et al.*, 2011). Haralambides (2002), De Borger (2008) and Dekker *et al.* (2011) also agreed that port expansion needed to compare the scale effects in the investment costs for the port with the congestion costs for its users in order to decide when to expand, and determine the size of the port. It should balance investment costs against reduced congestion costs. However, port expansion or else a new port are still some of the methods used when trying to optimise the shipping network based on infrastructure capacity reliability. Considering reliability costs in the analysis under uncertainty alters the investment decision considerably. For example, several attempts have been made to implement a port congestion surcharge in an attempt to reduce congestion in maritime transport and urban transport. Additionally, there is a growing body of literature that considers additional costs in the planning stage. If the design and operational planning of port facilities can effectively address trade under congestion and uncertain market demand, then the reliability of the shipping network could be improved.

Besides the physical infrastructure availability and capacity, studies have also considered the performance efficiency of the ports, including port planning and infrastructure efficiency. From the perspective of port planning, researchers have emphasised the berth allocation problem, the quay crane assignment problem, the effect of human factors, port call optimisation, etc (Fan, 2002; Moon and Woo, 2014; Comtois *et al.*, 2018; Martínez-Pardo *et al.*, 2018).

In addition to the availability of infrastructure in ports, part of the literature has applied a broader concept of infrastructure reliability, which emphasises the importance of transport services and infrastructure availability in the hinterland. Under this broader concept of reliability, studies highlight dry (i.e., inland) ports (Lättilä *et al.*, 2013; Wei and Sheng, 2017; Facchini *et al.*, 2020; Jiang *et al.*, 2020) as elements of a hinterland distribution network that stimulate a modal shift – leading to less traffic and congestion at port gates and port cities, and reductions in emissions by as much as 32 to 45% (Lättilä *et al.*, 2013). A dry port is an inland intermodal terminal directly connected to a seaport with high capacity transport means, where customers can leave/pick up their standardised units as if directly to a seaport (Facchini *et al.*, 2020). Under the hub-spoke network structure, hub ports face more containers, making the hub points more vulnerable. Dry ports provide an efficient way of reducing the stress on hubs. Therefore, an efficient dry port relies on the coordinated development of various parts of the supply chain and the cooperation mechanism among seaports and dry ports; thus, contributing to the integration of various transportation modes. Studies also point to the role of intermodal connections and the cooperation among seaports and dry ports (Bärthel and Woxenius, 2004; De Langen and Sharypova, 2013) and the integration of different transport services along the supply chain (Song and Panayides, 2008; Woo *et al*., 2013). Moreover, carriers are expected to select reliable ports and be willing to broaden their maritime services. Reliability is supported by a wider shipping network that allows access to the corresponding hinterlands.

2.3.2.2 Infrastructure risks

Another factor that highly affects infrastructure reliability is risks. Ports are very exposed to climate-related events, such as sea-level rise and flooding, strong winds and changes in storm patterns. These impacts materialise as direct damage to the physical infrastructure system, located within the port boundaries. This also increases the risk of delays or port closure, resulting in significant economic costs, with adverse effects on container shipping reliability. Additionally, other unexpected disruptions (e.g., COVID-19) can also affect port operations and ship turnaround time. All the unpredictable risks affecting the operations of port infrastructure increase the waiting time and operations time, as well as decrease the reliability of the port and propagate to the entire container shipping network. There is therefore, infrastructure reliability in the context of container shipping networks requires a complex infrastructure system that is designed and operated in a manner that can exhibit efficiency and also robustness in response to risks (Nguyen and Wang, 2018). In port infrastructure systems, the process of assessing reliability includes the identification of risks associated with the infrastructure and the development of prevention, contingency, and emergency plans that enable systems to maintain functionality. Mutombo and Ölçer (2017) and Romero-Faz and Camarero-Orive (2017) analysed the trends in the perceived climate risks at ports infrastructure including berth, protection barriers and so on. Mansouri *et al.* (2010) identified uncertainty in the port infrastructure system and devised resilience strategies regarding the known vulnerabilities of the system.

Traditional risk analyses – usually based on critical infrastructure failure – often do not incorporate risks in port areas and the inter-dependencies of assets. Recently, studies have also begun to focus on the failure of connectivity between port-related assets (Thacker *et al.*, 2017), and the interdependency between ports and hinterlands (Sriver *et al.*, 2018; Verschuur *et al.*, 2022). Given the existing studies, there is a clear trend in expanding the risk of infrastructures to a wider network, which also correlates with the analysis in Section 2.3.2.1. Enhancing a wider network of infrastructures can improve the accuracy of assessing the reliability of the network for basically two reasons. Stakeholders can identify the potential risks more comprehensively, especially concerning large-scale disruptions. The other reason is reliability can be improved from the network perspective not only by considering nodes in the network separately, e.g., failure of one system could affect the reliability of other systems (Goldbeck *et al.*, 2020), congestion in a port could propagate to the hinterland and other connected ports. A disruption in one port's operations can ripple through the maritime networks via the shipping routes and affect the performance of other ports that are directly or indirectly connected to that port. Infrastructure in ports and port-related assets are, thus, incentivised to make pre-disaster investments to increase their reliability and resilience to the range of disruption events.

In addition to the consideration of physical infrastructure, recent studies on reliable port infrastructure systems have focused more on digital aspects as being one of the risk management methods. Ports nowadays not only provide basic logistics and transport services but also value-added services, trying to reduce dependency on manpower, and utilise smart applications and sustainable technology to improve efficiency and reduce emissions (Douaioui *et al*., 2018; Yau *et al*. 2020). By adopting these advancements, the reliability of port infrastructure availability can be improved. The concept of the "smart port" has emerged as an important topic in the maritime field. Smart here refers to the integration of automatic computing principles (Spangler *et al.*, 2010). The literature highlights three aspects of smart ports that are linked to reliability:

- Information system, which has been deployed to the operation of ports including AIS data, maritime traffic and logistics data (Rajabi *et al.*, 2019). The information system facilitates the reduction of document transfers, improving the reliability of the network by protecting data security and improving efficiency. This fast and easy flow of information allows ports and stakeholders to make well-informed decisions in a timely manner. Research under this perspective also connects with studies on integrated transport systems, trade facilitation and information sharing along the supply chain, so as to increase the connectivity and coordination among different transport systems and stakeholders (Calatayud *et al.*, 2016), which will be further discussed in the following section.
- Smart applications. There are several smart applications that have been implemented in port operations, including smart vessel management, container transhipment management, port management, resource management etc. These applications contribute to various improvements, such as enhancing container arrival punctuality, reducing waiting time, reducing the time that ships spend in transhipping containers, improving the safety of the ports and optimising resource procurement and allocation to reduce congestion and turnaround time (Cho *et al.*, 2018).

- Efforts on sustainable construction. The construction of smart ports is also in response to the goal of reducing greenhouse emissions. Peris-Mora *et al.* (2005) and Chen. *et al.* (2019) discussed the relationship between port development and sustainable infrastructures. The growth of "smart" infrastructure and service not only leads to efficient and reliable container shipping networks, enhances port resilience but it also contributes to sustainable development and guarantees safe and secure activities (Molavi *et al.*, 2020).

Incorporating infrastructure availability – "smart" infrastructure systems and the construction of hinterland can improve port level reliable models, especially when facing disruptions in the aftermath of the COVID-19 period.

This theme included publications exploring infrastructure in ports and hinterlands, where reliability may be affected by factors such as infrastructure capacity, efficiency, operation ability, connections between hinterland and port, and risk management. The identified factors within infrastructure reliability in this section are listed in Table 2.3 (at the end of Section 2.3.4), along with the factors from the other two themes.

2.3.3 Network configuration reliability

The second theme to be investigated with regard to the concept of reliability is within the field of network configuration. In this theme, reliability is defined from the network configuration perspective and complex theory is applied. The evolution of container shipping networks, the development of hub-spoke network structures and the increasing container international trade volume have exposed a new set of risks in the connected shipping network: disruptions in maritime transport networks (Calatayud *et al.*, 2017). Disruptions in container shipping networks play an important role in maintaining the performance reliability of container shipping as well as an explanatory variable in the decision-making process of involved parties. Examples include the impact of the Fukushima nuclear disaster that closed the ports of Yokohama and Tokyo in 2011, and the bankruptcy of Hanjin Shipping which had significant knock-on impacts in 2016. On September 14, 2016, Typhoon Meranti landed in Xiamen and brought disastrous consequences to Xiamen Port. In April 2018, the heavy fog at Shanghai Port led to the delay of more than 1,500 ships. The potential disturbances to container shipping networks include many natural and human factors: port worker strikes, terrorist attacks, cybersecurity threats, regulatory barriers, changes in shipping companies' strategies, piracy, marine accidents, natural disasters, adverse weather conditions and so on.

All of these uncertain disruptions can cause the nodes and routes in container shipping networks to be congested or fail (Tang, 2011; Earnest *et al*., 2012).

Furthermore, due to the COVID-19 pandemic, ports and shipping lines in severely affected areas have experienced interference to varying degrees. According to the World Ports Sustainability Program (IAPH-WPSP) survey, ship calls, hinterland transport, capacity utilization of warehousing and availability of port-related workers were all affected by the pandemic. The efficiency of ports and products clearance had declined, and inland transhipment was not efficient enough, so that delays and congestion were inevitable. Typically, the disturbances described above have the potential to induce sudden interruptions in container flows within the container transport system and possibly resulting in a stoppage of cargo movement. However, the Covid-19 pandemic could be identified as a distinct event capable of causing severe and combined impacts. In the case of the Covid-19 pandemic, the situation diverges significantly from other disruptions since it concerns an external shock that rapidly affected all elements of the supply chain roughly at the same time (Notteboom *et al.*, 2021). The impact of the Covid-19 pandemic initiated with a supply shock, as lockdown measures significantly affected the availability of raw materials and workforce, leading to shortages in the supply chain. Subsequently, the widespread implementation of lockdown measures across the word resulted in a global demand decline due to lower consumer and industrial confidence, coupled with limited retail activity. Any sudden drop in consumer demand has an immediate impact on container shipping volumes and port throughput, potentially altering corporate strategies or even market structures. More specifically, in the context of container shipping, carriers maintained network integrity and resorted to blanked sailings to deal with declining supply. Blank sailings directly impacted the number of containers handled per call. Simultaneously, distribution capabilities can be impaired by restrictions on trade and the closing of ports. Moreover, the pandemic created risks in ship operations, yard activity, gate congestion and other landside operations challenges for ports. The combined effect of the Covid-19 pandemic created a complex and challenging operating environment for container shipping during the pandemic.

Moreover, the disruption occurring in one node or route can impact the reliability of the entire network. Such interruptions can be classified into four stages: ranging from congestion, deviation, stoppages, and to the complete loss of the service platform (Gurning *et al.*, 2013). Hence, a reliable container shipping network needs to meet the need of risk mitigation or prevention plans. As agreed by many researchers e.g., Notteboom *et al.* (2021); Xu *et al.*

(2021), the effects of the Covid-19 pandemic have been a short-lasting shock, which was of a lower scale and shorter duration than initially expected. This happened due to the improving resilience – the adaptation capabilities demonstrated by shipping lines and efficiently operations of container ports, and the collaboration and coordination among stakeholders.

This section is going to understand and explore container shipping network reliability from the network configuration perspective. Here, **the term reliability refers to whether the network could be affected by disruptions or risks and the ability of the network to perform well even when parts of the system have failed,** as defined by Snyder and Daskin (2005). With the development of containerisation, countries and firms need to improve reliability in their international trade under this new type of risk. Accordingly, a reliable network in this perspective refers to the systems that may limit their ability but are still able to provide sufficient operational functionality based on resistant coping capacities and their resilience in recovering from negative impacts caused by hazards.

2.3.3.1 Vulnerability and resilience

Studies on network reliability within the field of network configuration are numerous, and they concern inter-alia network robustness, adaptability, preparedness, vulnerability and resilience (Calatayud *et al*., 2017; Kireyev and Leonidov, 2018), and reliability is analysed and explained from various aspects to address different requirements (Wan *et al.*, 2018). The majority of the research defines reliability as a kind of capability of a network to face and overcome changes, which arise from its inherent configuration. Most researchers use this as a metric to measure performance when facing disruptions, although they may have used different terms such as "recover", "return" and "restoration". Network configuration reliability includes prevention, resistance, restoration, adaptation and optimisation. In this literature review, we note that the key metrics that affect reliability are divided into two parts: vulnerability and resilience.

Vulnerability can be defined as a kind of degree to which a system will suffer an adversely impact when a disaster event occurs. Berdica (2002) first introduced the concept of vulnerability into road traffic networks and pointed out that vulnerability was the characteristic of the decline of accessibility due to different reasons and defined it as the vulnerability of the traffic system to abnormal events. In the field of transportation, the vulnerability of transportation networks refers to the degree of impact on networks connectivity when the network is attacked or has partially failed. Holling (1973) described the “resilience” of ecosystems as the ability to maintain the level of performance of a system in the face of internal or external shocks, including how sensitive the system is when exposed to a threat, and the adaptability of the system to the threat. Resilience in freight transportation can be regarded as a system’s ability to resume normal operations after sustaining unfavourable conditions (Godschalk, 2003; Berle *et al*., 2011; Ivanov and Sokolov, 2013). A graphical understanding of resilience, as frequently depicted in the literature, is presented in Figure 2.3. Resilience, in this context, is defined with reference to the temporal occurrence of node attacks and the resultant impact on system performance. As illustrated in Figure 2.3, resilience is conceptualized as the ability of a system to prevent, absorb, recover and adapt to damages.

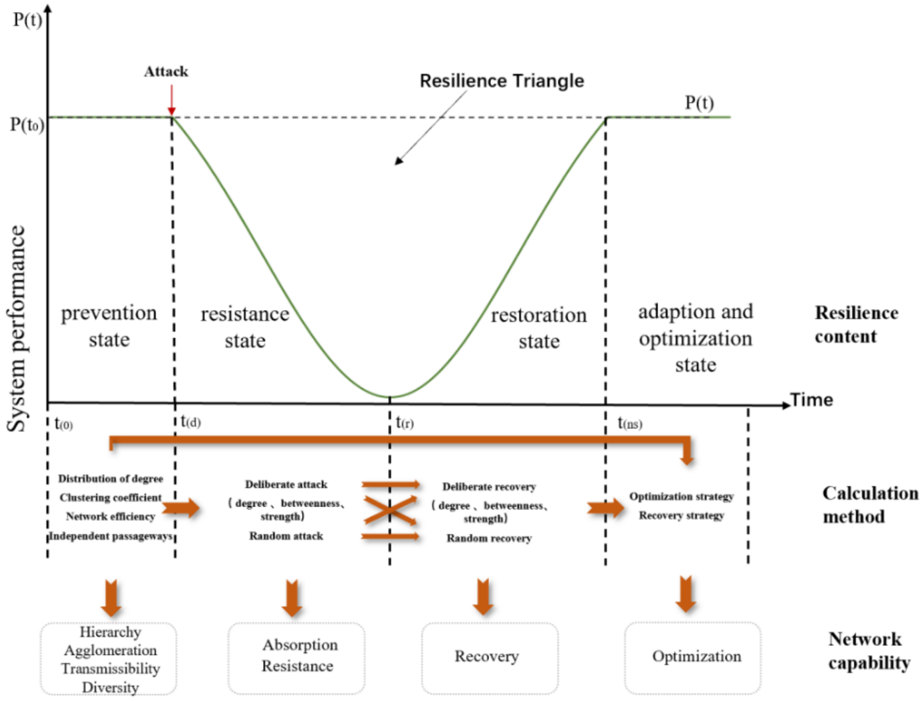

Figure 2.3 Resilience structure framework
(Source: Wan et al. (2018); He et al. (2022); Suryawanshi and Dutta (2022))

In the context of this research, resilience and vulnerability serve as pivotal performance metrics for assessing network reliability, as discussed above, these two metrics encapsulate a comprehensive range of network functions when confronted with disruptions. Resilience and vulnerability refer to the ability of a system to respond to various internal and external disruptions and shocks, with some debate as to whether the two concepts are fundamentally the same. It is generally agreed that resilience and vulnerability refer to the ability of a system to respond to various internal and external disruptions and shocks, similar to the positive and negative sides of a coin. However, some scholars believe that these two concepts are not completely opposite. In the face of disruptions, it is imperative to anticipate and avoid their impact before they occur; actions need to be implemented during the resistance state; the network need to recover from damage to the initial status subsequently. Specifically, resilience is more focused on the system's ability to respond and recover after an event, while vulnerability mainly refers to the inherent attributes of the system before the event, and describe the possible scenarios of system interruption (Berdica, 2002; Berle *et al*., 2011). This research project agrees that resilience reflects the ability to cope with and recover from a threat, but vulnerability reflects not only the inherent properties and decline of accessibility of the shipping network after the interruption, but it also includes the ability to effectively resist various disruptions before the event. The difference between vulnerability and resilience reflects two ways of understanding reliability. One regards reliability as the stability of the shipping network – the other refers to the dynamic ability to transform from one equilibrium state to another (Wan *et al.*, 2018).

In practice, studies on vulnerability include definitions, determining important nodes and links in the shipping network, cascading failure (redistribution of ships will cause congestion in other ports (Zsidisin, 2005; Miller-Hooks *et al*., 2012; Lhomme, 2016) and methods for quantifying vulnerability (Crucitti *et al*, 2003; Manzano *et al*. 2014; Wu *et al*., 2019). The improvements of port vulnerability assist port operators in resisting, coping with and recovering from negative impacts caused by hazards. The other studies on shipping network resilience focus on port infrastructure resilience and the resilience of liner shipping schedules. Shipping routes, together with the level of efficiency and connectivity of ports represent critical factors in the operational resilience of container shipping networks (Kashiha *et al.*, 2016). In defining resilience in the transportation studies area, similar terminologies are used as those in other research fields (Murray-tuite, 2006; Carvalho *et al.*, 2012; Chen *et al.*, 2017). In the literature about container networks, resilience is also related to the shipping schedule rerouting problem. For example, Xing and Zhong (2017) proposed a mixed integer program for solving a container rerouting problem from an individual liner shipping operator's perspective. Achurra-Gonzalez *et al.* (2019) investigated container rerouting after a disaster event that led to port capacity reduction. Omer *et al.* (2012) proposed schemes for improving a maritime transportation network's resilience by resourcing allocation and preparedness. Di Francesco *et al.* (2013) proposed a stochastic optimisation model for repositioning empty containers under possible port disruptions in a maritime network. These papers showed that the reliability could be improved by optimising the resilience of the shipping network.

In order to provide sufficient service even when parts of the network have failed, network configuration optimisation studies also consider the role of backup hubs and alternative route designs under disruptions in a holistic network configuration. Backup hubs refer to the unaffected hubs used for rerouting disrupted services when other hubs are unavailable. This type of research has received attention, including Cui *et al*. (2010), An *et al*. (2015), and Asadabadi and Miller-Hooks (2018). An *et al.* (2015) proposed a reliable hub-spoke network design strategy by considering the backup hub and alternative route decisions in the design stage. Azizi *et al.* (2016) proposed a mixed integer nonlinear formulation to design a hub-spoke network, taking into account the probability of hub failure and re-routing cost. Azizi (2019) found the optimal locations for the hub facilities, allocated the demand to these hubs and found the least expensive backup facility for each demand point in the network. The aim of designing the backup models is to minimise the operation cost and expected cost when one of the hubs experiences disruptions. The model should determine the optimal location and find the least cost facility for each demand point within the network configuration. At present, the studies on backup ports are concentrated in the field of air transport, and there is very little research in the field of shipping. Therefore, developing the backup ports holds significance for enhancing the study of network reliability, specifically focusing on cost reduction and responsiveness to emergencies in the network planning and design stage.

From this perspective, the understanding and definition of reliability within network configuration is the degree to which a network can resist disruptions and the ability to recover from disruptions. Container shipping is the cornerstone of the semi-manufactured and manufactured goods market with the objective of increasing transport availability and generating higher profits. The increasing interdependency of each part during transportation, in particular has made shipping operations more vulnerable to disruption (Lam and Bai, 2016). In the face of challenges, stakeholders have the responsibility of managing risks and enhancing port resilience against threats within the network configuration. Improving network reliability can improve transport accessibility and reduce costs when there is port congestion or port failure due to attacks.

2.3.3.2 Hub location problems

Research in the areas of Transportation, Geography, International Trade and Economics and, to some extent, Transport Economics has contributed with advances in network reliability and network configuration by regarding the selection of hub location. Hub location problems consider the design of a hub-spoke network structure by locating a set of hub ports, activating a set of links, and routing a predetermined set of commodities through the network while optimising a cost-based (or service-based) objective. The first recognised mathematical formulation and solution method to evaluate the hub location problem was proposed in the work of O'Kelly (1986), it presented the first quadratic formulation for the single allocation p-hub location problem. Based on this, many papers started to address hub location problems (Campbell, 1996; Skorin-Kapov, 1996; Ebery, 2001; Aversa, 2005; Marín, 2006; Nam and Song, 2011; Puerto, 2016). These studies presented a definition of hub location problem and introduced a mixed integer programming model to select hub ports. Campbell (1996) proposed the first linear integer programming for the p-hub median problem. The p-hub median problem aims at serving the origin-destination demands through a predetermined number of hub facilities with minimum total transportation cost (Gelareh and Nickel, 2011). These studies aim to find suitable locations for hubs, allocate the existing demand to these facilities, and direct the flow between origin-destination pairs at a minimum cost by developing efficient mathematical formulations and solution techniques (Azizi, 2019).

However, nearly all studies associated with the hub selection problem have assumed that the chosen hubs would always operate functionally as planned. According to the study of network vulnerability in Section 2.3.3.1 and infrastructure risk in Section 2.3.2.2, in practice of course, hubs could fail for a variety of reasons. If the performance of the hub is affected by disruptions, and the hub becomes congested or fails, then the shipment process is consequently delayed (Mohammadi and Tavakkoli-Moghaddam, 2016). However, most of the mitigation strategies are reactive, which are often costly to implement and inefficient, given that the initial network is designed for perfect conditions (An *et al.*, 2015). Hub location problems with reliability consideration have received very limited attention in the literature. Kim and O'Kelly (2009) proposed a single-allocation p-hub protection model with primary and secondary routes. An *et al.* (2011) and An *et al.* (2015) designed reliable single-allocation hub-spoke networks by taking hub unavailability into account with a given reliability value for each hub. Parvaresh *et al.* (2014) formulated a bi-level multiple allocation p-hub median problem under intentional disruptions. Mohammadi *et al.* (2019) designed a reliable logistics network through a hub location network that was less sensitive to disruptions in the hubs.

2.3.3.3 Complex networks

The analysis of network configuration investigates the risk of failures within, and the potential adaptation of, the shipping network, which is closely related to the position and inter-connectivity of the ports within this network. In line with this, studies in section 2.3.3 have expanded the notion of reliability, understanding it as the importance of a port as a node within the global container shipping network. Consequently, network analysis is a method frequently used in analysing transportation and logistics reliability.

Graph theory, social network analysis and complex networks research principally describe the respective situation of individuals with regard to the overall structure of the network and the existence of communities (Boccaletti *et al*., 2006; Barabasi, 2014). Network analysis is a method frequently used in transportation and logistics research, and complex networks have been successfully applied to communication and transportation networks (Calatayud *et al*., 2016). Transportation networks are being widely studied and there are different parameters in many literatures to describe the characteristics of different types of complex networks including air (Reggiani, 2013; Lordan *et al*., 2014), road (Sienkiewicz and Hołyst, 2005), and railway (Li and Cai, 2007) networks. Network analysis has also been applied to study maritime shipping networks in a lot of research (Notteboom 2006; Hu and Zhu 2009; Ducruet and Zaidi 2012; Jiang *et al*., 2019).

Kaluza *et al.* (2010) pointed out that complex network theory could be applied to container shipping networks, which provided a brand-new research tool for ports and shipping networks. Ducruet and Zaidi (2012) established the basis of this methodology. Ducruet (2013) investigated the degree of overlap among the different layers of circulation composing global maritime flows in recent decades. Wang *et al.* (2016) pointed out that the maritime network is a typical complex network mainly composed of ports, routes, ships and other main elements. Pais Montes *et al.* (2012) aimed to explain the evolution of the containerised and general cargo maritime routes using complex network analysis. Tsiotas and Polyzos (2015) used complex network theory to analyse the maritime activity in Greece. The papers about shipping networks mainly include three interrelated aspects: shipping networks design in theory, spatial structure analysis in practise, and mining dynamic evolution patterns in application (Yu *et al*., 2017). Network design aims to optimise shipping services and route schedules according to different container shipping modes. The analysis of the network configuration within the corresponding complex networks under the hub-spoke network structure will be the primary method considered in this project.

The network analysis method transforms all elements of a real system and the relations between these elements into nodes and links, and then connects the nodes in the network (Barabási, 2014). It represents a kind of spatial structural analysis. A multiplex network is defined as the possibility for nodes to be connected by two or more links of a different nature (Ducruet, 2017). In the context of complex shipping networks, ports are regarded as nodes, and the links are the shipping lines that directly connect each port. The complexity of shipping networks arises from the large number of nodes (ports) in the network, the variable connection modes of the nodes (shipping lines), and the susceptibility of nodes to various factors and disruptions. The essence of complex network analysis lies in transforming collected data into a description of the actual data and building a model of the real network. A non-weighted network model could be constructed based on the connections between ports and shipping lines. Alternatively, to further describe the transportation status and function of the maritime network system, the degree of network analysis can be deepened by assigning weights to each link and establishing a weighted network.

Network analysis has also been applied to study the vulnerability and resilience of maritime shipping networks in a lot of research. Lhomme (2016) assessed the vulnerability of the maritime network to single node breakdowns as well as the removal of a group of nodes. Ducruet (2017) analysed the dependency of the world maritime network on the Panama and Suez Canals. Calatayud *et al.* (2017) showed that the vulnerability of international freight flows to disruptions in maritime transportation services varies according to the country of origin of such flow and the role that the country plays in the multi-layered maritime transportation networks. Wu *et al.* (2019) showed the impact of main channel interruption on container shipping. It can be concluded that network analysis is essential in the study of shipping network optimisation.

Nevertheless, network analysis models exhibit certain limitations. Network analysis models primarily focus on analysing network structure and fail to capture fundamental aspects of network infrastructure beyond connectivity and network configuration, for example, partial capacity loss, routing and congestion (Almoghathawi *et al.*, 2019). Simultaneously, delays, disruptions, and time-sensitive cargo considerations are integral to the industry but might not be comprehensively addressed by network models. Moreover, network analysis typically represents ports as nodes, the reality is that ports are complex systems in themselves, comprising diverse sub-systems and components that exhibit substantial variations in terms of capacity, efficiency, and services offered. Furthermore, network analysis tends to simplify interactions between entities in a network. In the container shipping industry, interactions are often complex and involve various stakeholders such as shipping companies, port authorities, customs, and logistics providers. The oversimplification of these interactions may inadvertently overlook critical nuances that play a pivotal role in the industry's dynamics. Despite these limitations, network analysis remains a valuable tool for gaining insights into the configuration and behaviour of container shipping networks. This research, however, seeks to use a combination of network analysis and other methodologies to overcome these limitations and provide a more comprehensive understanding of the container shipping network.

To summarise, the concept of reliability in the context of network configuration refers to whether the network is easily affected by disruptions and the ability of the system to perform well even when parts of the system have failed. From the perspective of prediction, optimising methods need to consider when the disruption will occur and how long the effects will last before they can again operate as usual (Liu *et al.*, 2018). However, the occurrence of unconventional emergencies is difficult to predict. Therefore, there are two ways to deal with such disruptions, reduce the potential losses and improve the network configuration reliability. These objectives can be best achieved through a combination of improved network design and strengthened emergency response and recover capabilities (i.e., to deal with the configuration of the network and reduce the probability of the container shipping network being disrupted by unconventional emergencies; to strengthen emergency response capabilities and effective recovery capabilities, that is, when the system is facing the threat of unconventional emergencies, it can absorb disturbances in time before the interruption occurs; and to adapt to changes after the interruption, and recover quickly (Carvalho *et al.*, 2012)). In accordance with the preceding discussion, the identified factors within the network configuration theme, namely network vulnerability, resilience and network structure, are listed in Table 2.3 (at the end of Section 2.3.4), along with the factors from the other two themes.

2.3.4 Connectivity reliability

Connectivity has been regarded as one of the determinants when assessing the reliability of transport networks in many studies. The relationship between reliability and connectivity can be derived from the concept of the network, which is concerned with the probability of components in the network being connected (Bell, 2000). The literature reviewed in Sections 2.3.2 and 2.3.3 concentrated on container shipping networks and the interface between ports and shipping lines, but not the interface with stakeholders of the supply chain. With the extension of shipping networks, container shipping has become the backbone of not only maritime transportation but also logistics networks (Guerrero and Rodrigue, 2014). While shipping networks studies have long concentrated on the network comprising ports and shipping routes, it should also give importance on supply chain related issues (Ducruet, 2020).

The literature on connectivity reliability can be divided into two parts as a result of different influencing factors: transport engineering and supply chain management. The former one focuses on the connectivity between transport modes and services to ease time and cost. The latter one refers to the integration among partners across the supply chain in order to achieve better performance.

2.3.4.1 Reliability in the context of transport engineering

The concept of connectivity from the perspective of transport engineering is defined as the extent to which nodes in the shipping network are connected to each other (Notteboom, 2006; Calatayud *et al*., 2016). More specifically, it refers to the degree to which ships can reach a given destination, especially when links fail, which represents the accessibility of shipping networks. The failure of different components of the network, which are related to both infrastructure and services, may have diverse impacts on network performance. Researchers consider different variables to estimate connectivity between nodes in a given network configuration, e.g., by assessing the availability and capacity of transport services (Stathopoulos and Tsekeris, 2003; Salleh *et al.*, 2019), along with the transfer time, waiting time, tariffs and service connection ability for transhipment (Sun *et al.*, 2018), direct links between two ports, number of port calls (Ducruet and Zaidi, 2012; Ducruet, 2013) etc.

In addition to the perspective on connectivity reliability between nodes in shipping networks, there are papers focused on the connectivity between ports and hinterlands, which note that the port reliability is inherently influenced by the overall performance of the entire transportation process, with the port as a transfer hub connecting land and sea (Lam and Gu, 2013). Under this perspective, container shipping networks consist of ports, direct links between ports, and all the available intermodal routes (Wang *et al.*, 2016). Analytical work on reliability in this broader perspective has emphasised the importance of the availability and capacity of the service provided by the hinterland, as discussed in Section 2.3.2. With the growing amount of containers volume, congestion and delay happening in the hinterland is also an important influencing factor to the reliability of container transport. Port and hinterland operations must therefore grow together to match this growth. Not only concerning the infrastructure and operation of ports, but the efficient handling and distribution of cargo to and from the hinterland are crucial for the overall performance of ports and for the entire supply chain (Khaslavskaya and Roso, 2020). More than ever before, efficiency and reliability of hinterland transportation have become equally important as that of port operations and shipping (Notteboom and Rodrigue, 2007; Wilmsmeier *et al.*, 2011; Wang and Miao, 2016). Monios (2011), Wang and Yun (2013), Lättilä *et al.* (2013), and Haralambides (2017) have pointed out that reliable port hinterlands are deemed crucial in facilitating smooth goods movements and ensuring goods reach their final destinations in a quicker and more cost-effective way. Similar to port operation, hinterlands are vulnerable to various disturbances that are often unexpected and severe. Chen *et al.* (2017) dealt with the resilience of intermodal transportation networks.

From an integrated, door to door management perspective, reliability has been applied to the study of coordination across modes and integrated transport systems (Calatayud *et al.*, 2016). The optimisation of connectivity reliability between different modes can ease time and cost of traveling and transporting between different route systems. A large body of literature has focused on intermodal connectivity, including for example road-rail, port-road and port rail, and other available intermodal possibilities (Wanke *et al.*, 2011). To enhance interoperability across transport modes, a broader concept – **integrated transport systems** – has become a topic of interest in maritime transport research. According to the ITF (2012), integrated transport systems integrate different transport domains, including infrastructure, services, policies and information, with the aim of maximising connections among all shipping-related aspects at different levels. In line with the emergence of a better and seamlessly connected shipping network, studies on infrastructure reliability also consider how to maximise coordination, e.g., the inter-dependency of port infrastructures and connections between ports and hinterlands as discussed in Section 2.3.2. The aim of the integrated system is to integrate all transport-related aspects and to maximise connection and coordination (Potter, 2010; Preston, 2012).

2.3.4.2 Reliability in the context of supply chain management

There are different partners participating in supply chains from an origin to a destination as shown in Figure 2.4. In recent years, supply chains have extended beyond a single country's boundaries and are characterised by firms that cooperate across multiple countries, with facilities and sources coming from suppliers in different countries (Caniato *et al.*, 2013). Firms always seek to secure their competitiveness by finding the most suitable partners with low costs located around the world due to the development of globalisation (Gereffi and Lee, 2014). The distance between partners is thus greater than before. The reliability between each partner and participant is one of the important factors that ensure high service quality and minimum costs. From the perspective of supply chain management, the phase "connectivity reliability" is defined as the collaboration of partners upstream and downstream from the supply chain (Poirier, 1999), which relates to information sharing among stakeholders and the interactions among firms.

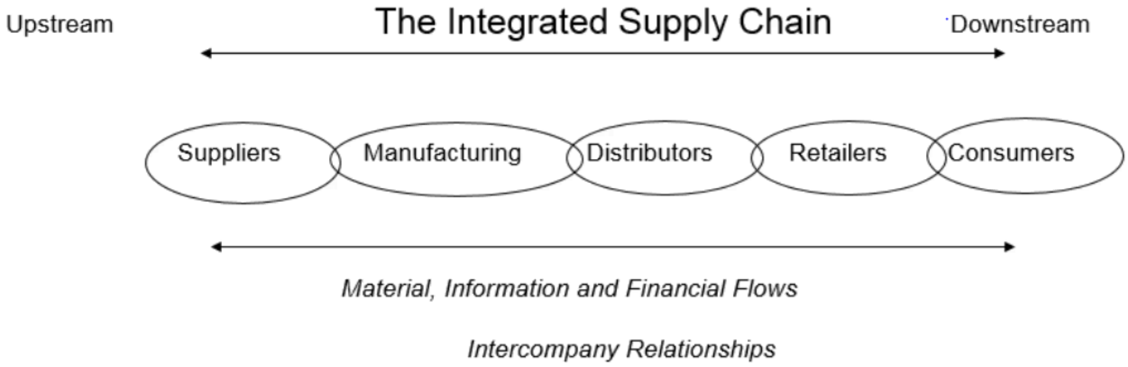

Figure 2.4 The integrated supply chain
(Source: Mangan and Lalwani (2016) and Shaw *et al.* (2021))

The measurement of connectivity reliability involves both the infrastructure and the behavioural responses of the users (Bell, 2000). Firstly, as for the downstream customers, the reliability of the supply chain refers to whether they can receive goods on time and the delivery reliability standard is defined as the minimum probability of meeting the announced delivery time. Late deliveries lead to a deteriorated delivery reliability for customers, and this will have a long-term negative effect on customers demand (Xiao and Qi, 2016).

Infrastructure inefficiencies, regulatory requirements and clearance procedures are the factors that could increase trade costs and the time to reach the consignee. Djankov (2010), Hummels (2013), and Calatayud *et al*. (2016) have pointed out that trade procedures along the supply chain can increase both cost and time delays and reduce freight value (e.g., perishability / shelf-life).

Furthermore, the impact of disruptions depends on how well the stakeholders can adapt. For example, in Section 2.3.3, introducing the resilience of the network, the researcher looked into whether there might be alternative routes or backup ports available, and if stakeholders could respond quickly with spare capacity. In such a case, the reliability of the shipping network would increase when being faced with disruptions. The state of network information-sharing and technological advances plays an important role in determining the impact of a disruption. Zacharia *et al.* (2011) found that information connectivity reliability was beneficial to both upstream and downstream stakeholders. In the context of container shipping, the adoption of such technologies contributes to better communications with shipping lines and ports (Song and Panayides, 2008; Calatayud *et al.,* 2016).

Collaboration on information-sharing through the supply chain offers insights to another research stream – the integration of the supply chain. The higher the degree of integration, the better a supply chain performs (Frohlich and Westbrook, 2001; Song and Panayides, 2008; Calatayud *et al*., 2016). Integration refers to the ability to remove technological barriers among stakeholders along the supply chain, and the ability to build information sharing networks (Wolf, 2014). The presence of technology and information-sharing stages is crucial in facilitating integration across stakeholders (Fawcett Stanley *et al.*, 2007; Song and Panayides, 2008; Wang *et al.*, 2017; Liu *et al.*, 2018). Regarding the interaction among firms, horizontal collaboration (also known as "coopetition" – cooperating with competitors to leverage supply chain advantages) is becoming more prevalent (Mangan and McKinnon, 2019). Benefits of enhancing integration along the supply chain include information sharing, better visibility, shorter order cycles, better monitoring of customers behaviour, greater delivery logistics performance (Fawcett Stanley *et al.*, 2007; Woo *et al.*, 2013). The integration between ports and supply chains includes communication with shipping lines, and the presence of information platforms to share data and computerised port service systems (Song and Panayides, 2008). The connectivity reliability of the supply chain is also important to shipping networks and port operations. The development of information and communication technology makes it possible to achieve high connectivity reliability across the entire supply chain (Coronado Mondragon *et al.*, 2009). Driven by technology, these supply chains will be "self-thinking" and will automatically manage demand, movement and supply chain performance (Calatayud *et al.*, 2019). As markets change and the logistics industry develops, it is notable that other new technology actors are entering the logistics marketplace and supply chains to make the network more reliable and efficient. The use of connectivity reliability is beneficial in communicating with shipping lines and in increasing efficiency in ports. This, because integration helps ports to better accommodate the capacity of containers and to avoid risks. This is also highlighted by the evidence from smart port considerations analysed in Section 2.3.2.

In the context of connectivity, network reliability may be affected by the accessibility of nodes within the network, the connection between transport modes (from the perspective of transport engineering), and information sharing and integration of firms (from the perspective of supply chain management). The identified factors in connectivity reliability are summarised in Table 2.3.

Theme	Definition	Influencing factors	References	Main focus regarding reliability
Infrastructure Reliability	Availability, efficiency and capacity of the transport infrastructures in ports and supply chains.	Infrastructure capacity	Balliauw *et al.* (2019), Dekker et al. (2011)	Port infrastructure dictates the turnaround time and waiting time for ships in port, which is highly correlated with the time reliability of container ships.
		Infrastructure efficiency	Cho et al. (2018), Yau et al. (2020)	
		Operation ability	Notteboom (2006), Moon and Woo (2014)	
		Hinterland construction	Lättilä et al. (2013), Facchini et al. (2020)	Infrastructure reliability in port-related assets, considering inter-dependency from the perspective of connection in port.
		Intermodal connection with hinterland	Bärthel and Woxenius (2004), De Langen and Sharypova (2013)	
		Infrastructure risks	Mutombo and Ölçer (2017), Romero-Faz and Camarero-Orive (2017), Verschuur et al. (2022)	Reliability is determined not only by port infrastructure construction but also the pre-disaster investments to increase their reliability in the context of the range of potential disruption events.
Network configuration reliability	Whether the network is easily affected by disruptions and the ability of the system to perform well even when parts of the system have failed.	Vulnerability	Sánchez-Silva *et al.* (2005), Lhomme (2016), Calatayud et.al. (2017), Wu et al. (2019)	The degree to which a system will have an adverse impact when a disaster event occurs.
		Resilience	Cui et al. (2010), Yuan *et al.* (2019), Asadabadi and Miller-Hooks (2020)	A system's ability to resume normal operations after sustaining unfavourable conditions, e.g., reroute and backup ports.
		Network structure	An *et al.* (2011), An *et al.* (2015), Mohammadi and Tavakkoli-Moghaddam (2019)	Network reliability can be improved by considering node failure potential during the network design stage.
Connectivity reliability	The probability of the components in the network being connected and the integration of stakeholders along supply chains.	Transportation accessibility	Stathopoulos and Tsekeris (2003), Notteboom (2006), Calatayud et al. (2016)	The degree to which nodes in the shipping network are connected especially when links fail.
		Integrated transport system	Monios (2011), Lam and Gu (2013), Lättilä *et al.* (2013), Khaslavskaya and Roso (2020)	The connectivity reliability of the supply chain depends on the coordination across different transport modes and systems.
		Information sharing	Poirier (1999), Bell (2000), Song and Panayides (2008), Zacharia et al. (2011), Woo (2013)	Connectivity reliability refers to the collaborative linkage and interaction of partners up and down the supply chain (trade procedures, integration degree, visibility, and information sharing).

Table 2.3 Summary of three themes and influencing factors.

2.3.5 Other factors

Following on from the systematic literature review, a framework was developed to illustrate reliability in the context of container shipping networks. The framework established three themes to understand reliability and it identified a set of determinants under each theme. However, according to the thematic analysis result, three factors were identified in the systematic literature review, but they do not sit easily within the framework / three themes because of their indirect connection to reliability and untested impact. Nonetheless, these factors are introduced and discussed below.

2.3.5.1 Freight rates

In May 2017, severe port congestion occurred at the Shanghai port, with congestion following soon after at the Qingdao port and Ningbo port. Xu (2017) analysed the reason for this serious congestion. One of the reasons was rumours that freight rates, after May 1, 2017, were expected to rise sharply. Many shippers thus had stepped up their shipments to avoid increasing freight costs. The export volume exceeded expectations, making the world's largest container port continue to face congestion. It was originally predicted that the freight demand in the first quarter of 2017 in Shanghai would increase from 1% to 3% year-on-year, but the actual increase was 3% to 5%. This situation showed that the prediction and judgment of future container freight rates is one of the influencing factors to the reliability of the shipping networks and the supply chain.

There is no doubt that the predominantly low shipping freight rates impose great challenges for shipping companies and suppliers in the supply chain when making operational decisions (Shi *et al.*, 2017). Transport economists have greatly contributed to understanding how freight rates are determined in theory. From the analysis of the historical container rates data, it can be concluded that container rates are decided by different factors. Most importantly, they depend on supply factors, such as the availability and capacity of different transport modes and their operating costs, as well as demand factors, such as the volume of goods to be transported (Gouvernal and Slack, 2012). Similar to other markets, container shipping markets are characterised by the interaction of supply and demand for container shipping services (Yin and Shi, 2018). The demand for container services is a derived demand that depends on world economic activity and the related macroeconomic variables of major economies (Stopford, 2009). Economists have long associated market conditions with freight rates. The equilibrium price in shipping markets is where the availability and quantity of freight to be carried is equal to the supply of shipping provided by the carriers. After the adjustment in shipping rates, shippers and carriers can find a balance between supply and demand. Carriers and shippers try to establish a freight rate through negotiation, which reflects a balance of available cargoes and shipping capacity in the market. Capacity management will therefore be key to reconciling slow growth in demand, high supply capacity and high operating costs. Market conditions certainly appear to have played an important role in accounting for the considerable spatial shifts that were the result of high volatility in rates (Gouvernal and Slack, 2012).

There is a large body of literature modelling the nature of shipping freight rates, either from the nature of a single time-series (Veenstra and Franses, 1997; Kavussanos and Visvikis, 2004; Erol, 2017) or from its relationship with others (Beenstock, 1985; Tsolakis *et al*., 2003; Xu *et al*., 2011; Adland *et al*., 2017; Kou *et al*., 2018). Munim and Schramm (2017) and Yin and Shi (2018) forecasted container freight rates on both weekly as well as monthly levels, which showed that the demand for container transport had obvious seasonal characteristics. The results showed that the peak season usually appears in spring and autumn. Several studies pointed out some important aspects of service quality that may affect freight rates, such as the frequency of port calls, the number of scales (Martínez-Zarzoso and Nowak-Lehmann, 2007) and the transhipment (Wilmsmeier and Hoffmann, 2008). The literature review shows that there are many factors influencing container shipping freight rates; however, some of these factors may be repeated every year and cause similar price fluctuations. As mentioned in both Nielsen *et al.* (2014) and Fusillo (2004), container freight rates are cyclical in nature and can fluctuate largely over the course of a single week. In theory, in a perfectly competitive market, the equilibrium market price resulting from the interaction between market supply and demand should be stationary. It may move up and down irregularly in the short term, but in the long term, it should fluctuate along a constant mean, which is viewed as a mean-reverting process (Tvedt, 2003). In the short term, the shipping supply is either fixed or else the increase in supply is not sufficient to offset the exogenous demand increase. When demand intercepts the supply curve at the vertical section, freight rates will increase, and may either appear to be trending towards stationary or non-stationary (Kou *et al*., 2018).

However, there are fewer studies that analyse the relationship between freight rates and shipping network reliability. Freight rates are rarely recognised as being one of the risks to the reliability of container transportation. In the face of declining rates and a difficult and unpredictable market environment, carriers have, at times, reorganised schedules to reduce capacity, leading to a series of blank, or cancelled, sailings which in turn disrupt regular schedules on these routes (UNCTAD, 2019). Stable freight rates play an important role in network vulnerability, both in shipping networks and in the wider supply chain.

2.3.5.2 Sustainability

The aim of supply chain management is to satisfy all customers with high service quality, reduced transport time, and ensure good quality (Falatoonitoosi *et al.*, 2013). As is the case in other domains, sustainability-related issues are playing a greater role in today's container shipping and supply chain management. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Compared with normal supply chain management, a sustainable supply chain not only simultaneously makes a profit and achieves its potential, but it is one that is also responsible to its consumers, suppliers, societies and environments (Kim *et al.*, 2014). Zhou *et al.* (2000), De Borger (2008), Seuring (2011), Pagell and Shevchenko (2014), Koberg (2019) and Shaw *et al.* (2021) emphasised that sustainable supply chains involved multiple objectives that are concerned with integrating economic, social and environment goals across supply chain processes.

Firms involved in the container shipping network are looking for ways to reduce costs and improve service quality in order to increase the performance reliability and enhance their competitiveness; however, governments and policy makers have an interest in reducing the negative externalities caused by shipping activities. For container transportation, the high environmental impact of container shipping is exacerbated by the increase in traffic volumes (as illustrated in Chapter 1) as well as an over-concentration of traffic flows in certain seaport regions (Ducruet, 2017). Increasing reliability from the perspective of sustainability along the supply chain has become a critical factor within the current trend. An extensive academic discussion has started on how to reduce the environmental damages caused by maritime transportation and maritime logistics without compromising its economic viability (Psaraftis and Kontovas, 2010; Lai *et al.*, 2011; Lam and Notteboom, 2014). This is also demonstrated by the increasing focus in the scientific literature on measures, policies, and initiatives aimed at reducing the carbon footprint of maritime activities. Firms also strive to reduce carbon emissions not only to meet current carbon emissions-related regulations, but also to hedge future carbon emissions-related risks (Lee and Park, 2020).

Regulatory actions concerning maritime pollutants try to reduce shipping emissions mainly by introducing new abatement measures and establishing minimum fuel quality standards. The main regulatory body responsible for the prevention of marine pollution by ships is the IMO – International Maritime Organization. The IMO (2015) has emphasised the importance of developing a holistic framework of corporate social responsibility in maritime shipping.

The main measure implemented by the IMO is the International Convention for the Prevention of Pollution from Ships (MARPOL), which came into force in 1983, with the aim of preventing and minimising pollution caused by ships for both operational and accidental reasons.

According to the IMO Fourth Greenhouse Gas Study (2020), CO_2 emissions from maritime transport represent a significant part of the total global greenhouse gas (GHG) emissions, which has increased by 8.4% over the period of 2012 through 2018, as well as for most ship types. The shipping industry has several options to comply with IMO requirements (Serra and Fancello, 2020). The first part is technological measures including energy-saving engines, efficient ship designs, cleaner fuels, alternative fuels and so on. The main drivers of the ongoing green revolution in the shipping industry are identifiable in the new stringent regulations being put in place to cut emissions (Serra *et al.*, 2020). A recent overview of the measures with high CO_2 reduction potential can be found in the review paper by Bouman *et al.* (2017). Winnes *et al.* (2015) distinguished three main categories of measures for potential emissions reduction: fuels, ship-design, and maritime operations. Significant reductions of emissions can be obtained by replacing traditional marine fuels with renewable or cleaner ones. There is also optimisation from the perspective of vessel design, which includes the optimisation of hull shape and superstructure, the improvement of propulsion systems or, more generally, and the development of energy efficient designs. Lindstad *et al.* (2012) investigated the effects of economies of scale on the direct emissions and costs of maritime transport by comparing emissions from the current fleet, with what can be achieved by increasing average vessel size. The results demonstrate that emissions can be reduced by up to 30% by replacing the existing fleet with larger vessels.

The second part is based on the operational measures, including speed optimisation, optimised routing and fleet management, efficiency of supply chain management, and others that impact the logistical operations (Lindstad *et al.*, 2011). From an operational perspective, many methods to reduce environmental damages caused by shipping and logistics have been explored, and some of those methods have been found to lead to cost reductions. For example, slow steaming, which refers to reducing ship speed to reduce emissions and bunkering costs, has been thoroughly discussed in the literature (Yin *et al*., 2014; Woo and Moon, 2014; Ferrari *et al*., 2015). Lindstad *et al.* (2011) presented investigations of the effects of speed reduction on the direct emissions and costs of maritime transport, revealing a substantial potential for reducing emissions in shipping.

In fact, it is widely recognised that a significant share of shipping emissions can be attributed to the time spent by ships in port (Styhre *et al.*, 2017). It is estimated that ships in port create emissions of around ten times higher than those from port operations (Habibi and Rehmatulla, 2009). Styhre *et al.* (2017) analysed the level of greenhouse gas (GHG) emissions from ships while in port and investigated four important emission-reduction measures: reduced speed in fairway channels, on-shore power supply, reduced turnaround time at berth and alternative fuels. Thus, port congestion and ship turnaround times (discussed in Section 2.3.2 above) can play an important role in the environmental impact of shipping. Furthermore, there is a growing body of literature that focuses on environmental governance in maritime shipping or the greening of port operations (Lun, 2011; Lam and Notteboom, 2014). Davarzani *et al.* (2016) provided a comprehensive review that examined research on green ports and maritime logistics, which focused on sustainability in maritime transport, published between 1975 and 2014. Generally speaking, among the various potential fuel reduction measures, operational measures are easier to adopt as they do not require major investments, are readily implementable and can yield significant benefits in a short time (Eide *et al.*, 2011). As both a large-scale user and a carrier of energy, maritime transport needs to operate in a more sustainable way without compromising network reliability. Digitalisation tools and smart logistics advance network efficiency and resilience and can help in this regard.

2.3.5.3 Ports' competition and selection

It is widely acknowledged that ports are the core nodes in shipping networks and have become a substantive factor in the development of a city or country (Robinson, 2002; Wang and Cheng, 2010; Deng *et al*., 2013; Notteboom, 2017), the reliability of the container shipping network is based on the reliability of the selected ports.

The word "reliability" appeared often in the fields about port selection and port competition which suggests that reliability is one of the important characteristics that ports should have. It is common that several ports that have geographic proximity share the same market, among which, one of the ports would be selected individually based on different requirements of the decision makers. The increase of routing options, each using a particular port, implies more competition between ports and thereby a need for adequate tools of analysis. Although there are limits to the choice of the port; for example, the size of the ship, port choice still remains to be a pertinent issue. The shipper, freight forwarder and carrier have the demand to choose a reliable port that can provide service that meets their requirements. From this perspective, reliability is defined according to the factors that influence the selection results. There is a significant number of factors that drive a port's service quality in different classification and they may affect the choices of different stakeholders (Parola *et al.*, 2016). In the 1980s, Willingale (1981), Collison (1984) and Slack (1985) suggested several components of port choice which covered ports in Europe, America and Southeast Asia. Based on these studies, Peters (1990) and McCalla (1994) revealed varying methodologies and major influencing factors. When determining the criteria that are used to guide a port's selection decision, most of the studies on this topic apply methods followed by expert surveys (Slack, 1985; Lirn *et al.*, 2004; Wiegmans *et al.*, 2008), fuzzy analysis (Chang, 2008; Chou, 2010; Yeo, 2011), Analytic Hierarchy Process (AHP) (Yedla and Shrestha, 2003; Lirn and Beresford, 2004; Yuen, 2012), Multinomial Logit Model (Nir *et al.*, 2003; Tiwari *et al.*, 2003; Veldman, 2016) and Data Envelopment Analysis (Tongzon, 2001; Barros and Athanassiou, 2015). Table 2.4 synthesises a literature review on factors affecting port choice since the 2000s, along with the methodologies applied to identify those factors. Table 2.4 shows that a considerable amount of literature is focused on factors affecting port selection. However, different projects that select different determinant factors and criteria are not equally weighted.

Figure 2.5 provides a summary of the influencing factors related to reliability based on the findings from Table 2.4. The potential determinants of port choice concerning reliability may be divided into two parts: quantitative and qualitative. Qualitative factors include subjective influences such as flexibility and ease of use, port's marketing efforts, tradition, personal contacts and the level of cooperation that can be established between the shipper and the port. Quantitative factors are those that can be potentially measured and compared using analytical measures (Malchow and Kanafani, 2004). Given that ports have diverse and complex goals related to output, throughput and productivity measures, and customers have different demands and requirements, they cannot be adequately assessed on the basis of one single indicator (Feng *et al.*, 2012). Due to the demand of a more reliable port, the criteria that connected with reliability become essential during the port selection. That is, in order to measure whether it is a reliable port, it is necessary first to identify the components or factors that influence the reliability of ports (Cabral and Ramos, 2014). A more comprehensive understanding of the factors can ensure more reliable ports.

Reference	Methodology	Criteria identified
Mangan *et al.* (2002)	Survey Modelling	Service availability; Sailing frequency; Risk of cancellation; Fastest overall route; Cost; Speed; Delays; Intermodal; Information availability
Tiwari *et al.* (2003)	Multinomial Logit Mode	Port and loading charges; Ship calls; Number of berths; Number of cranes; Water depth; Routes offered; distance of the port from shippers
Nir *et al.* (2003)	Multinomial Logit Mode	Highway travel time; Travel cost; Number of available routes; Frequency
Ha (2003)	Survey	Information availability on port activities; Port location; Port turnaround time; Facilities available; Port management; Port costs; Customer convenience
Lirn *et al.* (2004)	Analytic Hierarchy Process	Port location; Port characteristics; Port management; Port charges
Malchow and Kanafani (2004)	Multinomial Logit Mode	Distance; Frequency of sailings; Average size of vessel; Loading/unloading time;
Lirn *et al.* (2004)	Analytic Hierarchy Process	Physical infrastructure; Geographical location; Port administration; Carriers cost per call
Song and Yeo (2004)	Analytic Hierarchy Process	Cargo volume; Port facility; Port location; Service level; Port expanses
Guy and Urli (2006)	Multicriteria Analysis Analytic Hierarchy Process	Port infrastructures; Cost of port transit for a carrier; Port administration; Geographical location
Ugboma *et al.* (2006)	Analytic Hierarchy Process	Efficiency; Frequency of ship visits; Adequate infrastructure
Langen (2007)	Ranking of importance	Location; Efficiency; Operating quality; Equipment; Shipping services; Connection to hinterland modes
Tongzon (2001); Tongzon and Sawant (2007); Tongzon (2009);	Survey Ranking of importance and linear regression	Frequency of ship visits; Port efficiency; Adequate infrastructure; Location; Port charges; Port's reputation for cargo damage
Wiegmans *et al.* (2008)	Survey	Port infrastructure; Location; Efficiency; Interconnectivity; Reliability; Service quality; Costs; Security; Reputation
Chang *et al.* (2008)	Survey Exploratory Factor Analysis	Local cargo volume; Terminal handling charge; Berth availability; Port location; Transhipment volume; Feeder connection
Chou (2010)	Analytic Hierarchy Process	Port charge; Port operation efficiency; Load/discharge efficiency; Size and efficiency of container yard; Hinterland economy; Depth of berth
Yeo *et al.* (2008); Yeo *et al.* (2011)	Survey Fuzzy Analysis	Port service; Hinterland condition; Availability (Congestion); Convenience Logistics cost; Regional centre; Connectivity
Yuen *et al.* (2012)	Survey Analytic Hierarchy Process	Port location; Costs at port; Port facility; Shipping services; Terminal operator; Port information system; Hinterland connections; Customs and government regulation
Lam and Dai (2012)	Analytic Hierarchy Process	Port infrastructure; Port charge; Container traffic;
Veldman *et al.* (2013)	Logit model	Inland transport cost; Maritime transport cost; quality of service;
Cabral and Ramos (2014)	Cluster Analysis	Throughput; Berth length; Number of berths; Delay time for mooring; Port tariffs; Berth depth; Medium consignment rate; Medium board; Delay time for load/unload cargo
Cantillo *et al.* (2018)	Mixed Logit Model	Frequency of shipping lines; Maritime transit time; Inland transit time; Maritime freight rates; Inland freight rates; Population; GDP per capita

Kadaifci *et al.* (2019)	Analytic Hierarchy Process	Terminal location; Structure; Operation; Cost criteria
Vega *et al.* (2019)	Discrete choice models	Access cost; The frequency of the shipping line; Maritime freight; Maritime transit times; Cargo type
Lin and Wang (2019)	Survey Analytic Hierarchy Process	Freight rate; Side condition; Volume incentive; Freight stability; Quotation efficiency; Freight competitiveness

Table 2.4 Literature review on criteria of port choice (Ordered by date)

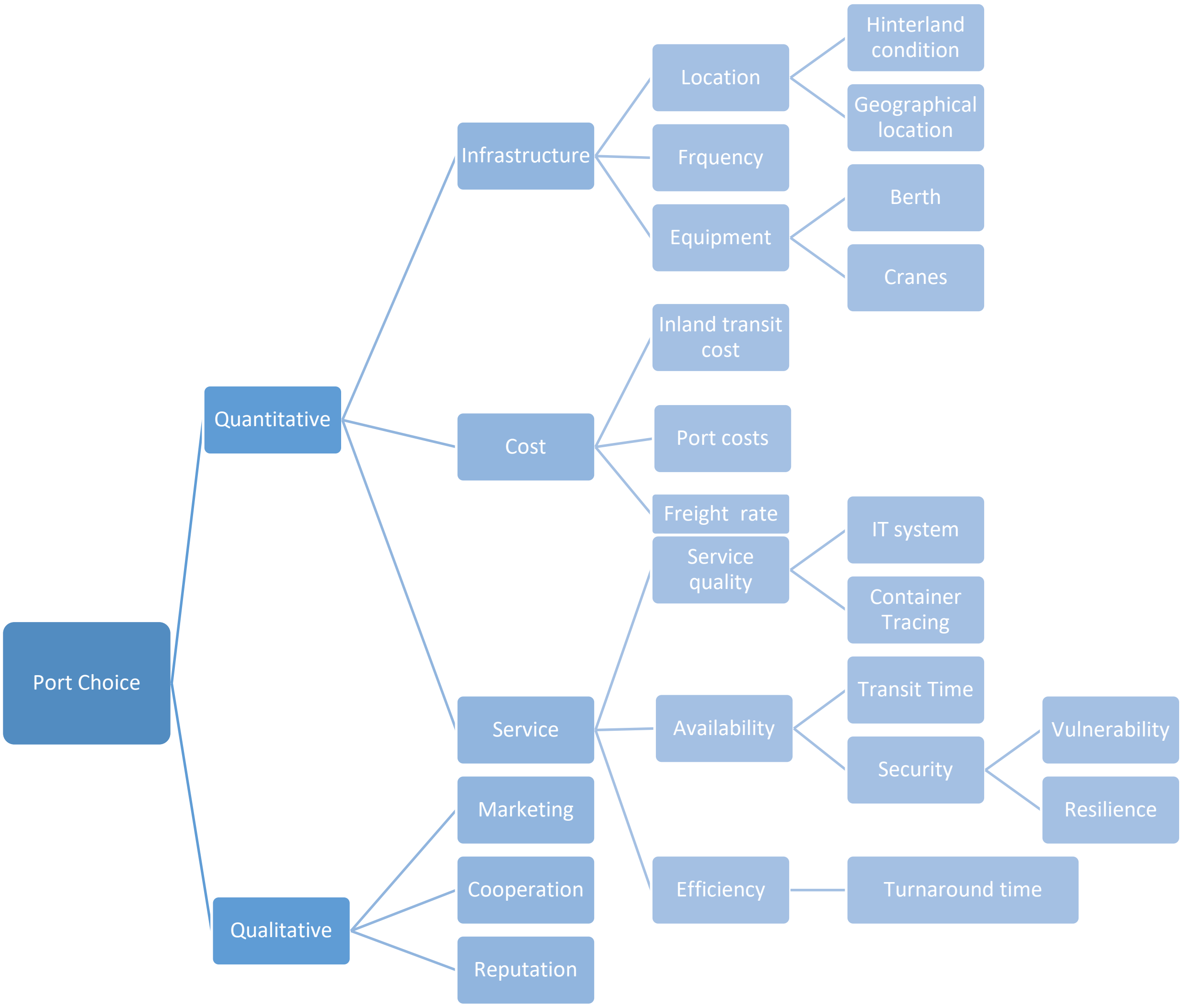

Figure 2.5 Port selection influencing factors
(Source: Author summarised based on Table 2.4)

The research on port selection has applied a narrow perspective of the framework summarised in this research. Analytical work on port selection emphasised the reliability of infrastructure and connectivity of assets in port, which has been discussed in Sections 2.3.2 and 2.3.4. However, studies have applied other influencing factors (e.g., costs and reputation when selecting), which have rarely been used to assess the reliability of the shipping network.

Moreover, even though ports are undoubtedly important nodes in container shipping networks, the reliability in relation to other components can also affect the performance of container transportation in which the port acts as only one node.

2.4 Conclusion

The definition of the shipping network reliability refers to the quality of liner performance under uncertainty from consignor to consignee. The literature review has highlighted how contemporary understanding and interpretations of shipping network reliability generally focus on one particular aspect, e.g., port performance. Ports are important nodes in container shipping networks since containers and trade flows rely on ports to transfer and reach destination markets. However, the container shipping network is not only made up of one part. In addition to ports' infrastructure availability and service quality, the network also gives insights into the procedures related to container logistics from consigner to consignee. Reliability of other components and aspects of shipping networks can also affect the performance of container transportation.

The literature is spread over a large variety of academic fields and involves multiple stakeholders, and the topic of reliability is relevant to many disciplines. Following on from the preceding SLR, two research questions are now posited:

RQ1: How is reliability best understood in the context of container shipping networks?

RQ2: What factors influence the network reliability?

The analysis has revealed that the existing literature encompasses different perspectives within the network. This suggested that the definition of reliability in the context of container shipping networks should be explored comprehensively and systematically across different fields rather than as an absolute concept. The key output of this chapter is that the analysis suggests an integrative **framework** that looks at determinants across sub-networks (ports, network structures and supply chains), and is summarised in three themes: (1) infrastructure reliability, which refers to the availability, capacity and efficiency of infrastructure within the network; (2) network configuration reliability, which addresses whether the network is easily affected by disruptions and the ability of the system to perform well even when parts of the system have failed; and (3) connectivity reliability, which refers to the probability of the components in the network being connected as well as the integration of different stakeholders among the supply chain (shown in Figure 2.6). The framework has demonstrated that **there is no unified or absolute definition of reliability in the context of container shipping networks, but that different approaches to understand it are taken depending upon the focus and frame of reference adopted.** This can be attributed to the fact that the reliability of the container shipping network does not fall into a discrete area, many aspects should be involved when assessing it.

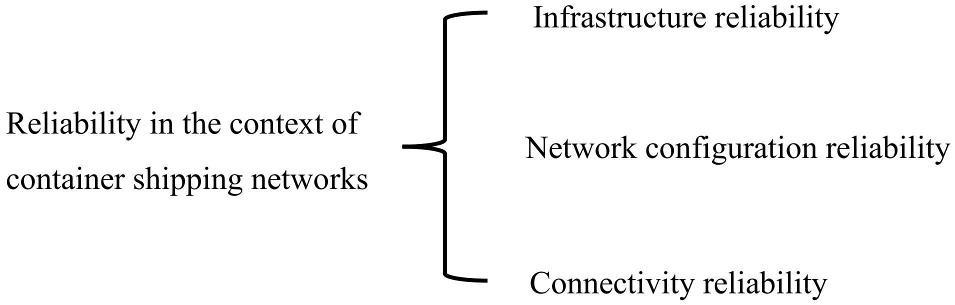

Figure 2.6 Illustration of the integrative framework

Meanwhile, the literature review revealed influencing factors under these three themes, summarised from the discussion in Section 2.3. In the framework, a total of 12 influencing factors were identified, some of which are common to more than one theme. Thus, the three themes are not mutually separate, there are shared features between each theme. For example, the infrastructure reliability also includes the inter-dependency between port assets, which encompasses connectivity reliability of the shipping network. The connectivity of the container shipping network is closely related to the position of ports within the network, which is in line with the analysis of network configuration reliability. It is also increasingly important to consider information sharing on infrastructure performance, therefore, infrastructure reliability can be viewed as fundamental to connectivity reliability.

This research project develops a framework for understanding reliability in the context of container shipping networks through a systematic and comprehensive analysis, and it also identifies influencing factors across different themes. The framework provides valuable guidance for all stakeholders (researchers, policymakers, industry, etc.), specifically in identifying barriers within container transportation and designing more effective polices for supply chain management. The research project highlights two gaps: little research is available on the reliability of container shipping networks, and the existing papers about reliability usually focus on one aspect of the shipping network. The aim of the research project is to fill in these gaps.

Chapter 3. Research design

3.1 Introduction

Chapter 2 suggested a new integrative framework that considered determinants across sub-networks and summarised it into three themes: infrastructure reliability, network configuration reliability and connectivity reliability. This framework provides a better guidance for comprehensively understanding reliability in the context of container shipping networks, identifying constraints for improving reliability and assessing the impact of those constraints. Based on the knowledge gap and the new integrative framework identified in Chapter 2, this chapter presents the research questions, research philosophy, methodology and methods that will be used to further investigate container shipping network reliability.

3.2 Research questions

In accordance with the research gap identified in the SLR, the research problems addressed in this research project were defined as follows: little research is available on reliability in the context of container shipping networks; the research about shipping network reliability mainly refers to one perspective of reliability. There is evidence in the literature that there are factors from different perspectives affect the reliability of container shipping networks, few studies have investigated reliability in any systematic and comprehensive way. There is indeed a need to provide a comprehensive analysis to explore the influencing factors of reliability and provide approaches for assessing reliability.

The research stated two research objectives:

(1) To investigate the relationship between reliability and container shipping networks.

(2) To determine the best approach for comprehensively assessing the reliability of container shipping networks.

The following research questions were developed to fulfil the research objectives:

RQ1: How is reliability best understood in the context of container shipping networks?

RQ2: What factors influence the network reliability?

RQ3: How can the impact of these factors on container shipping network be measured?

RQ4: Would there be a more comprehensive approach to assess the reliability?

Following on from the SLR in Chapter 2, RQ1 and RQ2 were posited. The rationale for RQ3 and RQ4 will be discussed further later in this chapter (Section 3.5) and are elaborated in depth in Chapters 5 and 6.

3.3 Research philosophy

According to Saunders (2015), the phrase research philosophy refers to a system of beliefs and assumptions about the development of knowledge, which shapes how researchers investigate research questions, research methods and analysis procedures. As the first step for the research, the research philosophy helps to develop the knowledge in a specific field and design the procedures of the research. In scientific research, there are two principal research paradigms, which are generally labelled: positivism and phenomenology (Mangan *et al.*, 2004). A paradigm is a general conception of the nature of scientific endeavour, within which, model problems and solutions are provided, and it is basically a “world-view” (Wittgenstein, 1961; Mangan *et al.*, 2004). A research paradigm is a framework that guides how research should be conducted based on research philosophies and assumptions. According to Burrell and Morgan (1979), the interpretivism (phenomenology) paradigm understands the world at the level of subjective experience. In contrast, the functionalist (positivism) paradigm applies the models and methods of the natural sciences to human affairs (Burrell and Morgan, 1979; Hussey and Hussey, 1997). According to Collis (2014), paradigms include three elements: ontology, epistemology and axiology. Ontology refers to the nature of reality (Collis, 2014). Epistemology is concerned with what is accepted as valid knowledge by the researcher (Saunders *et al.*, 2009). Axiology refers to the research’s view on the role of values in research (Saunders *et al.*, 2009). Table 3.1 compares the relevant characteristics and elements between positivism and phenomenology paradigms.

	Positivism	*Phenomenology*

Ontology	Social reality is objective and external to the research.	Social reality is subjective and socially constructed.
Epistemology	Knowledge comes from objective evidence.	Knowledge comes from subjective evidence from participants.
	Independent. The research is distant from phenomena under study.	Interdependence. The researcher is involved in defining the phenomenon under study.
Axiology	The results are unbiased and value-free.	The findings are biased and value-led.
Approaches	Quantitative	Qualitative
	Objective	Subjective
	Scientific	Humanist
	Traditionalist	Phenomenological
Research data	Highly specific and precise.	High quality and depth.
	Large samples.	Small samples.
	High reliability, low validity.	Low reliability, high validity.

Table 3.1 The comparison of positivism and phenomenology

Source: Author based on Burrell and Morgan (1979), Easterby-Smith *et al.* (1991), Mangan *et al.* (2004), Saunders *et al.* (2009) and Collis (2014)

Positivism had been the dominant paradigm in social sciences until researchers argued that it was impossible to separate the investigator from what was being investigated (Mangan *et al.*, 2004). As a result, phenomenology was developed as the opposed characteristics. However, Morgan and Smircich (1980), Easterby-Smith *et al.* (1991) and Hussey and Hussey (1997) proposed a middle bridge between these two opposing viewpoints. They suggested that instead of only adopting the issues from one extreme viewpoint, it was better to investigate research questions from both positivist and phenomenological perspectives. **Pragmatism** represents this middle stage between positivism and phenomenology, where a combined approach is possible (Saunders *et al.*, 2009). Pragmatism strives to reconcile both objectivism and subjectivism, facts and values, accurate and rigorous knowledge and different contextualised experiences (Saunders *et al.*, 2009). Figure 3.1 provides the research onion, which helps to understand the position of pragmatism within the research procedures.

The selection of the research philosophy and adopted paradigms has an impact on the selection of research methods. According to Saunders (2015), the selection of the paradigm should take into account the nature of the research questions rather than the researcher’s preferences. The purpose of this research project is to understand what reliability in the context of container shipping (i.e., liner) networks means, identify the influencing factors, and explore methods to assess reliability. The results from the SLR in Chapter 2 suggested that the reliability of container shipping networks does not fall into a discrete area, many aspects should be involved when assessing it. As this is a complex topic involving various disciplines, the research project requires an analysis of reliability-related problems in container shipping networks from different perspectives. Additionally, the research needs analysing from the industry perspective to gain understanding of the phenomenon. Given the assumptions and research questions, a range of philosophical perspectives is needed to explore the topic comprehensively. Pragmatism, which asserts that research starts with a problem and aims to provide solutions in reality that inform future practice (Saunders, 2015), lies between positivism and phenomenology, allowing for the utilisation of different approaches and multiple methods instead of relying on one particular knowledge or method. **Therefore, the selection of methodology and methods in this research project will be guided by the adoption of pragmatism,** which is detailed in Sections 3.4 and 3.5**.**

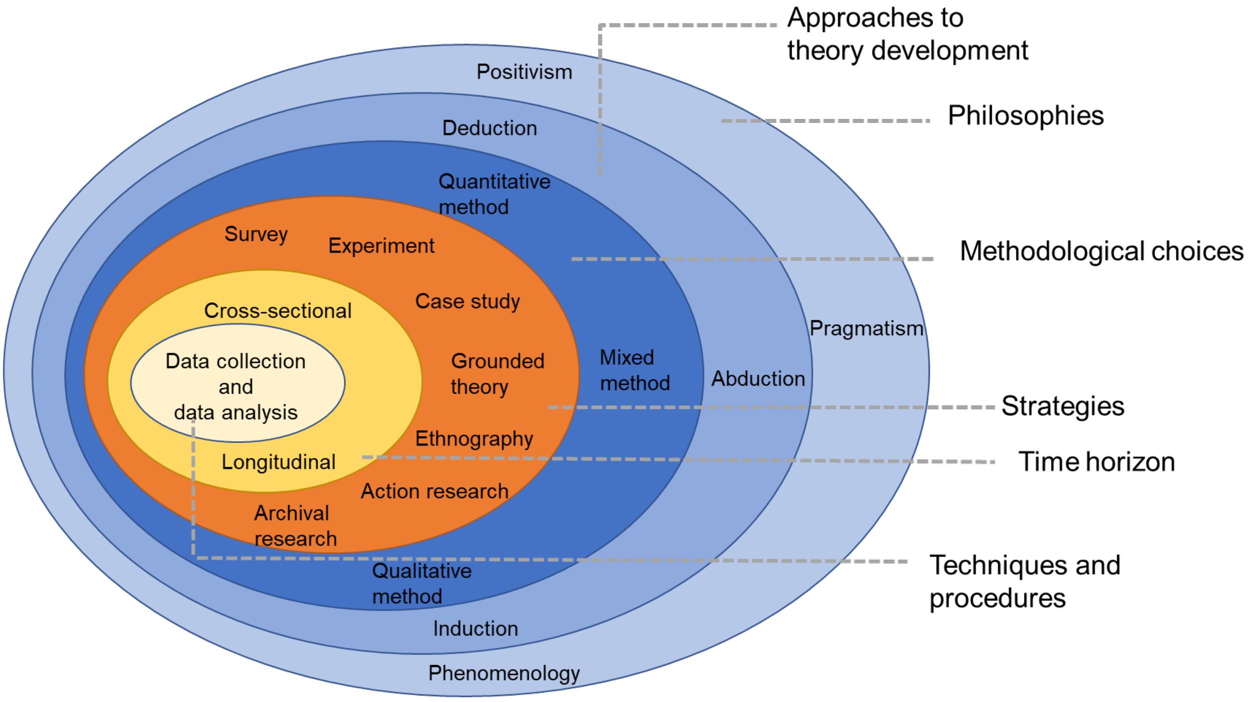

Figure 3.1 Research onion

Source: Author elaboration based on Saunders *et al.* (2009)

3.4 Research approach and methodology

The research philosophy stated in Section 3.3 drove the approach to the theory development and methodology adopted in this research project. The selection of pragmatism asserts that there are different ways of approaching the research questions, leading to various appropriate approaches within one research project. There are sometimes confusions regarding the difference between approaches to theory development and methodology. According to Ketokivi and Mantere (2010), approaches for theory development consider the relationships between theory and research. Theory is crucial, but the relationship between theory and research differs for each approach. There are typically two contrasting approaches to the reasoning of the adoption: deductive or inductive, as shown in Figure 3.1 above. The deductive approach refers to research that starts with a theory, and the data is collected to evaluate propositions or hypotheses related to an existing theory, which is associated with positivism (Azungah, 2018). Conversely, the inductive approach starts by collecting data to explore a phenomenon and generate a theory, which is associated with phenomenology. In accordance with pragmatism, which was selected in this research, the **abductive approach** was selected. According to Saunders (2015), data is collected to explore the phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth, effectively combining deduction and induction. The SLR indicated that there is no unified or absolute definition of reliability in shipping networks, but there are different approaches to understanding it. For the abductive approach, this research project can understand as well as assess reliability.

As defined by Mingers and Brocklesby (1997), methodology refers to a structured set of guidelines or activities that assist researchers in undertaking research or interventions. More specifically, it refers to the type of research activities that need to be conducted. Based on the decision of the methodology, the particular ways these activities can be performed are recognised as strategies, as will be discussed in Section 3.5. In areas relevant to this research project, such as logistics research, Mangan *et al.* (2004) and Näslund (2002) had pointed out the necessity of using both quantitative and qualitative methods. In order to analyse the phenomenon under this research project comprehensively, methodologies and approaches need to be combined instead of particularly using one. Therefore, in this research, a combination of quantitative and qualitative methodologies was chosen in order to explore the research questions holistically and comprehensively. The study of Saunders (2015) has established that a mixed-method methodology is a branch of multiple methods that integrates the use of quantitative and qualitative data and measuring methods in the same research. Hence, the **mixed-method** was selected as the methodological choice.

The selection of mixed-method has also been covered in the literature, advocating *triangulation*, which refers to the use of different approaches and techniques in the same study, enabling the researcher to overcome the potential bias of a single approach (Mingers and Brocklesby, 1997; Mangan *et al.,* 2004). Mangan *et al.* (2004) pointed out that triangulation "provides a middle ground and some bridging", and they listed four types of triangulations: multiple sources of data, more than one investigator, qualitative and quantitative methodology, and theories from different disciplines.

To select the appropriate approaches and methodologies, this section carried out a review of inductive and deductive approaches, as well as quantitative and qualitative methodological choices. After the review, pragmatism philosophy, abduction to theory development and a mixed-method methodology were selected in order to address the research questions.

3.5 Research theoretical framework and techniques

The philosophical underpinning of research influences the choice of techniques just as it does for the theoretical drive of the research endeavour. The selection of pragmatism, discussed in Section 3.3, led to the adoption of an abductive approach in this research. The review of approaches to theory development in Section 3.4 highlighted the distinction between inductive and deductive approaches for qualitative and quantitative research methodologies, respectively. Meanwhile, a methodology combining both quantitative and qualitative methods was selected to provide a holistic and detailed exploration of the phenomenon under investigation. Table 3.2 presents the overall research design. The following sections will discuss the theoretical framework employed in this research and outline specific strategies and techniques used for addressing each research question.

Research Objective	Phase	Research Question	Methods	Chapter

To investigate the relationship between reliability and container shipping networks.	Year 1	RQ1: How is reliability best understood in the context of container shipping networks?	Systematic literature review Interviews	2 4
	Year 2	RQ2: What factors influence the network reliability?		
To determine the best approach for comprehensively assessing the reliability of container shipping networks.	Year 2	RQ3: How can the impact of these factors on container shipping networks be measured?	Review and classification of measures	5
	Year 3	RQ4: Would there be a more comprehensive approach to assess the reliability?	Network analysis Simulation	6, 7, 9 8

Table 3.2 Overall research design

3.5.1 Theoretical framework

This research project suggests an integrative framework that looks at definitions and influencing factors from three themes based on sub-networks. Far from providing a unified or an absolute definition of reliability in the context of container shipping networks, each theme suggests that there are different approaches to assess the phenomenon depending upon the focus and frame. Assessments that concentrate only on parts rather than the entire network tend to ignore the interaction between each theme. There is a need to address these themes from a systems perspective. As a consequence, what is hypothesised in this research is that the reliability in the context of container shipping networks should be analysed from a **systemic perspective**. The core premise of systems thinking is that “systems are made up of sets of components that work together for the overall objective of the whole” (Barton *et al.*, 2004). It allows us to deal with complex things in a holistic way (Mingers and White, 2010). Systems thinking claims that learning from a systemic perspective enables understanding the interrelationships between each part and its environment in order to discover the most important structural and functional aspects that lie behind system performance (Jackson, 2009).

A development within the systemic approach is **complexity theory,** which has been applied to various disciplines. Forrester (1970) explained the fundamental differences between simple and complex systems and explored a number of applications for his theory, including urban systems. In engineering, new techniques that focused on complex systems rather than separate components became a discipline in its own right, termed "systems engineering" (Gorod *et al.*, 2008). As stated by Eisner *et al.* (1991), several interdependent systems formed, and in their combined operation, offered a multifunctional solution to an overall coherent mission. However, the optimisation of each system cannot guarantee the optimisation of the overall system of systems, despite the fact that they have been developed under quite disparate conditions and ground rules. The contextual nature of the research questions stated in this research is that of complex systems. With reference to the pragmatism incorporating abductive approaches, the selection of the systemic approach as the theoretical framework for this research allowed the researcher to involve the three themes retrieved in the literature review, as well as the incorporation of different disciplines and multiple methods, both quantitatively and qualitatively. Each theme can be regarded as parts of the complex system, and the reliability of the complex network depends on the optimisation of all three systems, which can adopt a more holistic view of reliability-related problems and show the impact of network components on the entire network, as well as the interaction between each component.

The science of complexity theory provides a useful framework for the analysis of shipping systems (Caschili and Medda, 2012). Complex systems can be represented as a set of interconnected entities in the form of networks and graphs (Spector *et al.*, 2001). Under the systemic approach, **network analysis** – the method that used to analyse the structure and dynamics of networks – was selected as the main tool to investigate this research. In reality, many things could be abstracted as a network and studied from a systemic perspective. For example, the social network built from the relationships between people, the transportation network between regional cities, etc. It can be concluded that the network is composed of individuals, and the relationships between individuals. Individuals are the nodes in the network, and the relationships between individuals form the links in the network. Network analysis principally describes the respective situation of individuals with regard to the overall structure of the network and the existence of communities. It is a method frequently used in transportation and logistics research (Barabasi, 2014; Calatayud *et al.*, 2016). Transportation networks are being widely studied and there are different parameters in many literatures to describe the characteristics of different types of complex networks. Network analysis has also been applied to study shipping networks in a lot of research (Notteboom, 2006; Ducruet and Zaidi, 2012; Hu and Zhu 2009).

At present, networks have experienced three stages: regular networks, random networks and complex networks. Before the emergence of complex networks, networks were mainly divided into random networks and regular networks. With the research of various real networks, researchers discovered that some real networks have “small-world” and “scale-free” characteristics. These networks exhibit a high degree of complexity between random networks and regular networks. Therefore, physicists call this kind of network a “complex network”. Complex networks have been deeply applied to many fields such as transportation, science, social economy and so on. It is an important content of academic research to study the relationship between the structural changes and network functions. The shipping network shows the characteristics of a complex network due to the combined actions of many factors, such as route distribution, port geographical environment, location relationships between ports, shipping company's planning and so on. Slack (1999) assumed that shipping networks generate “small-world” in which content may vary over space and time under the influence of trade and carrier patterns. In the shipping network, a few main ports have more connections, while a larger proportion of ports have very low connectivity. This structural evolution clearly demonstrates the general properties of a “scale-free” network. Since 2009, researchers had applied complex network theory to set a new standard for maritime analysis.

This research project aims to investigate the reliability of container shipping networks. As science and technology have advanced, network systems have evolved into large-scale, complex and systematic, making the study of network reliability increasingly crucial. The concept of network reliability was originally proposed by Moore and Shannon (1956) to analyse the reliability of electrical circuits with unreliable individual components. From the view of network analysis, the elements in the system are represented as nodes in the network, and the relations between the elements constitute the entire system. Network reliability, in this context, refers to the ability of the system to normally complete the assigned tasks under certain conditions. Network reliability needs the service capacity of the network can satisfy the flow in the network from the starting point to the destination point according to the original plan. Even if it is delayed due to unexpected disruptions, the network can be completed as soon as possible with the fastest response and the minimum loss. The reliability theory has been used among different transport networks (Chang, 2010; Yang *et al.*, 2010;

Ehmke *et al.*, 2015; Karsten *et al.*, 2015; Zhang *et al.*, 2017; Li *et al.*, 2019; Nath *et al.*, 2019; Prabhu Gaonkar and Mariappan, 2020).

3.5.2 Methods for RQ1 and RQ2

To answer the first two research questions, a combination of qualitative and quantitative methods was employed to explore the relationship between reliability and container shipping networks. A SLR was conducted to explore and understand the definition and identify the determinant factors that may influence the degree of reliability, ultimately leading to the establishment of a suitable conceptual framework. The analysis procedures, along with the detailed discussions have been explained in Chapter 2. The results revealed that the definition of reliability in the context of container shipping networks should be understood within different fields rather than as an absolute concept. The procedures in different parts of the container trade have varying degrees of impact on network reliability. It can be attributed to one topic that the reliability of the container shipping network is related to several fields and the determinants may be different.

Based on the insights from the SLR, interviews with key industry stakeholders were proposed to further explore the understanding of reliability from different perspectives, and its determinants (Chapter 4). In this exploratory stage, a semi-structured interview was decided to be appropriate to investigate the aspects that have not emerged from the literature review as well as to validate the results from the implementation of the systematic literature review. The purpose of the interviews was twofold, namely: (i) to understand the reliability-related issues from the industry perspective and to capture the determinants in reality; and (ii) to compare the findings from the interviews with the insights retrieved from the literature review; thus, enhancing the validity of this research. In order to gather information of all the different aspects and procedures from consignor to consignee, six semi-structured interviews with pre-determined questions (Appendix 2) were conducted. To encompass the entire container shipping network, interviewees were selected from different roles, including carriers, shippers, freight forwards, logistics company managers and captains of container ships. Interviewees were selected among leaders and managers who were confidential and experienced in their working firms in order to capture a high-level view of the understanding on reliability in this research project. During the interviews, responses were recorded, and notes were taken. After the interviews, the collected data was integrated, summarised and analysed by content analysis to generate meaningful insights. The results of the interviews are discussed in Chapter 4.

3.5.3 Methods for RQ3

A literature review (qualitative) was conducted to address the third research question, and the results are presented in Chapter 5. The researcher critically reviewed available commercial metrics and measures with the purpose of considering whether they could be used to evaluate the reliability of the container shipping network in this research. Through a thorough review, the available measures and metrics were analysed and classified based on the integrative framework adopted in this research project – infrastructure reliability, network configuration reliability and connectivity reliability. The classification of the measures allowed the researcher to explore the themes to which these measures belonged and determine whether it was possible to include all three themes comprehensively by one available measure. The review and classification of measures aimed to answer the third research question, explore the suitability and limitation of the available indices and propose an accurate measuring method according to the framework.

3.5.4 Methods for RQ4

As discussed in Section 3.5.1 on Systems Thinking, network analysis is widely employed in transportation and logistics research, and it has been selected to develop a new comprehensive approach to assess reliability in the context of container shipping networks, so as to address the last research question. As mentioned in Chapter 2, studies in the field of maritime network structures have applied graph theory and complex systems to generate topological networks and explore network robustness based on “small-world” networks, with high cluster densities among nodes, or “scale-free” networks, where limited nodes in the network are highly connected (Hu and Zhu, 2009; Ducruet *et al.*, 2010; Viljoen and Joubert, 2016; Liu *et al.*, 2018; Wu *et al.*, 2019). In the papers about shipping network analysis, ports are regarded as nodes, and the links are the shipping lines that directly connect each port. The essence of complex network analysis is to analyse the collected data, transform it into a description of the actual data, and build a model of the real network. Based on the connection between ports and shipping routes, a non-weighted network model can be constructed. Additionally, it can further describe the transportation status and function of the maritime network system and deepen the level of network analysis by giving weight to each link and establishing a weighted network on this basis.

The analysis results of the review and classification of measures revealed limitations in the existing approaches and methods when considering their appropriateness in the context of the identified three themes in this research. Specifically, there was a lack of measure that considered both the role and characteristics of nodes within the network as well as the connectivity between nodes. Furthermore, the samples selected for analysing each theme were not consistent in scale, and the combination of results from each theme was not connected logically. To address these limitations, network analysis was chosen as a method to develop a more comprehensive approach for assessing reliability for several reasons: (i) network analysis transfers all elements of a real system and their relationships into nodes and links, making it a more robust and realistic method to assess the reliability of the network; (ii) network analysis enables the researcher to understand not only the importance and characteristics of individual nodes but also their position within the network configuration. Additionally, it allows for the analysis of network dependency and the propagation effect from the perspective of connectivity; and (iii) network analysis allows the researcher to simulate the complexity of shipping networks, particularly in understanding how nodes may be affected by various factors and disruptions. The reasons for applying network analysis to the measurement of network reliability are extensively explained in Chapter 6.

In this section, the main features of network analysis and the collected data are introduced. This research project intended to use the shipping network between Asia and Europe (CSN) to assess the reliability. The trades between Asia and Europe were selected for several reasons:

- Asian countries (48) and European countries (50) include both developed and developing countries, which helps to avoid the biases that emerge from the level of international trade and GDP.
- According to the international maritime trade data provided by UNCTAD (2020), Asia has become a maritime hub that brings together over 50 per cent of global maritime trade volumes. Containerised trade routes between Asia and Europe handled 39.1 percent of worldwide containerised trade flows in 2019, which is the main corridor among container shipping networks. The container trade between Asia

and Europe makes the chosen corridor very representative to explore the global container shipping network.

- As for the port throughput, Asian ports with nearly two-thirds of the world's total port throughput, maintained Asia's position as the global hub for container port traffic. Europe was the second-largest container port handling region in 2020 (14.4 per cent).
- According to Lloyd's List (2020), 19 ports out of the top 20 container ports in annual container throughput are from Asia and Europe.

Data was gathered from five shipping companies that operate between Asia – Europe. The collected data included information about all ports of call, the frequency of transportation, the number of ships and their capacity, the time of departure and arrival, and the important sea lanes that the ships passed by. Take route AEU3 from COSCO for example (Figure 3.2). The frequency of transportation on this route is once a week, with a transportation time of 78 days per voyage and a fleet of 12 container ships. The ports of call include Tianjin, Qingdao, Shanghai, Ningbo, Singapore, Rotterdam, Hamburg, Antwerp, Shanghai, and Tianjin. The data was provided by the shipping companies.

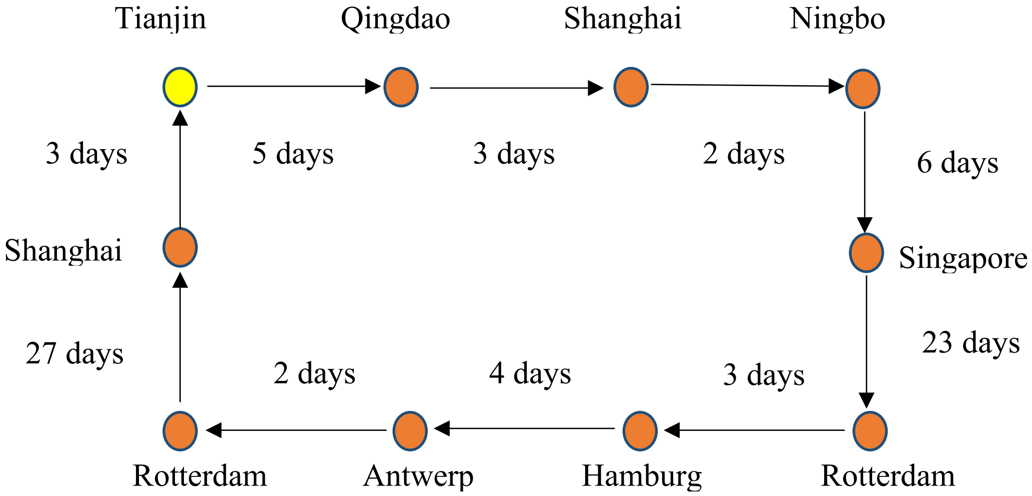

Figure 3.2 AEU3 Route from COSCO
(Source: author elaboration based on shipping company website https://lines.coscoshipping.com/home/Services/route)

The selected data was gathered and inputted into software named Gephi to visualise the shipping network. Gephi is the tool for interactive visualisation and detection of dynamic and layered diagrams of various networks and complex systems that is commonly used for network analysis. Gephi was selected as the tool for network visualisation for several reasons:

its selection is underpinned by its capacity to facilitate the creation of visually appealing and informative network representations; it supports interactive exploration of networks which is crucial for gaining insights into the network structure and identifying patterns; it is suitable for both small and moderately large networks, given the dataset dimensions inherent in this research. Gephi's adeptness in handling such data sizes aligns seamlessly with the study's scope; and it can be integrated with other data analysis and visualisation tools, allowing researchers to incorporate network analysis into a broader analytical workflow seamlessly. Gephi proves to be a versatile and effective tool for network visualisation, aligning well with the requirements and preferences of analysing the container shipping network in this research.

The characteristics of the network were analysed using metrics derived from graph theory, including network degree, weight, clustering coefficient, closeness and betweenness. The topology of the container shipping network was pivotal in exploring the role of ports within the network, the reliability of network connectivity (i.e., the probability of the components in the network being connected), and the interdependency of connected ports. The analysis of network topology and connectivity also provided insights into network vulnerability and resilience. Simulations were then conducted using MATLAB to assess the impact of disruptions on ports and the propagation effect due to interdependency; thus, exploring the network configuration reliability.

Analysis of infrastructure, with a focus on port performance reliability, was conducted based on the **AIS data** provided by Sea/net Clarksons Research Portal. AIS data here refers to the Automatic Identification System data, which is a ship tracking system that provides regular updates on a ship's movement and other relevant ship voyage data to other parties (AbuAlhaol *et al.*, 2018). AIS data identified the actual ship information, container carrying capacity, entry and exit calls, arrival and departure times to ports and so on. This real-time AIS data was used to analyse the performance of the network, specifically to examine the turnaround time in ports, including the time at anchorage and the time at berth. Further details regarding AIS data collection are provided in Chapter 6 and the analysis results are presented in Chapter 9.

The methodology and methods applied in this research project are graphically shown in Figure 3.3.

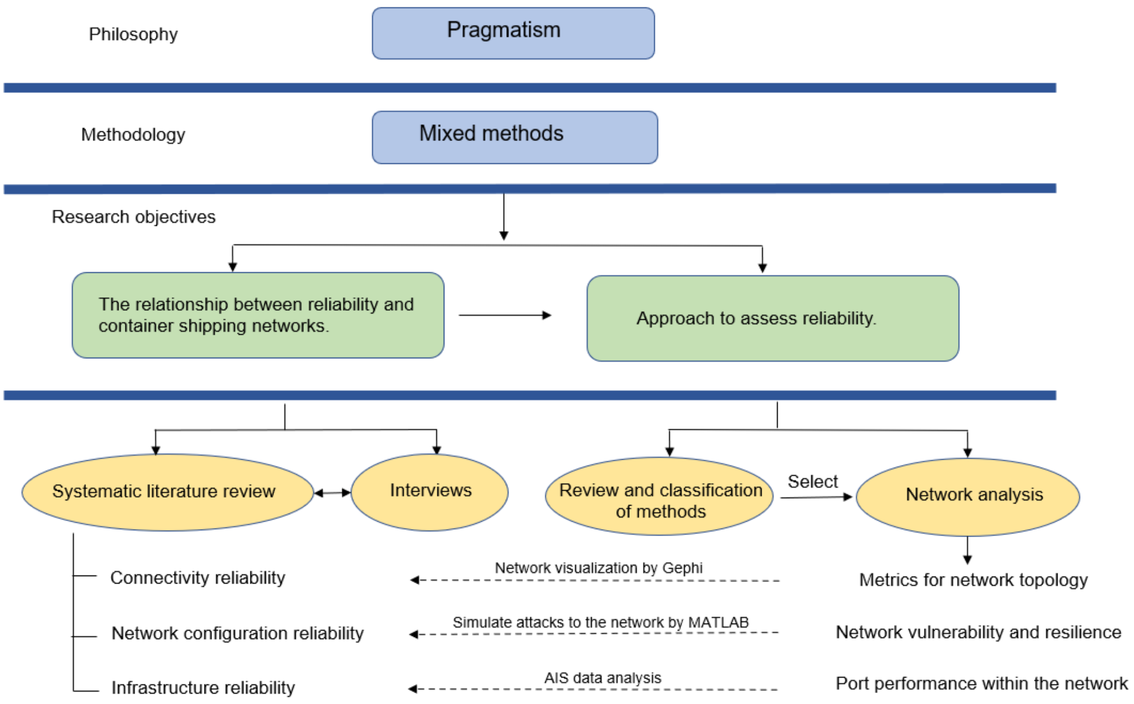

Figure 3.3 Diagram illustrating the methodology applied in this research

3.6 Conclusion

Based on the aim and research questions, this chapter reviewed the research philosophy to determine the most suitable approach for this research project and presented the selected research methods. The choice of the philosophical paradigm – pragmatism – was selected, along with an abductive approach for theory development and mixed methods, combining both quantitative and qualitative methods. The methods were adopted to explore the research questions holistically and comprehensively. Finally, specific techniques for addressing each research question were explained.

Chapter 4. Empirical evidence: Interviews and results

4.1 Introduction

The SLR in Chapter 2 established a framework for understanding reliability from three themes: (1) infrastructure reliability; (2) network configuration reliability; and (3) connectivity reliability. The findings drawn from the literature review suggested that instead of understanding reliability in only one field, the definition should be explored comprehensively and systematically rather than as one absolute concept. Based on the findings from Chapter 2 and the integrative framework, this chapter further explores RQ1 and RQ2: the understanding of reliability in the context of container shipping networks, and the influential factors affecting reliability, from an industry perspective. Section 4.2 introduces the design procedures for the interviews that are proposed by the researcher. Section 4.3 outlines the sample selecting procedures and the chosen interviewees. Section 4.4 reports on the analysis of the semi-structured interviews.

4.2 Interviewee selection

The major consideration of the interview is the careful selection of the sample to ensure the external validity and generalisability of the findings. It is not just necessarily about the quantity, but the quality of respondents. The researcher conducted interviews with diverse stakeholders during the period between June and July 2021, including:

- Carriers – representatives from American President Lines (APL) and China Ocean Shipping Company (COSCO).
- Shipper – representative from China oil and foodstuffs corporation (COFCO).
- Freight forwarders – representatives from Star Ocean Shipping LLC and Dalian Shipco Transport (Shanghai) Ltd. Dalian Branch.
- Logistics company manager – representative from Dalian Jilong Logistics Company.
- Captain of container vessel – representative from China Ocean Shipping Company (COSCO).

Details of the interviewees and interviews are shown in Table 4.1.

	DATE	TIME (MIN)	CITY	COMPANY	ROLE IN THE COMPANY	SHIPPING NETWORK(S)	MEDIA
1	25.06.2021	65	London, United Kingdom	Carrier	Senior trade analyst (pricing)	Mediterranean to Asia; Middle east; Oceania; North Europe	Teams
2	29.06.2021	50	Dalian, China	Logistics company	Customer Manger	85% of the vessels arriving at Dalian ports.	Phone
3	30.06.2021	45	Dubai, The United Arab Emirates	Freight forwarder	Marketing manager	Middle East ---- China Middle East ---- Europe Middle East ---- Iraq Middle East ---- Africa	WeChat
4	12.07.2021	50	Dalian, China	Freight forwarder Carrier	Deputy General Manager Manager	Asia --- Europe Asia --- North America China --- Southeast Asia	WeChat
5	13.07.2021	35	Shanghai, China	Captain	Captain	China ---- Europe China ---- United States Intra China	WeChat
6	15.07.2021	45	Dalian, China	Shipper (oil and foodstuffs)	Senior Manager (Design of logistics strategy)	Yingkou port and Jinzhou port ---- All the other container ports along the river and sea in China (Project: sending grains from the north to the south China)	Phone

Table 4.1 Background information of interviewees

This research component involved conducting interviews with a small sample of key informants. To gather information for all different aspects and procedures from consignor to consignee, the interviewees were carefully selected from multiple perspectives, including shipper, carrier, freight forwarder, captain of container ship and manager from a logistics company. This diverse selection encompasses key stakeholders in container transportation, ensuring a holistic understanding. Meanwhile, the interviewees were specifically selected among leaders and managers who were very experienced in their firms in order to capture a high-level view of the understanding on reliability in this research project. While the sample size of six may be considered small, particularly in light of the large and diverse population from which it is drawn, in opting for a smaller size, the research acknowledges the potential limitation in generalisability. However, this approach is intentional, as it allows for a more detailed exploration of individual experiences and perspectives. The smaller sample size facilitates in-depth qualitative insights, enabling a thorough examination of the nuances and intricacies associated with reliability in container shipping.

More specifically, Representative 1 worked as a senior trade analyst in the shipping company for more than four years and is experienced in conducting market research, and analysing ship performance, trade flow and pricing trends. Representative 2, stationed in Dalian, China, serves as a customer manager within a logistics company. His job includes the storage, management and transhipment of the containers importing and exporting from Dalian port. His company handles more than 85 percent of the shipping lines in Dalian port. Representative 3 brings a wealth of experience as a freight forwarder, having four years of working experience with Middle East-related shipping lines. Representative 4 has over 20 years of working experience in the shipping industry and used to work as a carrier but now as a freight forwarder, offering meaningful answers from diverse perspectives to the research. Representative 5 contributes as a well-experienced captain of a container ship. Representative 6, a senior manager of the logistics routes designing group in a shipper company, is experienced in designing the logistics strategy for their company and determining the suitable lines to deliver their products. It is pertinent to note that this research project intends to investigate the shipping network specifically between Asia and Europe. Five of the selected carriers and freight forwarders possess the shipping network(s) from Asia to Europe; thus, closely aligning with the focus of this research project.

4.3 Interview design

Based on the insights from the SLR, and with the intention of exploring the topic from an industry perspective, interviews with key industry stakeholders were proposed. In line with the research objectives, a semi-structured interview was decided to be the appropriate method in this research project. The semi-structured interview could be very helpful in finding out the in-depth understanding and provide important background for the research project (Saunders, 2015). Moreover, it serves as a means to explore the aspects that have not emerged before as well as to validate the results from the implementation of the SLR. The aims of the interviews are to (a) further explore the understanding of reliability from the industry's viewpoint; (b) investigate the determinants that influence the reliability in container shipping networks; (c) explore approaches for measuring the impact of determinants; (d) understand the actions taken in response to issues or concerns around reliability; and (e) compare the findings with the results generated by the literature review. The interviews were structured around a predefined set of questions, though the sequence may be adapted to the natural flow of conversations. Additionally, supplementary questions were required to explore specifically with different interviewees during the course of the interviews. These interviews were conducted through various platforms, including telephone, Teams, and WeChat, on a one-to-one basis, between June and July 2021.

The checklist provided by Saunders (2015) was used to prepare for the questions before the interviews: (i) Questions that seek to lead the interviewee or which indicate bias on your part should be avoided. (ii) Questions should avoid too many theoretical concepts since your understanding of such terms may vary from that of your interviewees. (iii) It is important to ask questions in the real-life experiences of your participant rather than being discussed as abstract concepts. (iv) Leave the sensitive questions at the end of the interview.

In accordance with the above checklist and the aim of the interviews, the following were some points that the interviewer would like to explore during the discussion:

Q1: Tell me a little about your company and your role within the company.

Q2: Please describe the container shipping network(s) that you use / operate.

Q3: In container shipping, what in your view, are the key performance-related and other criteria that are important?

Q4: “Reliability” is often regarded as a key performance criterion in container shipping – What is your interpretation / understanding of reliability?

Q5: In your experience, what reliability-related issues usually arise in your network?

Q6: In your opinion, what factors influence reliability in your network and which of these are of most importance?

Q7: How is reliability measured in your network?

Q8: What actions do you take when there are issues or concerns around reliability?

The list of the questions could be divided into three parts. The selected interviewees, as detailed in Section 4.2, included different industry stakeholders that were involved in container transportation. Q1 and Q2 were designed to get the background information about the interviewees, including details regarding their companies and roles within the company. The results would be analysed based on their position in the container shipping network to compare the understanding of reliability from different perspectives. The second part pertained to the key performance of container shipping. Q3 was formulated to shed light on whether reliability-related issues held significance in the context of container shipping performance from the viewpoints of various stakeholders. The last part comprised questions concerning the reliability of the container shipping network. Q4 and Q5 were explored to address the RQ1 outlined in Table 4.1, aimed at understanding reliability in the context of container shipping networks. The results were employed to gain insights into the practical understanding of reliability and its associated concerns, thereby investigating whether the understanding was different among various industry sectors. Q6 was designed to address the RQ2, and respondents were asked to identify the factors that influence the network reliability. The influencing factors could be aggregated and summarised from different interviewees comprehensively and the results could be compared with the preceding SLR results. Q7 and Q8 were asked to explore the actions and measuring methods that were used to solve the reliability-related issues in practice. These two questions could be used to provide suggestions and insights for the optimal approach to assessing reliability in the following chapters.

An interview agenda was designed as shown in Appendix 2.

4.4 Analysis of results

Based on the design of the interview questions and the research questions of this project, the collected data was analysed from three perspectives: interpretation of reliability, influencing factors and measuring actions. The dataset was summarised and categorised from the recorded audio and notes.

4.4.1 Interpretation of reliability

The first question (Q3), related to this perspective, was designed to shed light on whether reliability-related issues were essential to the performance of container shipping among different stakeholders. The responses provided diverse viewpoints regarding the paramount performance criteria and other significant factors that were important to container shipping. The majority of the interviewees (5) agreed that the freight rate or the cost of the shipping routes was the most crucial factor in container transportation. In agreement with pricing considerations, one of the freight forwarders highlighted the payload as an additional pivotal performance criterion. Commenting on the key performance of container shipping, one of the carriers explored the concept of container transport by comparing it with bulk shipping. The distinctive attributes of container transportation, characterised by efficiency, convenience and punctuality, were especially in contrast to bulk shipping. This can be attributed to the fact that time-related criteria such as transport time, transit time, efficiency of ports and so on were always considered by the container transportation stakeholders, which aligns with "infrastructure reliability" of container shipping networks as discussed in Chapter 2.

The interviewees could be categorised into two groups: one group encompassing service providers, such as carriers and representatives from logistics companies, and the other group consisting of customers in the network. The service providers that identified key performance criteria for container shipping were related to their capacity to meet customer expectations and the ability to deliver what they had promised while minimising cargo damage. Conversely, the customers' foremost requirement for container shipping performance was that the planning provided by the carrier should align with their specific needs, for example, the ports of call. Additionally, one freight forwarder suggested that the resilience of the container shipping network, along with the shipping company's responsiveness when facing disruptions were also important performance criteria that they would consider. The overall quality of container shipping services is of critical importance to the containerised trade and stakeholders. This is consistent with the definition of reliability proposed in this research project: the quality of liner performance under uncertainty from consignor to consignee.

For the second part of this section, the interview was formulated to explore the interpretation/understanding of reliability from the perspective of industry stakeholders. The majority of participants agreed with the statement that reliability to them referred to time delay. Specifically, one carrier opined that transportation could be deemed reliable as long as the delays were no more than 24 hours, which was echoed by another informant who worked as a freight forwarder. Time reliability was still the first consideration among the interviewees. Two interviewees, engaged as the container shipping routes designer from an oil and foodstuffs corporation and a carrier, expounded that reliability denoted the consistent and steady delivery of services, that is, the ability to deliver what they promised reliably. An example of this would be, whether there were enough containers to provide constant delivery and satisfy the customers; the fluctuations of the freight rate to provide stable delivery; the stability of the shipping schedules, and the frequency of changes to ports of call. Additionally, the captain of the container ship perceived reliability as pertaining to the safety of both the containers and the container ships.

These findings can be contributed to the fact that the requirement of time is still the most prevalent metric for assessing reliability. However, for certain stakeholders along the supply chain, reliability transcends a singular perspective, it encompasses other crucial aspects as well. The definition of reliability in the context of container shipping networks is a complex subject and should be understood systematically within different fields rather than as one absolute concept.

4.4.2 Influencing factors

The gathered data from the interviews was extracted from recorded interviews and detailed notes. In Chapter 2, the thematic analysis method was employed to explore the understanding of reliability comprehensively and systematically, with three identified themes: infrastructure reliability, network configuration reliability and connectivity reliability. In agreement with the results of the thematic analysis, the factors articulated by the interviewees were grouped according to the three identified themes. Then, **content analysis** was adopted to do the data analysis within each theme, which allowed deeper insight into the research questions. Content analysis is applied to categorise both the manifest and latent content of the data, which is used to analyse the influencing factors in this section. Within the definition from Berelson (1952) and Saunders (2015), content analysis represents a specific analytical technique of categorising data using a systematic coding method to analyse quantitatively.

According to Berman-Brown and Saunders (2008) and Saunders (2015), the data for quantitative analysis could be divided into two groups: categorical data and numerical data. The data collected from the interviews in this research project referred to the categorical data whose values and analysis results could not be quantified but could be grouped into different themes based on their characteristics and relevance to the research questions. More specifically, the collected data in this phase was characterised as descriptive data, which was not able to define the theme numerically or rank it. Its purpose was to provide a description and a simple count of occurrences within each theme. Although the data primarily served a descriptive role, it could shed light on the frequency of various influencing factors and the distribution of these factors across different themes.

Based on the framework of the research project, the outcomes of the interviews were categorised into the three themes (infrastructure reliability, network configuration reliability and connectivity reliability) as shown in Table 4.2. Within each theme, different factors and their impact were identified through the analysis. The red numbers in Table 4.2 indicate the frequency of mentions by the interviewees of each particular factor.

Theme	Factors		Impact
Infrastructure reliability	Terminal service	Limited efficiency (6) Port performance (4) Port operation (4) Congested port (1) Lack of containers (1) Human factors (3)	Delay Longer turnaround time and waiting time. Affect the reliability of next route. Higher transport cost and risk of freight damage.
	Land service	Congested road (1) Land transport infrastructure (1) Specialised infrastructure (1)	Longer transport time and higher transport cost. Higher transit times. Higher risk of freight damage.
		The price for land transport (1)	Higher transport cost.
		Sustainability limitation in the city (1) Limitation of trucks (2)	Lack of transport infrastructure, longer waiting time and higher risk of freight damage.
Network configuration reliability	Vulnerability	Disruptions in ports: Pandemic (5) Wind/ Weather (5) Strike/ human factors (2) Vessel equipment failure/ fire (2) Less of empty containers (1)	Delay or cancellation of the shipping routes. Longer waiting time and transit time. Higher risk of freight damage and vessel damage. Lower flexibility to arrange the following shipping routes. Increasing freight rate.
		Network configuration: Congested port (1) Accident (1) War (2) Policy (1)	
	Planning	Allocation of containers (3) Carrier planning (3) Too many ports of call (2) Cannot forecast/recover on time (1)	No available containers to transport and tranship. Longer waiting time. Higher risk for freight damage.
Connectivity reliability	Transportation accessibility	Port connectivity with land (1) Transit time (2) The speed of collecting and fixing containers (1)	Higher transit times. Longer waiting time and turnaround time. Increasing cost.
	Trade procedure	Cooperation between stakeholders (3) Communication with port (time window) (1) The speed of declaration for approval (1) Information sharing (2) Product clearance (2) Regulatory (1)	

Table 4.2 Summary of the influencing factors from interviews

The analysis of the interview results showed that the understanding of reliability in the context of container shipping networks is complicated, with diverse factors that affect reliability, and the results are different among stakeholders. The collected data from interviews were categorised according to the content analysis approach. A recurrent factor in the interviews was a sense amongst interviewees that the most important factor to reliability was the availability and efficiency of the infrastructure. The impact had experienced to varying degrees among different stakeholders. In addition to the concerns about infrastructure, carriers and the captain of container ship placed greater emphasis on vulnerability and potential disruptions that could happen during the journey. Another interviewee, a freight forwarder, pointed out that reliability was associated with time delays, but they often had limited options when disruptions occurred. From this point of view, the most important determinant to them was selecting a reliable shipping company that had better communication, supplier coordination, an effective information sharing system, and rapid response mechanisms for handling exceptional circumstances. Nevertheless, the interviews also revealed recognition among participants of the significance of network configuration and connectivity-related factors in their transportation operations. The responses provided by the six interviewees representing various sectors within the integrated container transportation system indicated that many procedures during the journey, from consignor to consignee, have an impact on reliability. The actions to addressing these issues varied based on the unique requirements of each stakeholder, and factors from multiple fields should be considered. One respondent said: "*the container transport and shipping networks are very complicated; the elements cannot be concluded from only one perspective*." Reliability in the context of container shipping networks is a complex topic that cannot be reduced to a single element, thus, demanding an integrated approach. As the results investigated in Chapter 3, the approach that was selected in this research project should integrate different disciplines across the entire supply chain systematically.

There is no doubt that **infrastructure reliability** is still the most important criteria to all the stakeholders. In all cases, the respondents reported the importance of port efficiency-related concerns. Less efficiency of ports operation, infrastructure availability, congestion in ports and issues arising from human factors contribute to extended turnaround times and waiting times in ports, which were the most obvious influencing factors in container shipping reliability. Furthermore, the interviewee from the logistics company demonstrated the availability of containers. This view was echoed by other informants who also raised concerns about allocation of containers, which has gained prominence recently. From his point of view, container availability here referred to the availability of empty containers for transhipment and the speed of container import and export processes. These aspects were related to the planning and distribution of containers. Additionally, a number of issues related to the reliability of land-based infrastructure were expressed. Road congestion, for instance, was identified as a factor that increased the transportation time, consequently impacting the delivery reliability of containers. In sufficient road infrastructure, including challenges related to the availability of trucks and drivers, were cited as prevalent issues in numerous ports, particularly during the pandemic. Due to the characteristics of cargo, specialised infrastructure also emerged as an important element to container transportation. Furthermore, one concern was raised regarding to the limitation arising from sustainability requirements. In certain cities, specific timeframes were designated for truck transportation, with restrictions imposed on truck access during other hours. To summarise, most of the interviewees emphasised the significance of infrastructure-related considerations. These factors have the potential to extend waiting time and turnaround time in port, subsequently increase transit times and affect the next journey of container transportation.

In the context of **network configuration reliability**, network vulnerability-related issues and the factors that appear at the network planning stage recurred throughout the dataset. Five of the interviewees all mentioned the importance of network vulnerability, including disruptions within ports and risks during the journey. Weather-related factors, for example, wind in ports, was one of the most frequently reported problems. The interviewees working as carriers and captain of ship pointed out the reliability-related issues caused by the failure of ship equipment or fire, which shed light on the importance of ship safety management. Furthermore, the influencing factors included the impact of war, strike, human factors, accidents, the specific policy in the country and so on. Network vulnerability is getting increasing attention between the stakeholders, especially when the impact of the pandemic was strongly felt recently.

Some interviewees alluded to the notion of network configuration at the planning stage, especially the representatives from carriers and freight forwarders. Within these factors, two main aspects emerged: allocation of the containers and carrier planning. Allocation of the containers referred to the balance between demand and the effective maritime transport capacity. An imbalance between container availability and increasing demand could result in carriers being unable to promptly provide containers for transhipment on time, thereby precipitating serious congestion and an unprecedented increase in freight rates. In addition to the allocation of planning, container availability-related problems had also been mentioned from the perspective of port operation. Extended time of container stranding within ports could disrupt port operations and lead to delays, accentuating port congestion. The strategic orchestration of container allocation, the transhipment of empty containers, and port operation ability emerged as pivotal factors contributing to the provision of reliable container services.

The other aspect relevant to network configuration reliability emanated from route planning considerations. One concern expressed the difficulty in meeting customer requirements, as sometimes the planning provided by the carriers was not realistic. The captain also emphasised that the shipping routes with an extensive number of ports of call, were more likely to be affected. Even if there were disruptions at a few of the ports, it would end up causing a lot of delays. In the planning stage, there were widespread concerns regarding predicting emergency response methods. This entails the ability of the system to anticipate and manage unconventional emergencies. The network should be capable of absorbing disturbances in time before interruptions occur, adapting to changes after the interruptions, and recovering quickly. The influencing factors from the perspective of network configuration reliability could result in delays or cancellations of shipping routes, increased risk of freight damage, reduced flexibility of subsequent routes, and increased cost.

The last body of the findings falls within the theme of **connectivity reliability**. The views surfaced mainly in relation to transportation connectivity and information connectivity. A subset of these factors concentrated on the reliability of transportation connectivity. Four interviewees expressed concerns regarding container transhipment between ports and land, as well as the interface between carious modes of multimodal transport. The manager of the logistics company contented that the pace of container collection and fixation was linked to container availability. Furthermore, the connectivity between ports and other transportation modes within an integrated transport system was essential for determining transit times – a factor intrinsically tied to land service availability. Connectivity reliability here stressed the importance of transit times, particularly for routes involving more ports of call.

The other part of the factors pertained to trade facilitation and communication or information sharing among stakeholders. One respondent explained that effective communication between ships, carriers, and ports was necessary to determine specific time windows, particularly during periods of port congestion. Not only concerning ports, but three interviewees emphasised the importance of shared information among stakeholders, facilitating the tracking of shipments and the collaborative resolution of disruptions. Two respondents stressed that information sharing was also essential for enhancing mutual trust. Two of the interviewees highlighted the importance of trade facilitation, including efficient freight clearance, streamlined trade procedures, and adherence to container transportation standards by shippers. They also explained that while procedural issues might not be the determinants throughout a journey, they assumed greater importance when disruptions happened.

4.4.3 Actions in response to reliability-related issues

In response to RQ3 and RQ4 in this research project, participants were asked about their approaches to measuring reliability within their networks and the actions they employed when there were reliability-related issues or concerns. Regarding the container shipping network configuration, most of the interviewees indicated that there were several actions that the carriers could take. A range of responses was elicited, with two carriers highlighting their typical approach if circumventing congestion or affected ports. One way is to skip calling at the port directly, moving to a different hub port or an alternative tranship port, and then either rerouting cargo back to the original port or exploring other transport modes. If the disruptions were caused by ship-related issues, interviewees stressed the imperative of finding alternative ships in time. Another strategy discussed by the interviewees was to control freight rates in order to discourage customers from booking the affected destination. From the viewpoint of shippers, addressing issues promptly is essential; however, a more competitive approach is pre-planning in order to avoid disruptions within the selected container network. This could be accomplished by, transporting containers to hubs in advance to reduce tranship time and minimise container shortages, as well as re-planning the schedule of the shipping network and making adjustments to avoid peak time. One respondent, acting as a freight forwarder, pointed that the actions they could take were limited when disruptions happened during the journey, especially from the perspective of cargo owners or freight forwarders, who typically concentrate more on the planning stage.

Regarding the perspective of infrastructure reliability, the majority of respondents commented that enhancing port operation and performance would contribute to solving the reliability issues in ports. In agreement with that, there was a consensus that the operational capacity needs to be increased and infrastructure modernisation efforts need to be undertaken. Other actions were around improving connectivity within the network. Two respondents highlighted the significance of communication and collaboration with terminals when addressing reliability concerns. Effective communication allows for determining optimal time windows and adjusting ship speed during the journey. Beyond ports, effective communication with other stakeholders was also deemed a useful course of action.

4.5 Conclusion

One informant stated: "*reliability-related issues is not a new topic, but it remains consistently essential and requires ongoing improvement*." The evidence provided by the semi-structured interviews explained that the understanding and definition of reliability in the context of container shipping networks varied among different stakeholders and industries. Interviewees emphasised distinct perspectives based on their positions within the supply chain, and many procedures throughout the journey from consignor to consignee exhibited reliability requirements. The results from the industry perspective proved the view postulated by the SLR that the container shipping network is not only made up of one part. Procedures across different parts along the container trade have varying degrees of impact on network reliability. An interviewee pointed out: "*the analysis of reliability in the context of container shipping networks cannot be explained easily or from one single view, it is complicated, influenced by many factors*." Confining analysis to a solitary domain would result in difficulties across other procedures. The influencing factors delineated by interviewees align with the framework of this research project. Infrastructure, especially port-related issues emerged as the most common factors that will increase the waiting and turnaround times. Nevertheless, in the context of container shipping networks, factors extending beyond infrastructure reliability – including disruptions, planning, connectivity along the supply chain and trade facilitation-related factors manifest comparable significance.

From the perspective of industry, a holistic consideration of the influencing factors becomes imperative, necessitating systematic approaches to evaluate and assess the impact of the factors. The next chapter will delve into an examination of available metrics that could comprehensively measure these factors and their implications.

Chapter 5. Methods for measuring reliability

5.1 Introduction

The comprehensive SLR and the interviews address the first and second research questions: (RQ1) How is reliability best understood in the context of container shipping networks? (RQ2) What factors influence the network reliability? After understanding the basic definition of reliability and the associated influencing factors, it leads to the third research question which serves as the focus of this chapter: **(RQ3) How can the impact of these factors on container shipping networks be measured?** This research question is related to how to investigate the impact of the factors identified in the previous analysis, and are there available indices or measuring methods that allow for a measurement of these factors? Based on the research purpose, in this chapter, the researcher conducted a comprehensive review of available indices and existing measurements that can be used to measure the factors that impact network reliability. Section 5.2 presents the widely used indices in the maritime sector. Sections 5.3 and 5.4 summarise reliability-related metrics and methods from the perspective of infrastructure and network configuration. Section 5.5 introduces supply chain-related metrics. Finally, section 5.6 conducts a comprehensive analysis and classification of these metrics and methods, in alignment with the identified integrative framework of the research project.

5.2 Container reliability-related commercial indices

At present, the commercial indices employed for the analysis of container shipping network reliability are mainly focused on schedule reliability. Schedule reliability refers to the actual on-time performance of individual ship arrivals in ports around the world. For example, the **Global Liner Performance (GLP)** report, developed by Sea-Intelligence Maritime Analysis, estimates the liner reliability by assessing schedule reliability. This report offers insights into schedule reliability and ship delays for all deep-sea liner services, based on more than 12,000 ship arrivals, and it measures and benchmarks the schedule reliability performance of more than 60 container carriers in 34 different trade lanes, across more than 300 liner services/loops (Sea-Intelligence, 2020). The metrics in the GLP include:

- The average delay for all ships, which is calculated as a simple arithmetic mean of the delay of individual ship arrivals. The delay of individual ship arrivals is calculated as the number of transport days between the scheduled and actual ship arrival.
- The average delay for late ships, which is calculated as a simple arithmetic mean of the delay of individual ships that are recorded as being late.

The metrics are used to analyse the global schedule reliability performance, carrier performance and trade lane performance. The GLP serves to introduce and establish rankings for the on-time performance of individual carriers and trade lanes based on the metrics comprehensively. In addition to ship reliability, it encompasses trade lane reliability, which takes into account the configuration of the container shipping network.

In addition to the GLP, there are similar indices that are used to assess the schedule reliability. Copenhagen-based eeSea, for instance, has developed a platform to accurately gauge the on-time performance of liner services. The **Liner Schedule Reliability Report**, developed by eeSea, is supported by the Automatic Identification System (AIS) data to track information transmitted by all cargo ships. It has examined the reliability performance of carriers and over 150 global liner ports. According to the report, during 2019, just under 50% of arrivals were classified as on-time (within eight hours of their standard proforma arrival), with some 10% of ships delayed by more than three days. However, the report in 2019 was rolled out initially on the three major east-west trade lanes only. The **Global Carrier Schedule Performance (GCSP) index,** developed by Shanghai Shipping Exchange, also focuses on analysing liner schedule reliability. The GCSP encompasses the on-time rate of global main lines (10 lines), major liner companies (17 carriers), and the global major ports

(50 ports). The GCSP index consists of arrival and departure on-time rates, receipt and delivery on-time rates and comprehensive service level index. The receipt and delivery on-time rate refers to the Estimate Berth (ETB), published by the liner company 15 days before the Actual Berth (ATB) of the ship, and the deviation is within 24 hours. The arrival and departure on-time rates are determined by the ETB announced by the liner company at the time of ship departure, and the ETB is within 24 hours as compared to the ATB. The comprehensive service level index is the product of the on-time rate and the dependency density. A higher index value indicates a more elevated comprehensive service level. The schedule data and ETB information are provided by the sample liner company, and ATB information is from the ship's AIS data.

In addition to the analysis about liner schedule reliability, Container xChange published the **Container Availability index (CAx)**, which serves as a tool for forecasting the availability of containers, thereby facilitating more informed repositioning and trading decisions. The CAx is expressed as a numerical value, with a CAx value of 0.5, indicating that an equivalent number of containers have departed from and arrived at a port within the same week. CAx value over 0.5 means that more containers enter, and CAx value below 0.5 means that more containers leave a specific port. Consequently, when the CAx value is at a very low level, it suggests that the safety stock of containers at a specific port is nearly empty. Conversely, when the CAx value is very high, the port is more likely to reduce its safety stock first before accommodating new incoming containers. This index ensures the reliability of container trade by maintaining appropriate inventory levels while efficiently manging the flow of containers.

5.3 Reliability metrics in relation to infrastructure

5.3.1 Metrics with regard to time in port

A large part of the indices employed in the maritime sector have been developed to assess the schedule reliability of ships, as introduced in section 5.2.1. Containerisation has facilitated "just in time" production through its improved schedule reliability (Notteboom, 2006). In this context, "just in time" refers to the punctuality of maritime services, particularly to the schedule reliability. Delays from the planned shipping timetable not only decrease the reliability of the liner service, but also increase logistics costs to the stakeholders as a consequence of additional inventory costs, and sometimes additional production costs. Travel time reliability is one of the most concerned issues for shipping companies and customers, and it is also a key measure in infrastructure reliability analysis which has been widely studied in other transport modes.

Research in this field has mostly applied the liner schedules to encompass the service reliability level of the container shipping infrastructures. Statistical methods are employed to track whether container ships operated by liner companies called at ports are consistent with the pre-announced ship schedules. With the improvement of information sharing technology, ship data is more available; thus, facilitating its utilisation in diverse network analysis approaches. An example is the Automatic Identification System (AIS), which provides a ship tracking system and guarantees high reliability of the ship traffic information.

The delay degree in arrival is one of the metrics to measure the time reliability. The delay of the time between planned and actual traffic time has been used for reliability quantification (Chang, 2010). Wu *et al.* (2009); Prabhu Gaonkar and Mariappan (2020) used the probability (R) that the ship completes all the intended operations within the allowable time limits in order to estimate the time reliability.

$$R = prob(Lower\ Allowance\ Limit \leq T \leq Upper\ Allowance\ Limit); T, LAL, UAL \geq 0 \quad (5.1)$$

Delay time can be measured by:

$$T_d^+ = T_{Actual} - \ Upper\ Allowance\ Limit \quad (5.2)$$

The statistics calculation of the on-time rate (Eq. 5.1) focused on the arriving and leaving time compared with the timetable. The probability of time reliability can be used to assess the network reliability, but it does not consider the reasons and influencing factors for the unreliability of the shipping network. Meanwhile, it ignores the study of the influence of interference disruptions on container shipping networks from the perspective of the overall container transport journey, which is not convenient for liner companies to analyse, optimise or design the network structure and timetable to improve their service reliability.

Different from the indices that only compare the actual arrival time with a pre-planned shipping schedule as introduced in Section 5.2, the approaches in this section focused on the statistical assessment of the unreliable results of the shipping routes and the methods that can be used to improve the reliability of the shipping schedule from the perspective of planning, operation and management. According to Guericke and Tierney (2015), the total trip time consists of three parts: sea duration, port duration and buffer time (Eq. 5.3).

$$Round\ Trip\ Time = Sea\ Duration + Port\ Duration + Buffer\ Time \tag{5.3}$$

The main factor that affects the time a ship requires to transport from the origin to the destination is its sailing speed along the shipping routes it travels, and this refers to the sea voyage time between ports. Disruptions that occur during the sea voyage would affect the trip time. The second factor is the time that ships spend at each port for loading and unloading cargo, which refers to turnaround time. Turnaround time is one of the most widely used metrics to assess the infrastructure reliability in port. The current practice for considering the port duration time in the context of reliability is to estimate the service time to improve the time reliability (Eq. 5.4). Prabhu Gaonkar *et al.* (2013) applied the application of fuzzy set and rule base logic as an appropriate approach to assess the operational reliability of maritime transportation systems. To model several listed parameters, using the sum of all stages travel times and its various stage components and then the reliability optimisation problem with budgetary constraints and stage-time limitations were formulated. Lee *et al.* (2015) used the number of "moves" and the speed of the cranes to calculate the estimated service time. "Move" was defined as the operation of loading or unloading one container in port, and the speed of the cranes was measured by the number of moves per hour at the ports. A certain amount of time, called "port contingency" was also added as a buffer to deal with randomness.

$$Estimated\ service\ time = \frac{D_k}{v} + \mu_k + \beta_k \delta_k \tag{5.4}$$

D_k denotes the distance from port k-1 to k; v is the ship planned speed; μ_k and σ_k are the mean and standard deviations of port time W_k; and W_k is the port time that a ship spends at port k, including both the waiting time and the operation time. In other words, W_k is the amount of time calculated from the ship arrives at port k until it leaves from port k. The coefficient β_k is a parameter chosen to denote the "port contingency", which plays the role as a buffer to mitigate any delay.

The last factor in Eq. 5.3 is the buffer time. According to Guericke and Tierney (2015), the buffer refers to the journey time with minimum speed minus the journey with maximum speed. That is, besides the normal operation time, port duration time is also related to whether the ports are affected by disruptions. Literature review and interviews also pointed out the importance of considering disruptions and risks in the network when assessing reliability. Prabhu Gaonkar *et al.* (2011) introduced the factors that directly affect the reliability of the maritime transportation system: congestion at the original port, congestion during the sea voyage, congestion at the destination port, weather or environmental conditions, age and condition of the vessel, technological problems of the vessel, experience of the operational or navigation crew, experience of the maintenance workforce, effectiveness of maintenance programmes, effectiveness of the emergency system on the ship, unforeseen events, and overall past operational history of the ship. According to the references and influencing factors identified from SLR in Chapter 2 and interviews in Chapter 4, the causes of delays can be classified into four groups:

(1) Disruptions that happen during the sea voyage.
(2) Terminal operations - port/terminal congestion or unexpected waiting times before berthing or before starting the loading/discharging.
(3) Port/terminal productivity below expectations (loading/discharging).
(4) Unexpected waiting times.

Buffer time is used to react to such delays. When designing the timetable and container shipping services for the network, liner carriers often add buffer time in the total transport time for each route in order to reduce the effect of such delays and increase the reliability of schedules. Since port-related uncertainty is the dominant source of ship schedule unreliability (Notteboom, 2006), it is important to take into account the uncertainties in the system so that a reasonably high service level can be achieved when designing the liner service schedules in advance (Qi and Song, 2012), e.g., Tierney *et al.* (2019) designed a speed model by using a chance constraint to ensure that the shipping route has enough buffer at each port to avoid the additional waiting time caused by punctuality. Wu *et al.* (2009) estimated the time reliability of the given OD pairs in the container shipping network by calculating voyage time at sea and normal call time in ports without errors. Then, Wu *et al.* (2009) simulated K times with error ratio f, and different error degrees induced different added waiting times. The algorithm analysed the time reliability of the shipping network more comprehensively by adding waiting time in error nodes to calculate the least time t of all pairs of routes, which consist of transport cargo on sea and waiting time in nodes.

It is clear to see that in order to meet the need of considering the interference of influencing factors, variation in travel time and the operation time have been the popular measure to compute the reliability of transportation (Prabhu Gaonkar and Mariappan, 2020). More specifically, related problems focus on short operation time combined with a high degree of schedule reliability.

5.3.2 Metrics with regard to port performance

The growing availability of port and shipping data helps the maritime industry to monitor the performance of ports and infrastructure. UNCTAD (2020) introduced a new index called the port performance scorecard, which is regarded as the port performance component of the TrainForTrade Port Management Programme. The data was collected through a series of questions to the container ports, including indicators under six categories:

- Finance: EBITDA/revenue (operating margin); labour/revenue; vessel dues/revenue; cargo dues/revenue; concession fees/revenue; rents/revenue.
- Human resources: tons per employee; revenue per employee; EBITDA per employee; labour cost per employee; training cost/wages.
- Gender: female participation rate (global); female participation rate (management); female participation rate (operations); female participation rate (cargo handling); female participation rate (other employees).
- Vessel operations: average waiting time (hours); average gross tonnage per vessel; average oil tanker arrivals; average bulk carrier arrivals; average container ship arrivals; average cruise ship arrivals; average general cargo ship arrivals; average other ship arrivals.
- Cargo operations: average tonnage per arrival (all); tons per working hour, dry or solid bulk; tons per hour, liquid bulk; boxes per ship hour at berth; 20-foot equivalent unit dwell time (days); tons per hectare (all); tons per berth metre (all); total passengers on ferries; total passengers on cruise ships.
- Environment: investment in environmental projects/total; CAPEX Environmental expenditures/revenue.

The port performance scorecard index has the potential to become a global benchmark with compatible data and key indicators and standards, and it aims to become an industry standard for ports and shipping companies to continuously improve its efficiency (UNCTAD, 2020). It also allows analysts to compare and report on differences among ports, countries and fleets, which, in turn, helps governments and maritime authorities make adjustments to their activities and policies.

5.4 Reliability metrics in relation to shipping networks

5.4.1 Metrics with regard to network connectivity

UNCTAD developed the Liner Shipping Connectivity Index in 2004 (LSCI), and it is used to compare the connectivity of different countries in container shipping networks. That is to say, to capture the position of the country in the global container shipping network. The index has five components: the number of ships deployed to and from each country's ports; their combined container-carrying capacity; the number of companies that provide regular services; the number of services; and the size of the largest ship (UNCTAD, 2017). The index was updated and improved in 2019 to offer additional country coverage, and it added a component covering the number of country pairs with a direct connection (UNCTAD, 2020). The current version of the liner shipping connectivity index comprises six components:

(1) Number of scheduled ship calls per week in the country concerned.
(2) Deployed annual capacity in TEUs (total deployed capacity offered in the country).
(3) Number of regular liner shipping services to and from the country.
(4) Number of liner shipping companies that provide services to and from the country.
(5) Average size in TEUs of the ships deployed by the scheduled service with the largest average vessel size.
(6) Number of other countries that are connected to the country through direct liner shipping services.

The countries are standardised to have a maximum value of 100 and are assigned an equal weight. Then, the index assigns a score to countries according to their performance in these six components, and ranks the countries based on the score. Figure 5.2 shows the result of the top 10 countries from 2006 to 2019. The LSCI index has been used in several studies to analyse maritime connectivity. What's more, UNCTAD has generated a new liner shipping connectivity index for ports, called the Port Liner Shipping Connectivity Index, which is generated for all container ports in the world that receive regular container shipping services. This new index applies the same methodology as from the country level introduced above. The liner shipping connectivity indices are the indicators in the deployment of the world's container ship fleet, and the help to analyse trends among countries and ports. The higher the connectivity degree in the network, the easier it is for the country or port to enter the global market. Additionally, UNCTAD is working on developing a bilateral LSCI, which takes into account both direct and indirect services in order to estimate connectivity.

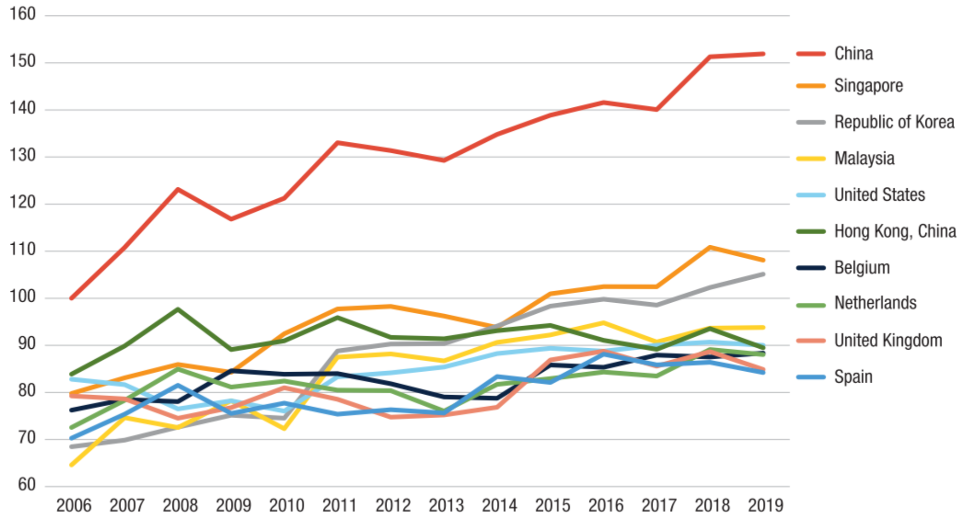

Figure 5.1 Liner shipping connectivity index, top 10 economies, 2006–2019
(Source: UNCTAD Review of Maritime Transport 2019)

The LSCI considers the connectivity and value of each country or port quantitatively, based on the LSCI, Bartholdi *et al.* (2016) built the Container Port Connectivity Index (CPCI). Compared to the LSCI, the CPCI combined container ports with network topology, and focused on the port position in the configuration of the shipping network. The CPCI weighted each link between ports according to LSCI components, and then used the HITS algorithm, which is an eigenvector-based algorithm to rank web pages. The result of the CPCI shows that, the connectivity of a port is related to both the port itself and the ports it is linked to. It points out that the analysis should base on the entire network configuration.

In line with the measuring approach used by the CPCI, this research project considers the impact of connectivity reliability when a node acts as a part of the entire shipping network. Studies in the field of maritime network configuration explore the network connectivity based on network characteristics. There are many metrics that used to evaluate network connectivity (Barabási *et al.*, 2000). Research in this field applied graph theory to generate topological shipping networks – with ports regarded as nodes and shipping routes (the voyage between ports *i* and *j*) as links. In other words, the shipping network is built based on the ports of call and container movements (Liu *et al.*, 2018). According to Barabási *et al.* (2000), a_{ij} represents the links of the network. If a_{ij} equals to 1, it means that there is a link between port i and port j. Otherwise $a_{ij} = 0$. **Node degree** is a graph theory metric to describe how many links (k_i) are connected with the node (i). **Degree distribution** *p(k)* refers to the ratio of ports with degree k to the total number of ports (Eq. 5.5).

Degree distribution:

$$p(k) = {}^{nk}/_{n} \tag{5.5}$$

In the container shipping network, usually, more ports are connected with a hub port, so that the node degree of the hub port is generally larger. The characteristic of degree distribution is that there are fewer ports with higher degree values, and the proportion of lower degree values is larger, which proves that the shipping network satisfies the scale-free characteristic. The results of node degree and degree distribution imply that the hub ports are connected with the majority of the shipping routes in the shipping network.

The **Average Path Length (APL)** (Eq. 5.6) refers to the number of links on the shortest path between two nodes (Barabási *et al.*, 2002). d_{ij} is the number of edges for the shortest path between nodes i and j.

Average path length:

$$APL = \frac{1}{\frac{1}{2}n(n-1)} \sum_{i>j} d_{ij} \tag{5.6}$$

Network diameter (D) (Eq. 5.7) is defined as the maximum of all d_{ij}. A small network diameter value indicates that the network is better connected.

Network diameter:

$$D = MAX d_{ij} \tag{5.7}$$

Additional metrics based on the average path length, for example, **network efficiency,** can be used to analyse network reliability. Network efficiency is used to describe how information is transferred through the network, and it is related to the shortest path length. The efficiency ε_{ij} between the node i and j is the inverse of the shortest path between i and j (l_{ij}), $\varepsilon_{ij} = \frac{1}{l_{ij}}$. The efficiency of the network E (Eq. 5.8) is the sum of n nodes efficiency in the network.

Network efficiency:

$$E = \frac{\sum_{i \neq j}^{n} \varepsilon_{ij}}{n(n-1)} \tag{5.8}$$

When the nodes in the network are facing random failure or deliberate attacks, the node will be removed from the network, and the efficiency will be affected. The maximum value of E reaches 1 when the network is fully connected (Liu *et al.*, 2018).

The **clustering coefficient** (Eq. 5.9) is the portion of actual network links L_i between node i and its neighbourhood nodes, divided by the maximum possible edges ${k_i(k_i - 1)}/{2}$ between them.

Clustering coefficient:

$$C_i = \frac{L_i}{k_i(k_i-1)/2} \tag{5.9}$$

The clustering coefficient is used to describe the degree to which a node and its neighbours tend to cluster together. When C_i is larger, it indicates that the node i has a more compact system of connections with its neighbours. In a fully connected network, C_i is equal to 1. The clustering coefficient of the network C (Eq. 5.10) is the average of all nodes. In the shipping network, a lager value of C indicates that there are fewer transfer routes.

Network clustering coefficient:

$$C = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{5.10}$$

Studies estimated network connectivity by calculating the metrics and identifying the topological characteristics of container shipping networks. Compared with the connectivity indices, metrics derived from graph theory and network analysis consider node position within the network – port reliability not only depends on the port itself, but also the port’s position in the shipping network and the ports it is linked to.

5.4.2 Metrics with regard to network vulnerability

The damage to the transportation networks caused by the Kobe (Japan) earthquake in 1995 made the studies on transport network reliability attract the attention of scholars. However, most of the papers on transport network reliability mainly focus on the reliability of such networks as road networks, bus networks and railway networks. The field of Road Transportation has been very prolific in the development of reliability metrics and analysis metrics. The metrics developed to measure reliability from the perspective of vulnerability and resilience have been influenced by the definition of reliability as to whether the network would be disrupted, and the ability of the system to perform well even when parts of the system have failed. Network configuration-related metrics are useful tools to assess the reliability of shipping networks.

From a topological perspective, the factors that affect network configuration reliability can be grouped into four categories, as explained by Thadakamalla *et al.* (2004): robustness, efficiency, flexibility and adaptivity, as shown in Table 5.1.

	Related metrics	Definition
Robustness	Degree distribution; Size of the network's largest connected component	How many disruptions a network can endure before the functionality is destroyed.
Efficiency	Average Path Length; Node Efficiency	How quickly commodities or information proliferate throughout the network.
Flexibility	Clustering Coefficient	Ensure alternate paths to facilitate dynamic rerouting.
Adaptivity	Resilience after attack	Rewire the network itself efficiently.

Table 5.1 Four components in network structure reliability
(Source: Author based on Thadakamalla *et al.* (2004))

Some of the metrics in Table 5.2 are used to assess the connectivity of the network that has already been introduced in section 5.4.1. The studies about network vulnerability are usually connected with the selection of important nodes or elements in the network. Important nodes refer to those most vulnerable elements in the network configuration. The importance of each specific node is quantified by many metrics and under the global network configuration. The importance of a node can be expressed by centrality-related metrics. According to Viljoen and Joubert (2016), centrality-related metrics measure the number of a node's links to its immediate neighbours, which can reflect the importance of the node. Centrality was introduced to the field of shipping transportation as early as the 1990s, as an indicator of the relative importance/status of ports. In recent years, as an important tool in network analysis, centrality-related metrics have been widely researched and applied in the field of maritime complex networks, e.g., degree centrality, closeness centrality and betweenness centrality. These represent how close the individual node is to the centre of the group and the importance of the node in the entire network.

Degree centrality:

$$C_D(i) = \sum_{j=1}^{n} a_{ij} \tag{5.11}$$

Closeness centrality:

$$C(i) = \frac{n-1}{\sum_{i \neq j \in n} d(ij)} \tag{5.12}$$

d(ij): shortest path length between node i and j. n: number of all the nodes in the network.

Betweenness centrality:

$$\mathrm{B(v)} = \sum_{i \neq j \neq v} \frac{\sigma_{ij}(v)}{\sigma_{ij}} \tag{5.13}$$

$\sigma_{ij}(v)$: All the shortest paths between nodes i and j that pass through node v. σ_{ij} refers to all the shortest paths between nodes i and j.

In order to provide comprehensive information about ports, multi-centrality is usually used to rank the importance of the nodes. Different methods are used to aggregate different topological measures. Liu *et al.* (2018) used the multi-centrality model to identify the important nodes in the shipping network based on the Borda count method. The Borda count method is a voting method in which voters rank candidates in order of preference. Nie *et al.* (2015) and Lordan *et al.* (2015) showed examples of strategies that combined different metrics to create more effective disruption strategies. The Container Port Connectivity Index, developed by Bartholdi *et al.* (2016), which was mentioned in section 5.4.1, combined the metrics with the port ranking index. By applying the Hyperlink Induced Topic Search (HITS) algorithm, Bartholdi *et al.* (2016) ranked web pages and created a better classification of the roles that global ports play.

Apart from the metrics that take into account the importance of nodes and links in a network, more complex experiments and analysis methods are used to examine the vulnerability of the network configuration. Viljoen and Joubert (2016) examined the robustness and flexibility of the network by removing the important nodes. Xing *et al.* (2018) estimated the network reliability of the 21st Century Maritime Silk Road by assessing the average connectivity reliability of all OD pairs when partial nodes fail in the container shipping network. It generated random failure nodes and recalculated the adjacent matrix of the network in order to determine whether any pair was connected or not in the network.

The traditional hub location problem aims to find out the suitable location for hub ports. When considering the reliability of the network structure, more complex models were applied (Azizi, 2019). An *et al.* (2015) reviewed several hub location models to assess the reliability of the shipping network. In the single allocation model, one route from i to j can be represented by a 4-tuple (i, k, m, j) where k and m represent the first and the second hubs on the route. α refers to the discount factor of the economic scale. The objective function of this model is the expected transportation cost, considering both the regular and the disrupted situations. The cost of one route is:

Cost of route:

$$F_{ikmj} = C_{ik} + \alpha C_{km} + C_{mj} \tag{5.14}$$

It is assumed that when there is a disruption between i and j, there will be no traffic volume between them. The routes can be divided into four types: (1) a route that is not affected by the disruption, (2) a route that uses the disrupted node as the first hub, (3) a route that uses the disrupted node as the second hub, and (4) a route that originated from or is destined to a hub node. The cost is calculated under each type. This model is to assess the transport cost, considering both the regular and the disrupted situations. Compared with the single allocation model, the multiple allocation hub-spoke model does not restrict flows from one source (or to one destination) to route through the same hub. An *et al.* (2015) provided alternative routes and backup ports to improve the transport network reliability. The result of the model shows that a reliable network can transport more passengers by its regular routes than a network with the classical configuration. According to this model, Azizi (2019), Barahimi and Vergara (2020) proposed a mixed integer nonlinear model to solve the network reliability related problems.

Within the context of evaluating the reliability of the network configuration through the aforementioned metrics and methods, currently, two main approaches have emerged. The first approach is to judge nodes based on static indicators of nodes, such as degree value, centrality value, clustering coefficient, etc. By leveraging either a single or multiple indicators, the ports can be ranked, and the importance of nodes can be identified within the network. More specifically, metrics within this approach can be divided into two categories. The first category of metrics is based on the port's own impact – port characteristics. The other category of evaluation metrics is based on the position of ports within the global shipping network – the impact to other ports in the network due to the connectivity. The other approach is based on the idea of simulation – to “destroy” different nodes in the network. After observing the destruction, the indicators that reflect the overall network performance, such as the average path length of the network or the network diameter, etc., are used to assess the reliability of the nodes and networks (Wu *et al.*, 2018; Xing *et al.*, 2018).

5.5 Reliability metrics in relation to supply chains

The reliability-related metrics and indices, as reviewed in sections 5.3 and 5.4, refer to the definition of reliability from the perspective of vulnerability, connectivity of the network configuration and availability of infrastructure and service. The definition reviewed in Chapter 2 presented that the term “reliability” in the context of container shipping networks in this research is regarded as the quality of liner performance under uncertainty from consignor to consignee. The influencing factors from literature review, coupled with the insights from interviews, also proved that integrated transport systems, information sharing, trade facilitation procedures and so on needed to be considered. In agreement with the analytical exploration, the researcher also delved into the metrics in the supply chain field. Although it is acknowledged that logistics performance-related metrics may not exhibit a direct connection with the inherent reliability of container shipping networks, it is important to note that such metrics can provide valuable insights into the understanding of connectivity reliability identified in the literature review. This section served to amplify the comprehension of metrics and indices by extending their applicability to the broader domains of logistics and supply chain management.

Similarly with the connectivity indices introduced in 5.4.1, in order to develop a logistics advantage, governments have to assess the current country-level logistics system and identify which subsystems need to be optimised, developed or removed completely. In agreement with this, an international country-level logistics rating could be used by the government as a benchmarking tool that allows the comparison of individual indicators, so as to shed light on specific individual areas within the logistics system. The current leading ratings that are used to measure country-level logistics systems are the Logistics Performance Index (LPI), produced by the World Bank, the Agility Emerging Markets Logistics Index (AEMLI), produced by the Agility Logistics Company, and the Global Competitiveness Index (GCII), issued by the World Economic Forum. Beysenbaev and Dus (2020) compared these three indices. Based on the scope of each index and the closeness of the relationship between the general trade of the country and the various efficiency ratings of logistics systems, it was concluded that the LPI is the most accurate and broad logistics efficiency assessment tool to date.

The **LPI** is calculated on the basis of a global survey of global freight forwarding companies and logistics carriers. It is an online benchmarking tool which is designed and implemented by the World Bank International Trade and Transport Departments every two years to improve the reliability of the indicators and to build a dataset comparable across countries and over time (Beysenbaev and Dus, 2020). Each survey respondent evaluates eight overseas markets based on six key logistics performance indicators. The eight countries are selected on the basis of the most important export and import markets of the country in which the respondent is located. The six key indicators are:

- The efficiency of customs and border management clearance.
- The quality of trade and transport infrastructure.
- The ease of arranging competitively priced shipments.
- The competence and quality of logistics services - trucking, forwarding, and customs brokerage.
- The ability to track and trace consignments.
- The frequency with which shipments reach consignees within scheduled or expected delivery times.

The LPI is based on these six indicators, and it is calculated using Principal Component Analysis (PCA); a standard statistical method used to reduce the dimension of a data set. A direct correlation is observed between elevated values of the LPI and the advanced state of the logistics systems within a given country. The above six indicators are fundamentally divided into two categories: the policy regulation areas based on the basic infrastructure and logistics services of the supply chain, and the service performance outputs (timing, regulation of shipments, monitoring and traceability). The LPI index is one of the most complete sources of data for analysing country-level logistics performance and for finding ways to simplify international trade to improve efficiency and reliability (Çemberci *et al.*, 2015). The countries that occupy the top positions have large distribution platforms and industries specialized in logistics services. A few studies have also used the LPI to analyse and understand the logistics performance. For example, Martí *et al.* (2014) used the LPI as a proxy for trade facilitation, concluding that the more complex goods were in terms of transport, the greater the influence of logistics was.

In 2023, an updated edition of the LPI was introduced, augmenting the conventional survey based LPI described earlier. This latest edition incorporates a new set of key performance indicators that were, methodologically derived from a Big Data approach, measuring the speed of trade around the world. The indicators entail the actual movements of maritime shipping containers, air freight, and postal parcels by trade lane and gateway. The new assessment of the LPI underscores delays encountered at ports and airports, as well as international connectivity (i.e., the number of international connections by countries and modes). The new indicators emphasise the significance of considering the turnaround time in ports; thus, shedding light on service reliability within the network. Additionally, new indicators based on the speed of trade are more affected by disruptions, which further highlights the imperative of delving into the impact of network vulnerability.

5.6 Classification of reliability-related metrics

Chapter 5 reviewed the indices and metrics that can be used to assess reliability and these are summarised in Table 5.2. Some of the reviewed metrics – for example graph theory metrics and time reliability-related metrics, are specifically developed to evaluate container shipping reliability. From the broader definition of reliability, a number of metrics developed for other purposes could also be used to measure reliability for their useful information, e.g., metrics for logistics performance. In agreement with the framework of reliability (identified in Chapter 2), the metrics were systematically divided into three themes: infrastructure reliability, network configuration reliability and connectivity reliability. Figure 5.2 groups the metrics detailed in this chapter.

Category	Index/Metric	Criteria identified
Container shipping related commercial indices	Global Liner Performance	Schedule reliability, on-time rates, ship delays
	Liner Schedule Reliability Report	
	Global Schedule Performance index	
Metrics in relation to infrastructure	Time delay	On-time rate, delay
	Trip time	Voyage time, turnaround time, buffer time
	Port performance scorecard	Finance, human resources, gender, vessel operations, cargo operations, environment
Metrics in relation to shipping network	Liner Shipping Connectivity Index	Ship calls, capacity, number of services, companies, ship size, connected countries (ports)
	Port Liner Shipping Connectivity Index	
	Container Port Connectivity Index	Network topology metrics
	Network connectivity related metrics	Degree, average path length, network diameter, network efficiency, clustering coefficient, centrality-related metrics
	Network vulnerability related metrics	
Metrics in relation to supply chains	Logistics Performance Index	Efficiency, infrastructure quality, ease, competence and quality of logistics services, track and trace, on-time rate

Table 5.2 Main indices and metrics discussed in this chapter

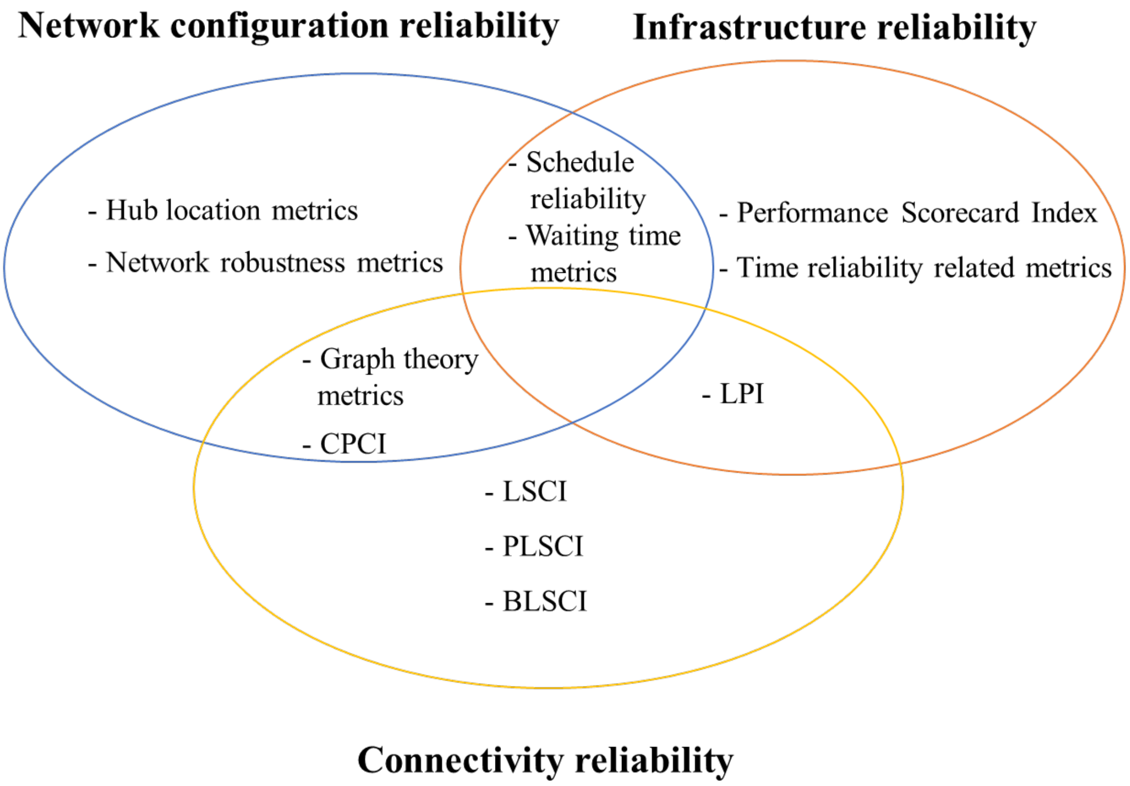

Figure 5.2 Classification of reliability related metrics

Network robustness metrics and hub location-related metrics – related metrics encompassing network topology and simulations of node attacks – have been placed in the group of network configuration reliability. These metrics shed light on the vulnerability and resilience of the network, offering insights into network flexibility and the reliability of network configuration. Compared with these metrics, LSCI, PLSCI and BLSCI indices are used to evaluate the connectivity of ports and countries, with a particular emphasis on assessing the accessibility of nodes. Aligned with these two themes, graph theory-related metrics and the CPCI connectivity index have taken into consideration the impact of shipping network configuration on port connectivity. Hence, they have been positioned within the overlapping area that bridges both connectivity reliability and network configuration reliability.

The port performance scorecard index and time reliability-related metrics focus on assessing the performance of ports and the turnaround time in ports, which are related to the operational efficiency and infrastructure availability. However, schedule reliability and waiting time-related metrics and indices take into account the impact of disruptions and uncertainties, which are closely connected with network vulnerability. As a result, they have been placed in the overlapping area between network configuration reliability and infrastructure reliability.

As reviewed in section 5.5, supply chain-related metrics, e.g., LPI, provides information about the connectivity of the supply chain, trade facilitation and infrastructure performance. Hence, it has been positioned in the overlapping bubble between infrastructure reliability and connectivity reliability. However, the purpose of LPI is to analyse the performance of logistics at the country level and to devise strategies for streamlining international trade to improve efficiency, so they may provide less focused information for assessing network reliability in comparison to other reliability-related metrics.

The results from the metrics review and classification showed that graph theory metrics were developed to assess network reliability specifically, while time reliability metrics were developed to assess port reliability specifically. Other reviewed metrics could also have a contribution to other themes that related to reliability in the context of container shipping networks, including metrics for infrastructure efficiency, network disruptions and trade facilitation. However, in accordance with the framework identified in this research project, these approaches and metrics entail certain limitations. This is due to the fact that:

- The metrics developed to assess network reliability specifically tend to concentrate on one perspective, thereby are not enough to support the research with regard to the identified framework. They cannot evaluate the reliability of the shipping network and discover the potential risks comprehensively.
- Existing metrics in the overlapping areas provide partial information compared with the dedicated metrics. For example, schedule-reliability related metrics and indices illuminate the reliability of port efficiency and the effects of disruptions, however, they provide relatively limited information regarding the role of port within the network and the underlying reasons of reduced reliability.
- The metrics did not sufficiently account for the impact of network dependency and how the performance of one theme might affect the reliability of the other two themes, and consequently, the entire shipping network.

As a result, the review of available metrics and approaches suggested that it is useful to provide a new approach for measuring reliability in the context of container shipping networks specifically and comprehensively.

5.7 Conclusion

Drawing upon the definitions of reliability and the identified influencing factors presented in the literature review and interviews, Chapter 5 introduced how to investigate the impact of these factors. Furthermore, it delved into the existing indices and measuring methods available for assessing network reliability. The researcher conducted a comprehensive review of available indices and existing approaches employed to measure the factors that impact network reliability from three perspectives: infrastructure, network and supply chains. The amalgamation of these metrics was classified into three groups, aligning with the integrative framework of the research project: infrastructure reliability, network configuration reliability and connectivity reliability.

Each metric discussed in this chapter addresses different aspects of reliability, and thus, provides only partial insight for the analysis of container shipping network reliability. In conclusion, the research gaps identified in this chapter are: the available indices on container shipping reliability for commercial purposes only focus on schedule reliability and connectivity reliability; and the available metrics have not provided a specific approach to assess the reliability in the context of container shipping networks considering the definition and determinants of the network comprehensively. The analysis of the existing metrics in this chapter suggests that there is a need for an approach that can specifically and comprehensively assess container shipping networks’ reliability. Chapter 6, therefore, will start to introduce the methodology to be employed in this research in order to develop such an approach.

Chapter 6. A systematic approach for assessing reliability in container shipping networks

6.1 Introduction

The analysis of the existing metrics in Chapter 5 suggested that there is a need for an approach that can specifically and comprehensively assess the reliability of container shipping networks. Then, it leads to the last research question: **(RQ4) Would there be a more comprehensive approach to assess the reliability?**

The following chapters (Chapters 6-9) will be dedicated to the exploration of the new approach for the systematic assessment of reliability in container shipping networks within the identified three themes. As stated in Chapter 3, network analysis was chosen as the method to develop a more comprehensive approach for assessing reliability. This chapter presents the rationale behind the selection of network analysis (Section 6.2) and the research design for developing the new approach (Section 6.3).

6.2 Network analysis in shipping networks

6.2.1 The use of network analysis

Network analysis is a method frequently used in transportation and logistics research. Transportation networks are being widely studied and there are different parameters in many studies to describe the characteristics of different types of complex networks. Research in maritime also has benefited from the adoption of network analysis since 2009, which provided a brand-new research tool for ports and shipping networks. Kaluza *et al.* (2010) pointed out the applicability of complex network theory to container shipping networks, elements of graph theory – nodes and links – have been applied to model the relationships in the shipping network.

There are several reasons for choosing network analysis in this research project: (i) Network analysis transfers all elements of a real system and their relationships into nodes and links. For container shipping networks, ports are regarded as nodes, and the links are the shipping lines that directly connect each port. Shipping networks show the characteristics of complex networks due to the combined actions of many factors, such as route distribution, port geographical environment, location relationship between ports, shipping company's planning of network configuration and so on. Network analysis is able to show the entire shipping network, making it a more robust and realistic method to assess the reliability of the network. (ii) The aforementioned definition of reliability in the context of container shipping networks is the quality of liner performance under uncertainty from consignor to consignee. More specifically, under the network configuration reliability theme, reliability refers to whether the network would be affected by disruptions or risks. Meanwhile, the complexity of shipping networks shows that there are a large number of nodes (ports) in the network, and the connection modes of the nodes (shipping lines) are variable. Network analysis allows the researcher to simulate the complexity of shipping networks, particularly in understanding how nodes may be affected by various factors and disruptions. It is possible to analyse the relationship between the structural changes and network functions. (iii) The review of available metrics and measures in Chapter 5 also shed light on the importance of analysing reliability from the perspective of network configuration. For example, compared with the Liner Shipping Connectivity Index (LSCI) developed by UNCTAD, the Container Port Connectivity Index (CPCI) developed by Bartholdi *et al.* (2016), combined container ports with network topology and focused on the port position within the structure of shipping networks. The result of CPCI shows the role of ports when acting as a node within the network, thereby enhancing the importance of taking into account the network configuration. Network analysis enables the researcher to understand not only the importance and characteristics of individual nodes, but also their position within the network configuration. Additionally, it allows for the analysis of network dependency and the propagation effect from the perspective of connectivity.

6.2.2 Network analysis and network structure

In the context of the framework identified in this research, two themes are related to the network structure: connectivity reliability, which focuses on the probability of the components in the network being connected; and network configuration reliability, which focuses on whether the network is easily affected by disruptions and the ability of the system to perform well even when parts of the system have failed. The characteristics of shipping services, e.g., number of ships, the capacity of ships, and service frequency are being used to build the structure of the shipping network. Based on the basic network configuration, researchers use metrics to identify and analyse the topology of the network, as introduced in

Chapter 5. Among all the metrics, network degree, average path length, clustering coefficient, diameter and centrality are the widely used metrics selected for analysing network topology in this research.

Available literature explored the **connectivity** of the shipping network by network analysis. For example, Ducruet and Zaidi (2012); Jiang *et al.* (2019); Ducruet (2022) provided connectivity analysis to investigate how nodes were connected in the network, along with the topological characteristics and the level of connectivity of nodes. With regard to the use of this method, this research project also intends to use network analysis to investigate the connectivity reliability of the container shipping network between Asia and Europe with three research aims: (i) To understand the structure and topological characteristics of the selected network. (ii) To investigate the importance and function of each node within the network. (iii) To compare and assess the connectivity of the entire container shipping network.

The concept of connectivity reliability, as delineated in this research project, refers to the probability of the components in the network being connected and the integration of different stakeholders along supply chains. The influencing factors in this theme include transportation accessibility, integrated transport system, and information sharing. The analysis of the integrative transport system and information sharing were laid out in the previous chapters. However, these two components pertain to the level of supply chain management, which lies outside the current research scope. The data collection for understanding other components is conducted at the scale of shipping. In contrast, information sharing and the integration of transport systems take place at the land and multimodal level. It was difficult to aggregate data at the same time without losing robustness. Meanwhile, the fact that our research could not involve these two components when assessing reliability shed light on the importance of a different approach that could account for data from a different scale in future analysis.

There are some attempts to assess the **vulnerability** of the shipping network by network analysis. Calatayud *et al.* (2017); Achurra-Gonzalez *et al.* (2019); Wu *et al.* (2019) used network analysis to simulate attacks in order to develop the impact of disruptions to shipping networks. The definition of network configuration reliability identified in the framework refers to whether the network could be affected by disruptions or risks. Additionally, it also includes the ability of the network to perform well even when parts of the network have failed. This research project also intended to used network analysis as a methodology to develop the **resilience** of the network. Network analysis is used for analysing network configuration reliability with three aims: (i) To simulate attacks to the network with the aim of investigating the impact of disruptions and risks. (ii) To discover the importance of each node from the perspective of network configuration, and the propagation effects due to network dependency. (iii) To assess the network configuration reliability of the network when considering both vulnerability and resilience.

6.2.3 Network analysis and infrastructure performance

Existing studies on measuring port infrastructure performance mostly rely on industrial and port authorities' data. As a result, it is difficult to compare the performance with different regions. With the Automatic Identification System (AIS) data - introduced in Chapter 3, this research project intends to assess the infrastructure reliability of each node within the network. Furthermore, the performance will be divided into two areas: at berth and at anchorage. The research on port performance commonly used the queuing model and simulation on ports. This research introduces the method to assess the performance of port infrastructure from AIS data with high accuracy, building on the work of Peng *et al.* (2022).

Although infrastructure reliability delves into the performance of individual ports through data analysis, a novel perspective is embraced in this research by connecting infrastructure reliability with network analysis. By adopting network analysis, the research aims to investigate not only the performance of ports, but also the impact of port performance on other ports within the network, along with the propagation effect. From one point of view, network reliability needs the service capacity of the network to satisfy the flow in the network from the starting point to the destination point, according to the original plan. Even if it is delayed due to unexpected disruptions, the network can be completed as soon as possible with the fastest response and minimum loss. From another point of view, infrastructure reliability could be affected by the other nodes within the same network. Different from the previous analysis that treated ports as independent nodes in the network, this research project assessed the infrastructure reliability at the network level and addressed it closely with other themes (network configuration reliability and connectivity reliability).

6.3 Research design for network analysis

Network analysis is used to assess the reliability in container shipping networks in the following chapters. The approach was developed according to the identified themes in

Chapter 2, that is, using network analysis to assess infrastructure reliability, network configuration reliability and connectivity reliability. Both the reliability of separate nodes within the network as well as the reliability of the entire network were developed.

6.3.1 Terminology introduction

This research project selected the shipping network between Asia and Europe to assess the reliability of container shipping networks. In order to better understand the following analysis, the terminologies (Table 6.1) that are used in this research project are classified in this section first.

Terminology	*Definition*
Trade	All the shipping voyages between Asia and Europe.
String	A network operated by a carrier or an alliance of carriers comprising one or more ships making calls to multiple ports in sequence on a continuing rotation. All strings in the Asia Europe trade are divided into two voyage sequences e.g., eastbound, westbound.
Node	Port of call within a network.
Link	A direct service between two nodes.
Route	The path of voyage(s) (i.e., the link(s)) between any pair of nodes in the network.

Table 6.1 Glossary for terminologies used in network analysis

Real-world container shipping transportation is complicated, and reliability is not an absolute measuring metric; therefore, it is crucial to clearly show the transportation performance among different strings and ports, the limits or barriers of the existing network and the developing trend of container trades. The first step for network analysis is to transfer elements from real container transportation to the constructed network. The researcher selected the trade between Asia and Europe to construct the container shipping network (CSN), which serves as the specific focal point for the subsequent analyses in this research.

The blue line in Figure 6.1 represents the trajectory of voyages between the two areas.

Figure 6.1 Trade between Asia and Europe
(Source: Author elaboration based on ArcGIS)

The string refers to a network operated by a carrier or alliance of carriers comprising one or more ships making calls to multiple ports in sequence on a continuing rotation. Container shipping transportation has the characteristics of multi-port mode, that is, there are several ports of call alongside one string. Some analyses were conducted under the assumption that the shipping network under consideration constitutes an indirect network, and the direction of ship movements was not taken into account. Given the observed variations in port calls along different strings within the selected shipping network, port sequences may not consistently align in both directions. Consequently, to accurately capture this dynamic, the strings in the CSN were divided into two distinct voyage sequences, e.g., eastbound, westbound.

More specifically, Figure 6.2 shows the westbound and the eastbound of strings from three container shipping companies. As can be seen from Mediterranean Service 1 (MD1), ports of call in westbound and eastbound were the same, although there was a little difference on the calling sequence. It could be discovered from the string Far East Pacific 1 (FP1), there was one more port of call on westbound compared with eastbound. A noteworthy observation within the string AEU2 from COSCO, was the existence of a direct link between the port of Singapore and Le Havre, however, the reverse link, directly from Le Havre to Singapore, was not reciprocated. The ports of call between the two directions of the string were readily apparent. The strings in the network can be divided into three categories: same ports of call on both westbound and eastbound; slightly different ports of call; and large differences in ports of call. Considering the observations, the CSN possesses an asymmetric matrix. It is more appropriately to characterised it as a directed network with two voyage sequences, e.g., eastbound, westbound. Based on this, the analysis encompasses the trade between Asia and Europe, including strings from Asia to Europe (westbound) and Europe to Asia (eastbound). Furthermore, the nodes in the network are inclusive of both inbound (arrivals) and outbound (departures) services, which will be elaborated upon in subsequent discussions.

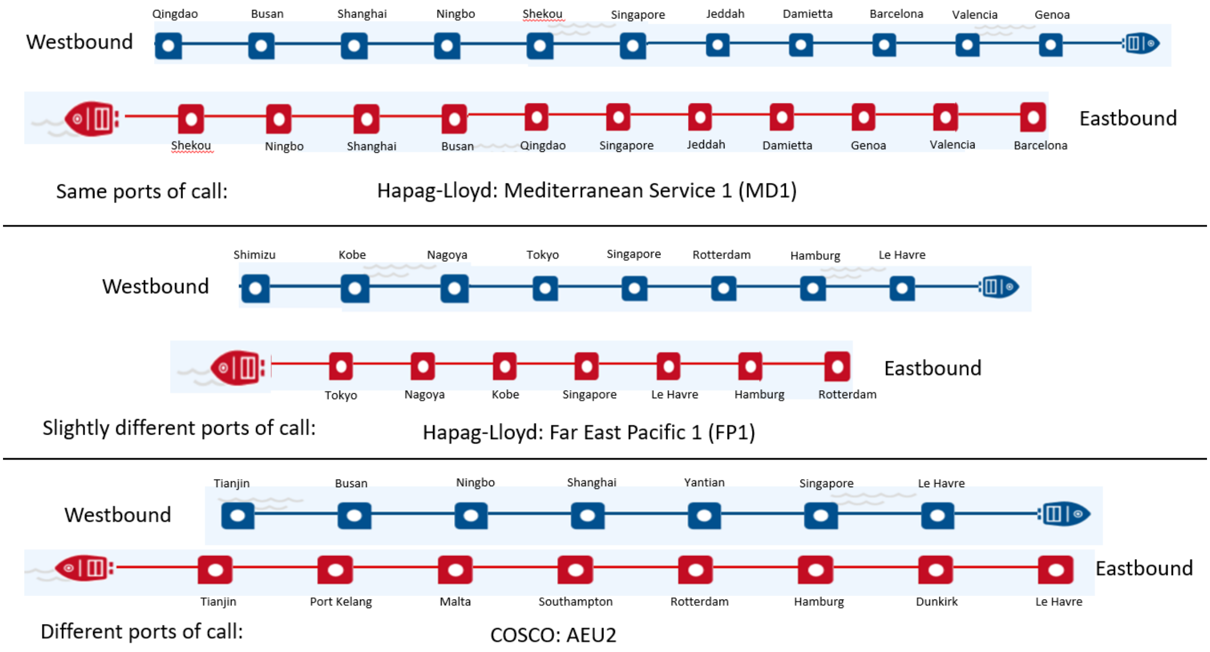

Figure 6.2 Westbound and eastbound from three shipping companies
(Source: Own elaboration based on container shipping company websites[1])

The term “node” refers to the port of call within the shipping network. The link is regarded as the direct service between two ports of call. Take AE1 Eastbound from Maersk for example (Figure 6.3). The ports of call include Bremerhaven, Rotterdam, Port Tangier, Salalah, Hong Kong, Ningbo, Xiamen, and Yantian. There are a total of eight nodes in this string. The links in this string are: Bremerhaven--Rotterdam; Rotterdam--Port Tangier; Port Tangier--Salalah; Salalah--Hong Kong; Hong Kong--Ningbo; Ningbo--Xiamen; Xiamen--Yantian, – a total of

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[1] The information was searched on the shipping companies’ websites:
Maersk: https://www.maersk.com/local-information
MSC: https://www.msc.com/en/solutions/our-trade-services/east-west-network
CMA CGM: https://www.cma-cgm.com/products-services/flyers
COSCO: https://lines.coscoshipping.com/home/Services/route
Hapag-Llyod: https://www.hapag-lloyd.com/en/services-information/routes-trades/routes/route-finder.html

nine links. Meanwhile, all the links in the network point to only one direction, so the container shipping network inherently is a directed network[2].

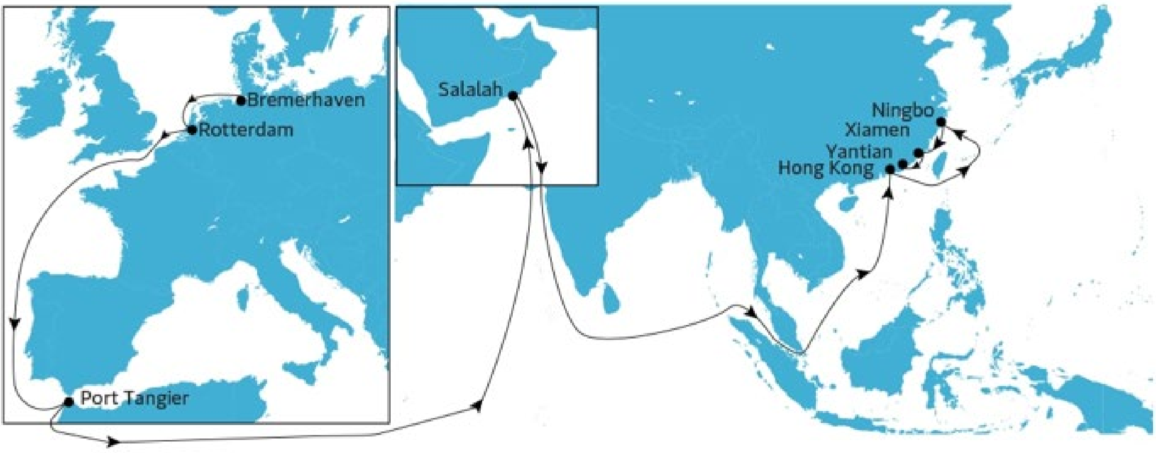

Figure 6.3 AE1 Eastbound from Maersk
(Source: https://www.maersk.com/local-information/shipping-from-asia-pacific-to-europe/ae1-eastbound)

The route in this research project is regarded as the path of voyage(s) (i.e., the link(s)) between any pair of nodes in the network. Routes are defined as “direct” when the freight is not transshipped (i.e., moved to another ship) even when the ship calls to more than one intermediate port before arriving at the destination port. As the example shows in Figure 6.3, there are, in total, 28 routes in this string.

6.3.2 Sample data selection

The target population of this research project consisted of the shipping strings from the top five shipping companies in the world: APM-Maersk, MSC-Mediterranean Shipping Company, CMA-CGM, COSCO-China Ocean Shipping Company, and Hapag-Lloyd. According to the data from Alphaliner in December 2021, the total TEUs of the top five container shipping companies account for approximately **65** percent of the global container shipping market. The list of the companies is shown in Table 6.2. TEU refers to the nominal TEU capacities of all the ships deployed on a given day by such operator. Market shares are

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[2] Given the observed strings, it is possible that one of the links within a string is oriented in the opposite direction, i.e., an eastbound string might contain one link heads to west. It will be further introduced in Section 6.3.3.

computed in TEU terms, based on the overall TEU capacity deployed on liner trades (Total liner TEU count) around the world. The shipping strings in the five companies were manageable to do the data collection and analysis feasible; meanwhile, they occupied more than half of the container shipping market, which made the data representative to the selected container shipping network (CSN).

Operator	TEU	Market share by TEU
Maersk	4,121,964	16.9%
MSC	3,897,002	16.0%
CMA CGM	3,011,123	12.4%
COSCO	3,009,071	12.4%
Hapag-Lloyd	1,776,545	7.3%
Total		65%

Table 6.2 The top five container shipping companies selected in this research
(Source: The Alphaliner TOP 100 (https://alphaliner.axsmarine.com/PublicTop100/))

Among these five shipping companies, **115 strings** (58 eastbound, 57 westbound) and **939 links** were collected (Maersk: 24; MSC: 18; CMA CGM: 25; COSCO: 26: Hapag-Lloyd: 22). Information was provided by their companies, including all ports linked by liner during a voyage on each string, ship-related information, the frequency of transportation, and the planned time of departure and arrival. Figure 6.5 provides the example of the shipping strings between Asia and Europe for each selected shipping company. The strings were selected based on:

- The ship starting from a port in Asia and finishing at a port in Europe, and vice versa.
- The ports of call during the string were considered even if they were not from Asia or Europe. For example, the route AE11 Eastbound from Maersk, was called at the following ports: Barcelona, Valencia, Gioia Tauro, Port Said, King Abdullah, Abu Dhabi, Jebel Ali, Singapore, Yantian, Qingdao, Busan, Ningbo, and Shanghai. Port Said is the port in Egypt but as one of the important nodes in the CSN, Port Said was also included in the network.

It is essential to note here that the target population of this research encompasses the strings connecting Asia and Europe. Consequently, two kinds of shipping strings were excluded from consideration: round-the-world service and feeder services, as illustrated in Figure 6.4. This research chose to narrow the focus to main strings connecting major ports within the network, which handle the majority of the containers. Furthermore, feeder services and round-the-world services often have different operational characteristics, such as vessel sizes, frequency, and transit times, in comparison to the strings selected for this research. By concentrating solely on strings between Asia and Europe, the study aims to ensure a more consistent analysis of network metrics and performance indicators.

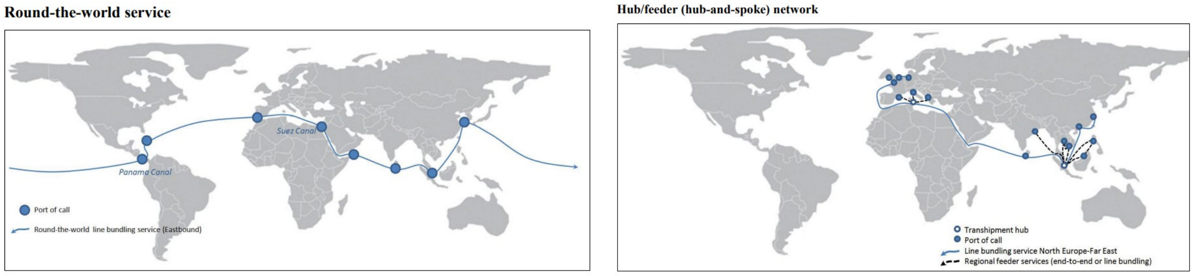
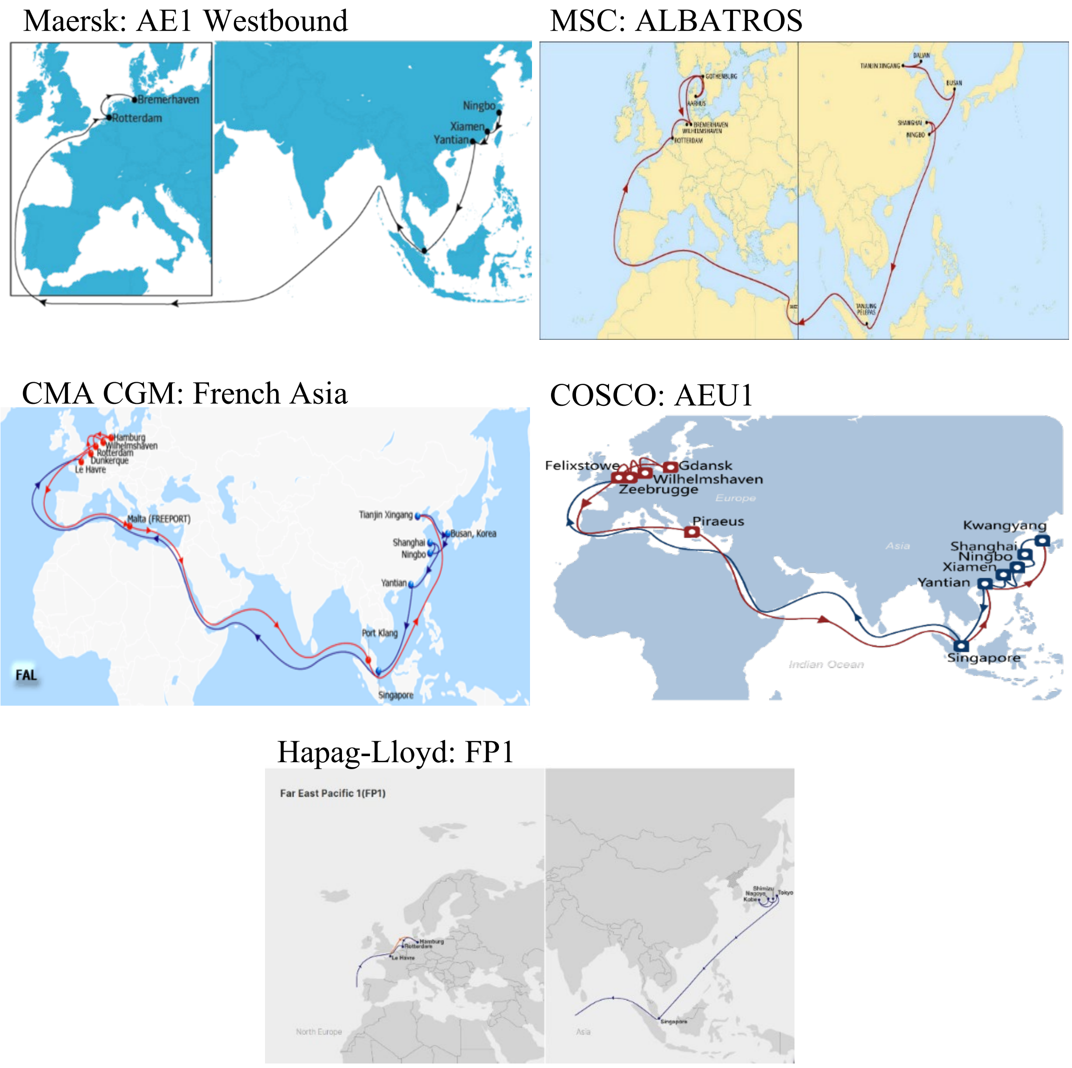


Figure 6.4 Round-the-world shipping string and feeder string
(Source: Ducruet and Notteboom (2021))


Maersk: AE1 Westbound

MSC: ALBATROS

CMA CGM: French Asia

COSCO: AEU1

Hapag-Lloyd: FP1

Figure 6.5 Example strings from selected shipping companies
(Source: Shipping company websites [1])

The number of the selected links (939) was sufficiently large enough to accurately build the network structure of the shipping network from Asia to Europe and analyse its reliability for further research.

Among 115 strings, **89** nodes from **38** countries were involved. The list of the ports and countries is presented in Table 6.3. The number of involved ports was feasible and manageable to build the network configuration. At the same time, the number of ports was enough to do further analysis accurately. The distribution of these ports is shown on the map in Figure 6.6.

	Port	Country		Port	Country		Port	Country
1	Aarhus	Denmark	**31**	Jebel Ali	United Arab Emirates	**61**	Mundra	India
2	Gothenburg	Sweden	**32**	Khalifa	United Arab Emirates	**62**	Jawaharlal Nehru	India
3	Gdansk	Poland	**33**	Dammam	Saudi Arabia	**63**	Laem Chabang	Thailand
4	London Gateway	UK	**34**	Al Jubail	Saudi Arabia	**64**	Colombo	Sri Lanka
5	Southampton	UK	**35**	Jeddah	Saudi Arabia	**65**	Singapore	Singapore
6	Felixstowe	UK	**36**	king Abdullah	Saudi Arabia	**66**	Vung Tau	Vietnam
7	Bremerhaven	Germany	**37**	Doha	Qatar	**67**	Cai Mep	Vietnam
8	Wilhelmshaven	Germany	**38**	Hamad	Qatar	**68**	Port Klang	Malaysia
9	Hamburg	Germany	**39**	Alexandria	Egypt	**69**	Tanjung Pelepas	Malaysia
10	Rotterdam	Netherlands	**40**	Port Said	Egypt	**70**	Kaohsiung	Taiwan
11	Sines	Portugal	**41**	Damietta	Egypt	**71**	Taipei	Taiwan
12	Salalah	Omen	**42**	Tangier Mediterranee	Morocco	**72**	Hong Kong	China
13	Ambarli	Turkey	**43**	Tangier Med2	Morocco	**73**	Xiamen	China
14	Mersin	Turkey	**44**	Zeebrugge	Belgium	**74**	Nansha	China
15	Tekirdag	Turkey	**45**	Antwerp	Belgium	**75**	Yantian	China
16	Yarimca	Turkey	**46**	Fos	France	**76**	Shekou	China
17	Istanbul	Turkey	**47**	Dunkirk	France	**77**	Chiwan	China
18	Iskenderun	Turkey	**48**	Le Havre	France	**78**	Mawan	China
19	Aliaga	Turkey	**49**	Barcelona	Spain	**79**	Shanghai	China
20	Izmit	Turkey	**50**	Algeciras	Spain	**80**	Ningbo	China
21	Karachi	Pakistan	**51**	Valencia	Spain	**81**	Dalian	China
22	Ashdod	Israel	**52**	Piraeus	Greece	**82**	Qingdao	China
23	Haifa	Israel	**53**	Rijeka	Croatia	**83**	Tianjin	China
24	Novorossiysk	Russia	**54**	Trieste	Italy	**84**	Busan	Korea
25	Tripoli	Lebanon	**55**	La Spezia	Italy	**85**	Gwangyang	Korea
26	Beirut	Lebanon	**56**	Genoa	Italy	**86**	Tokyo	Japan
27	Constantza	Romania	**57**	Gioia Tauro	Italy	**87**	Shimizu	Japan
28	Koper	Slovenia	**58**	Malta	Malta	**88**	Kobe	Japan
29	Aqaba	Jordan	**59**	Hazira	India	**89**	Nagoya	Japan
30	Odessa	Ukraine	**60**	Mumbai	India			

Table 6.3 Ports and countries included in the research

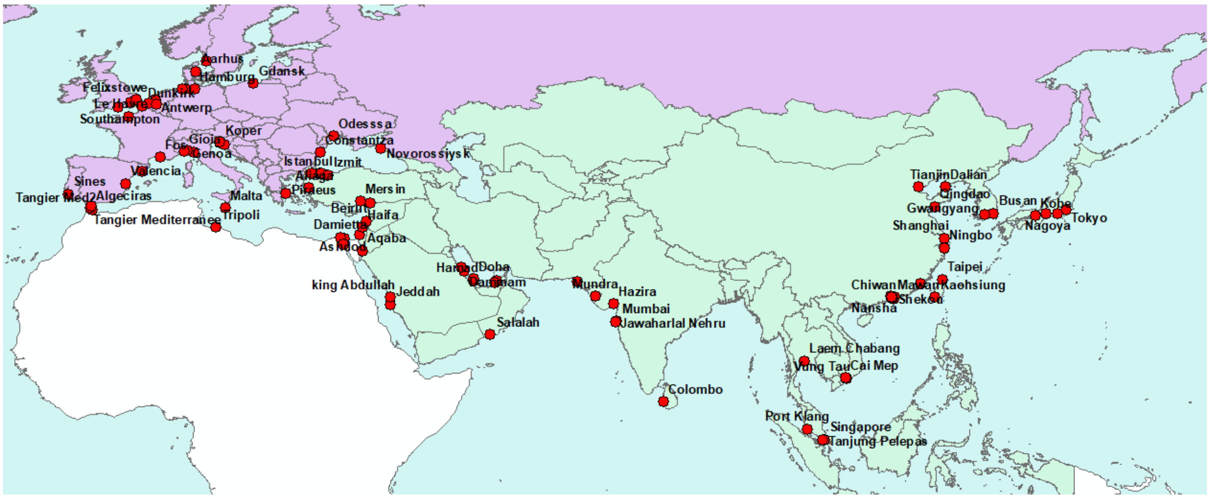


Figure 6.6 Distribution map of container ports on the selected strings.
(Source: Author elaboration based on ArcGIS)

6.3.3 Building the Container Shipping Network

To construct the container shipping network between Asia and Europe, three metrics were employed for analysis. Based on the definition of network analysis, the **Container Shipping Network (CSN)** of this research consisted of:

$$CSN = (N, L, W_{ij}) \tag{6.1}$$

Where N = (1, 2, …, n) is the number of nodes (ports) in the network. L is the direct links between pairs of nodes. W_{ij} refers to the weight of the link between different pairs of nodes, measured in TEUs (Eq. 6.2). Following Ducruet (2013), Calatayud *et al.* (2017) and Wu *et al.* (2019), the weight of the link between pairs of ports depended not only on the number of times a link was made between the ports, but also the capacity on that link. Due to the limitation of available data on the actual container capacity of TEUs on the specific ship, the capacity of the link is linked to the cumulative cargo capacity of the ship travelling on that voyage, along with the frequency of the routes.

$$W_{ij} = \sum_{S}^{n} \left(V_S^{ij} F_S^{ij} \right) \tag{6.2}$$

Where W_{ij} is the weight of the links between different pairs of nodes, measured in TEUs. n refers to the total number of times a trip is made between node i and j by the container shipping companies. S refers to the string that included sailing between node i and j (range 1-115). V_{ij} refers to the size of ships providing services on string S from node i to j, measured in

TEUs. F_{ij} refers to the number of ships that operated services on string S during the selected period.

To summarise, the weight of the link depended on the total number of times a trip was made between two nodes and the cumulative capacity (TEUs) on the link. To account for the weight of the links, the strings of departures from the period 1 November 2021 through 31 January 2022 were selected. This time period was considered for analysis since: (1) the impact of COVID-19 strongly impacted the transportation industry since the start of 2020. Container shipping throughput, container ports operation and management in severely affected areas experienced varying degrees of interference. Meanwhile, the cancellation of shipping routes could have impacted the validity of the analysis results. According to UNCTAD (2021), due to the growth in e-commerce, maritime trade volume started to recover and return to normal in 2021, especially for containerised trade. The end of 2021 was an appropriate time period to observe the shipping network after the pandemic and the emergence of new maritime trade patterns. (2) This time interval could clearly reflect the frequency and the number of ships. For example, the AE5 Eastbound string from Maersk consisted of 12 ships during the three-month period (1 November 2021 through 31 January 2022), with the frequency being one ship per week, including (number in brackets is the ship TEU capacity) Mumbai Maersk (20,568), Maren Maersk (18,270), Morten Maersk (18,270), Maribo Maersk (18,270), Maastricht Maersk (20,568), Murcia Maersk (20,568), Mette Maersk (18,270), Munich Maersk (20,568), Merete Maersk (18,270), Madrid Maersk (20,568), Margrethe Maersk (18,270), and Milan Maersk (20,568). Therefore, the total capacity of this string is 233,028 TEUs, which contributed to the weight of each link connected by this string.

For the 115 strings in the target population and in the period of 1 November 2021 through 31 January 2022, a total of 1,383 ships operated on the CSN (Maersk:285, MSC:218, CMA CGM:318, COSCO:328, and Hapag-Lloyd:234). For container shipping transportation, the frequency of one specific string was usually one ship per week. Sometimes, this would increase to multiple ships per week or decrease to one ship in multiple weeks. The number of the ships that travel on this link (F_{ij}) represented the frequency of the string.

V_{ij} in Formula 6.2 referred to the ship size provided in the service S from port i to j and measured in TEUs. For each link, there were several strings involved. For example, the link from Piraeus port to Rotterdam port. In this link, there were three strings from two companies that provided the service during the period under investigation (Figure 6.7):

- AEU3 Westbound from COSCO (12 sailings, totaling 237,558 TEUs).
- French Asia Line 2 Westbound from CMA CGM (15 sailings, totaling 297,696 TEUs).
- French Asia Line7 Eastbound from CMA CGM (12 sailings, totaling 176,516 TEUs).

The weight of the link from Piraeus to Rotterdam should be the sum of the ships from these three strings. To account for this, the weight of the link between Piraeus to Rotterdam was 711,700 TEUs. The data collected from the actual ship schedule could reflect the importance of the link more accurately, while the building network could more closely imitate the real container shipping network.

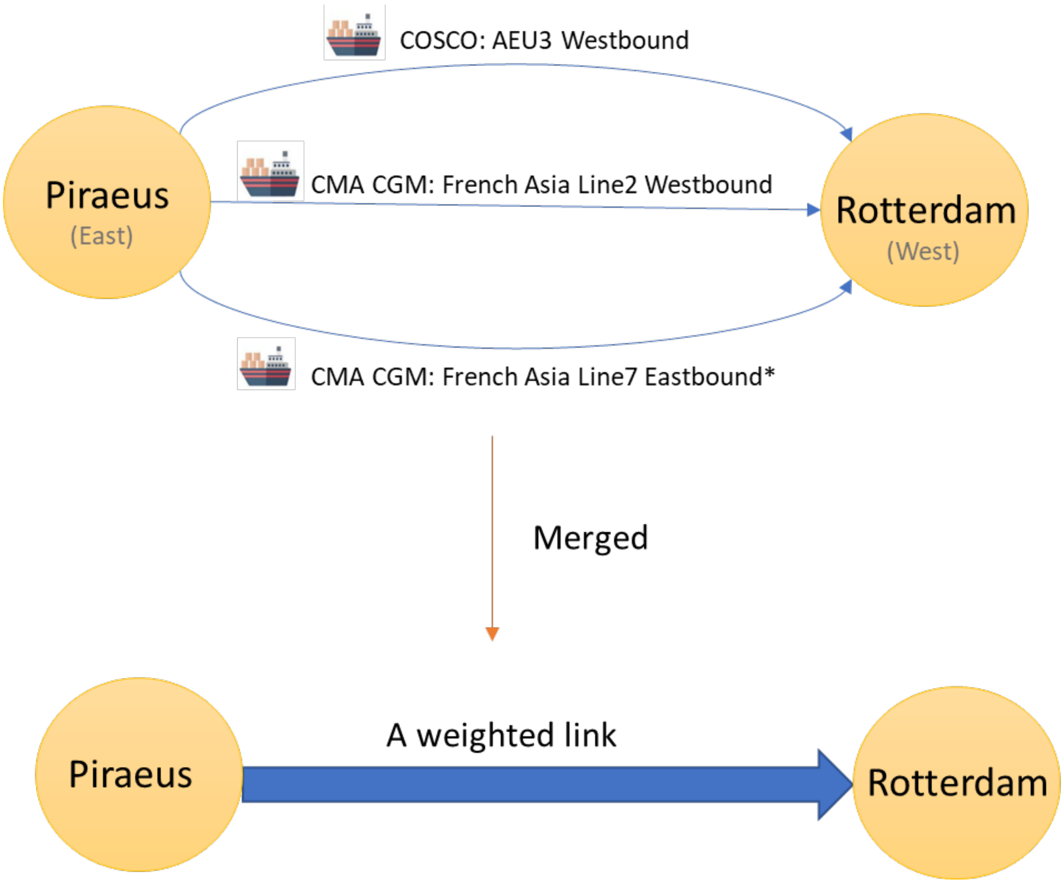


Figure 6.7 Procedure for calculating weighted link

(*Notice: French Asia Line 7 Eastbound was actually started at Piraeus and voyaged west to Rotterdam and then headed east to Asia, which was a string designated as eastbound, but included a westbound link, introduced in Section 6.3.1, Footnote 2)

The link in this research project refers to the direct service between two nodes. According to the sample selection result, there were 939 separate and distinct links from five shipping companies. In agreement with the calculation procedures, as shown in the example above (link Piraeus to Rotterdam), the links from different strings that provided the same services for the same pair of nodes were merged together. Take the link from Piraeus port to Rotterdam port for example again (Figure 6.7). There were three strings that provided services on this link. After calculating the weight of the link as shown above, three separate links merged and became one **weighted link**. Here, the weighted link refers to the direct connection between two nodes that comprise one or more links. The weighted link between Piraeus and Rotterdam comprises three separate links. According to this calculation procedure, 939 links from 115 strings were merged into 353 weighted links (Table 6.4).

Link	Weighted Link
The direct service between two nodes.	The direct connection between two nodes that comprises one or more links.
The entire target sample network has 939 separate and distinct links.	The entire target sample network has 353 weighted links.

Table 6.4 The differences between link and weighted link.

The weight of the link W_{ij}, depends on the number of TEUs, the number of ships and the frequency of the route. The **weighted degree of a node** (port) refers to the total weight of the links to and from port *i* which included both the export link (departure from port *i*) and the import link (arrival to port *i*):

$$W_i = \sum (W_{ij} + W_{ji}) \tag{6.3}$$

Where W_i is the weight of node i. W_{ij} refers to the weight of the out-bound link from port i. W_{ji} refers to the weight of the inbound link to port i. In contrast to the available literature, e.g., Kaluza *et al.* (2010) and Ducruet and Zaidi (2012), this research project adopts the perspective of a directed network, encompassing both inbound and outbound links. This approach enables the research to have an asymmetric matrix for network analysis.

Figure 6.8 provides the procedures for data selection and collation. First, the container shipping network between Asia and Europe (CSN) was selected and strings from five shipping companies were collected (step 1). Then, the links and nodes for each string were summarised (step 2). To calculate the weight of each link, the researcher computed how many ships and capacity they carried during a three-month period (step 3). Finally, the links were merged into weighted links and nodes according to the weight (step 4). A total of 89 nodes and 353 weighted links were counted and used for further analysis.

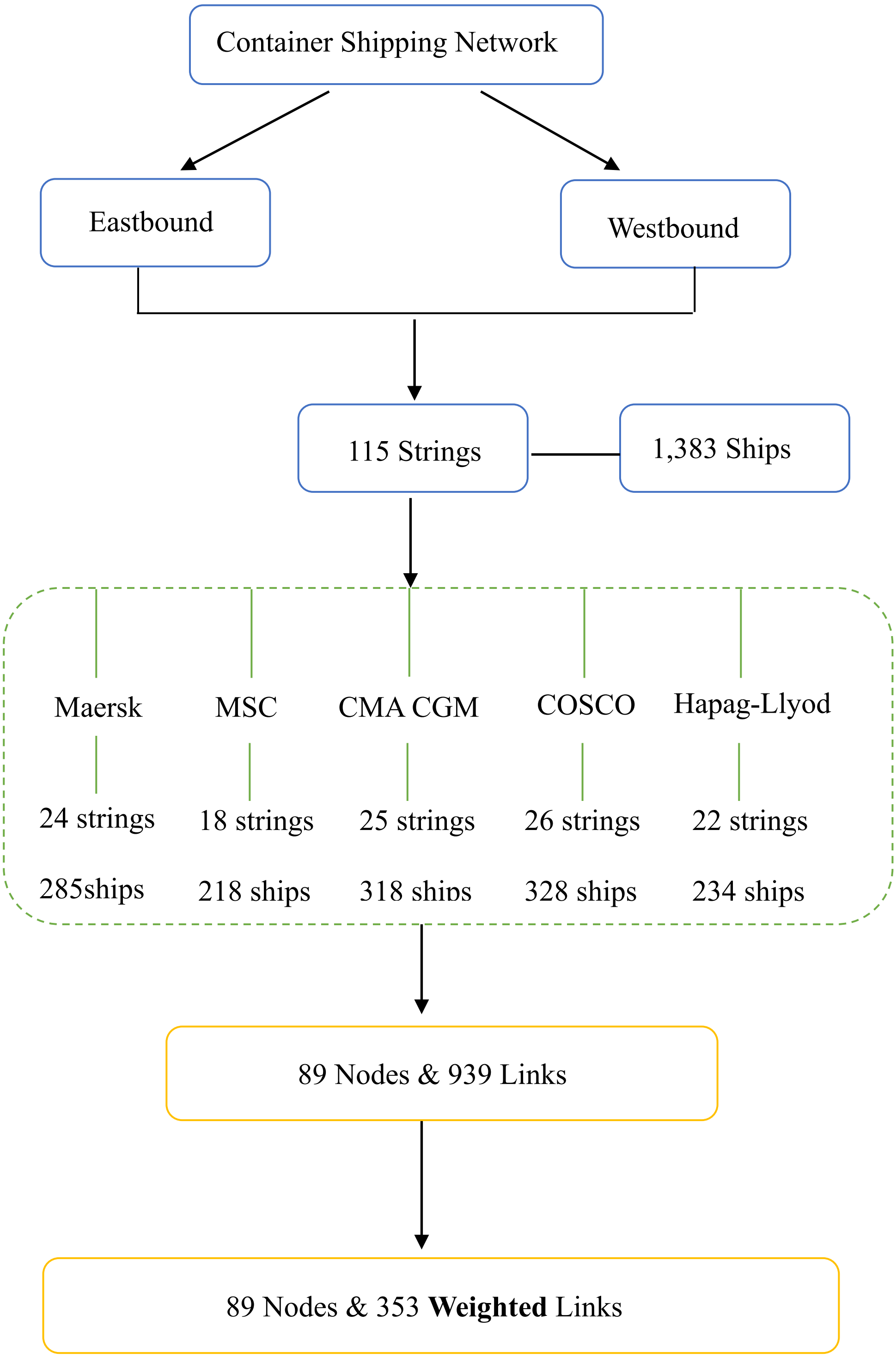


Figure 6.8 Data selection procedures for the CSN

6.3.4 Sample data collection for network performance

Section 6.3.3 explained the data collected for analysing connectivity reliability and network configuration reliability. This section explains the data and data sources selected for the analysis of infrastructure reliability. As established in Chapter 2 and corroborated by interview findings, ports are the key components of the shipping network, with their infrastructure performance playing the main role in the entire network. Furthermore, the research has posited that the time spent in ports can serve as an indicator for assessing infrastructure and service reliability at the port level, as stated in Chapter 5. In accordance with the research purpose and the research scope (confined on the shipping scale as explicated in Section 6.2.2), the analysis focused on assessing the efficiency of container movements, the on-time rate, and the degree of delay in ports and so on. The system data on port performance was collected.

To build the network that reflects the performance of container shipping realistically, the researcher gathered data by observing the transport process of the selected ships in order to build the Performance of the Container Shipping Network database (PCSN). Since the AIS data can guarantee a high reliability of ship traffic information in port waters, the AIS data-based ship traffic analysis becomes extremely promising to precisely capture ship navigation activities and understand ship traffic in port waters (Shelmerdine, 2015). A number of empirical studies have analysed ship traffic using AIS data (Wholin *et al.*, 2013; Zheng *et al.*, 2014). Real-time based data is more authentic and accurate, and it can better reflect the real shipping network. AIS data provides valuable insights into ship movements and maritime activities, but it also has its limitations, such as, the coverage and availability in some remote or less-travelled regions, not all the ships are required to have an AIS transponder, and some small and military ships tend not to use it or turn off it which can create gaps in the data.

Meanwhile, Clarksons Research Portal is a well-established and reputable global provider of shipping services and maritime intelligence. The variety of sources and quality control help to ensure an accurate and reliable data source.

The sampling frame refers to the complete list of all cases in the target population from which the sample will be drawn. In line with the available data between Asia and Europe, collected by the CSN (Section 6.3.3), 1,383 ships from 115 strings were selected as the sampling frame on the analysis of the PCSN. The sampling frame included all the ships that operated on the strings between Asia and Europe by five shipping companies, and that departed in the period of 1 November 2021 through 31 January 2022. The sampling frame was complete and accurate for sample selection. The ships that used to observed were selected from the sample frame.

One of the most important aspects of sample selection is that the results should represent the target population. In order to select the perfect PCSN to answer the research questions and to build a comprehensive shipping network for analysing network performance, the research project used purposive sampling. The choice process considered several influencing factors in order to accurately provide the maximum variation possible, including strings operated by the ship, date of departure, shipping company and ship size:

- Strings and shipping companies: The target population of this analysis is the shipping strings between Asia and Europe among the top five shipping companies (Maersk; MSC; CMA CGM; COSCO; Hapag-Lloyd), which included 115 shipping strings. The sampling frame encompassed a total of 1,383 ships that operated on these 115 strings. Due to the characteristics of container shipping, and to capture a comprehensive representation of the shipping network, each of the 115 strings was treated as an individual cluster. Subsequently, a sampling strategy was employed wherein sample ships were chosen from each of these clusters, fostering a holistic and well-rounded representation of the container shipping network.
- A number of strings were operated by the cooperation of two or three companies. For example, the AE5 Eastbound from Maersk, the ALBATIRS Eastbound from MSC, and the FE7 Eastbound from Hapag-Lloyd shared the same ships during the observation period. Therefore, amalgamation of these duplicate strings was deemed necessary. After merging all duplicate strings, a total of **86** clusters were eventually identified. The sample ships for analysis were then strategically drawn from these 86 clusters, resulting in a selection of **1032** ships.
- Usually, one string was operated by the ships with similar TEUs. For example, AE12 Eastbound from Maersk, was operated by 11 ships (number in brackets is the sip TEU capacity): Maersk Hanoi (15,226), Maersk Houston (15,226), Maersk Horsburgh (15,226), Maersk Hangzhou (15,226), Maersk Hamburg (15,226), Maersk Havana (15,226), Maersk Halifax (15,226), MSC Genova (14,036), Maersk Huacho (15,226), Maersk Hong Kong (15,226), and Maersk Hidalgo (15,226). The ships in this cluster had a similar ship capacity, which would not affect the result of sample selection. However, in some strings, there are outliers that are far away from the average ship

capacity within the same cluster. For example, French Asia Line 8 Eastbound from CMA CGM, consisted of 12 ships during the selected period including: Thalassa Mana (13,806), Theseus (14,424), Thalassa Avra (13,806), Thalassa Niki (13,806), Thalassa Hellas (13,806), Tampa Triumph (13,900), Thalassa Axia (13,806), Ever Gifted (20,150), Thalassa Elpida (13,806), Thalassa Patris (13,806), Thalassa Doxa (13,806), and Triton (14,424). The ship capacity of Ever Gifted was much larger than other ships in this string which was regarded as the outlier data in this cluster. The outlier data was not intended to be selected into the sample database.

- Date for departure: The occurrence of unconventional emergencies or disruptions happening in the container shipping network is random and difficult to predict. In order to avoid the biases that emerge from the random events or disruptions, the selected ships were supposed to be in the same external environment. The sampling frame included ships departed during the period 1 November 2021 through 31 January 2022, and the start date of observation was 1 December 2021. The departure date closest to 1 December in each cluster was selected. In total, **86 ships** were selected.

The selected 86 ships made up the PCSN database to measure the performance of container transportation in each node and link. The AIS data of 86 ships within the network in the period of 1 November 2021 – 31 January 2022 was captured to analyse the network performance. This necessitated observing the different AIS position and movement signals of each of the 86 sample ships every day over the three-month period.

As introduced in section 6.2.3, the available literature usually used the traffic volume that arrived and departed in the berth area to measure the performance of ports. What’s new in this research project is that the turnaround time is represented by the time at berth, which reflects the infrastructure utilisation and also the time at the anchorage area, which is one of the most important factors for measuring waiting time in port. In agreement with the division of turnaround time, the container transportation process was divided based on three points: departure, at anchorage and at berth (Figure 6.9).

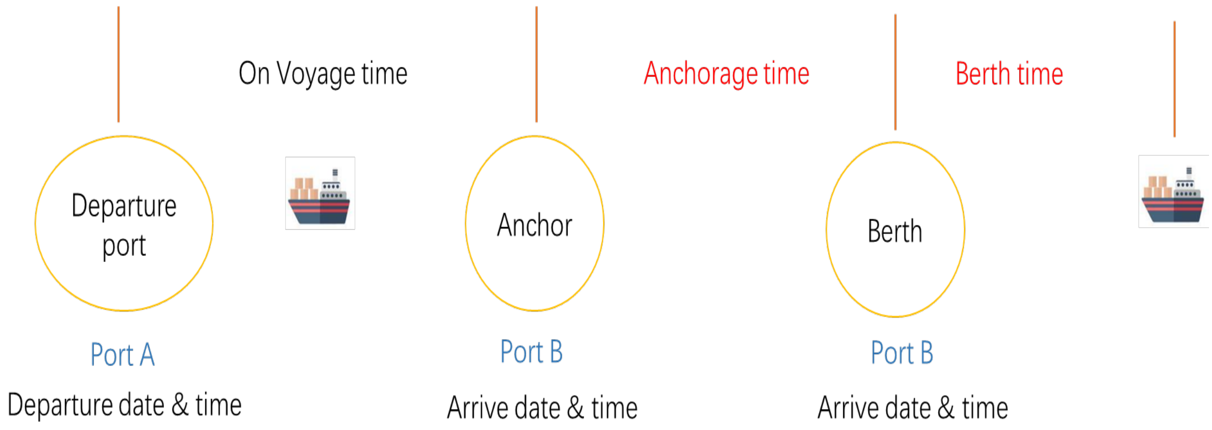


Figure 6.9 Procedures to observe the selected ships in this research.

The observation database intended to identify:

- Actual departure time from origin node A.
- Actual arrival time to the anchorage of destination port (node B). For some links, ships would not arrive to the anchorage; they would go straight to the berth. For these links, actual arrival time to the anchorage was regarded as the time that the ship entered the port area. AIS data from Clarksons provided the “First seen”, which refers to the time that ships moved into the port area.
- Actual arrival time to the berth of destination port (node B).
- Ports of call. Although the designed strings had already been collected from published sources, the actual ports of call might change in response to the real situation.
- Special cases and disruptions. During the observation time, there were disruptions, including the effect of the pandemic, port congestion, strike, bad weather and so on. The observation data included the actions that ships preferred when facing disruptions as well as the special trajectory during the journey.

Additionally, for the purpose of assessing the on-time rate, data pertaining to planned schedules (the scheduled departure time at the origin port and the scheduled arrival time at the destination port) was obtained from shipping companies. By utilising both the planned and actual data, a comparative analysis of the time reliability across nodes, links and carriers was facilitated. This dataset also offered the opportunity to delve into the underlying causes of delays in the shipping network.

6.4 Conclusion

Employing the method – network analysis, this chapter started to present a more comprehensive approach for assessing the reliability of the entire network. Section 6.2 reviewed available literature concerning the utilisation of network analysis in shipping networks, with a particular emphasis on its application in assessing network configuration and network performance. Moreover, it presented how network analysis would be used in this research project. Section 6.3 presented the research design for developing a new approach with regard to RQ4, including the terminologies used for the following analysis, as well as the data selection procedures.

The following chapters will start to assess the reliability of the shipping network. More specifically, Chapter 7 will present the connectivity reliability of the network. Chapter 8 will investigate the network configuration reliability, including the impact of disruptions to the network and the recovery procedures. In Chapter 9, the shipping network is explored with a focus on nodes within the network, in order to investigate the infrastructure reliability of ports. The analysis will also give an insight into the dependency of the network components.

Chapter 7. Analysis of the network connectivity

7.1 Introduction

Following the methodology developed in Chapter 6 – network analysis – and the selected data, the CSN connecting Asia and Europe was built for analysis. Given that one of the fundamental functions of container transportation is network accessibility, it is paramount for ports in the network to establish connections with other ports in order to facilitate efficient container export services. Chapter 7 starts to analyse the CSN with a focus on the connectivity reliability of the network, which refers to the probability of the components in the network being connected, as identified in Chapter 2. The network was put into the software – Gephi – for visualisation and analysed based on the metrics identified in Section 5.4. Having a thorough investigation into network connectivity, this chapter explores how the nodes are connected in the network with the interdependency analysis between connected ports, the function of ports within the network, as well as the characteristics of the entire container shipping network.

The analysis of network connectivity reliability is structured as follows: Section 7.2 builds the CSN based on the selected database. Section 7.3 starts to analyse how the nodes in the network are connected and their functions within the network with identified metrics. Finally, Section 7.4 summarises the findings in this chapter.

7.2 The Container Shipping Network (CSN)

To explore the reliability in the context of container shipping networks, this research selected the network between Asia and Europe (CSN) to do further analysis. The research first built the network structure. Following the selected data and designated methodology developed in Section 6.3.2 and 6.3.3, a directed and weighted CSN was built based on nodes, direct links and weight of the links – comprising a total of 89 ports, 115 strings and 353 weighted links – represented the container transportation relationship and movements in 38 countries along the trade.

Network analysis and graph theory were applied to discover the CSN, as stated in Section 6.2. The selected nodes and links were put into Gephi, a visualisation software for network analysis (Bastian *et al.*, 2009; Heymann and Grand, 2013) and displayed in the Fruchterman and Reingold algorithm – nodes with higher degree and weight were located near the centre of the figure. Figure 7.1 and Figure 7.2 provide visualisation graphs of the CSN. Considering that the CSN consisted of both the number of direct connections and the weight, as stated in Eq. 6.1 of Chapter 6, it is crucial to understand whether there is a difference in network configuration based on the number of connections and the carried TEUs of nodes. Given this question, the research then proceeds to evaluate the reliability of nodes from two perspectives separately.

In Figure 7.1, the size of the nodes varies according to the degree of the nodes, which refers to the number of connections between two nodes. The size of the links varies according to the weight (including the number of times and capacity of the link introduced in section 6.3.3) of the link. The nodes with higher degree were placed in the centre of the topological diagram with deeper colour. In Figure 7.2, the size of the nodes varies according to the weight of the ports, that is, the total weight of the links to and from the node, measured in TEUs. The size of the links still matters according to the weight. The nodes with higher weight were placed in the centre of the topological diagram with deeper colour.

The results of network visualisation indicated variations in the network's structural composition. The central positioning of ports within the network changed, casting light on network characteristics when considering different node functions. The following sections provide further analysis using network-related metrics, and the objective is to give insight into the connectivity-related issues – including how the network is connected, the interdependency between nodes, the structure of the network and the role of nodes within the network.

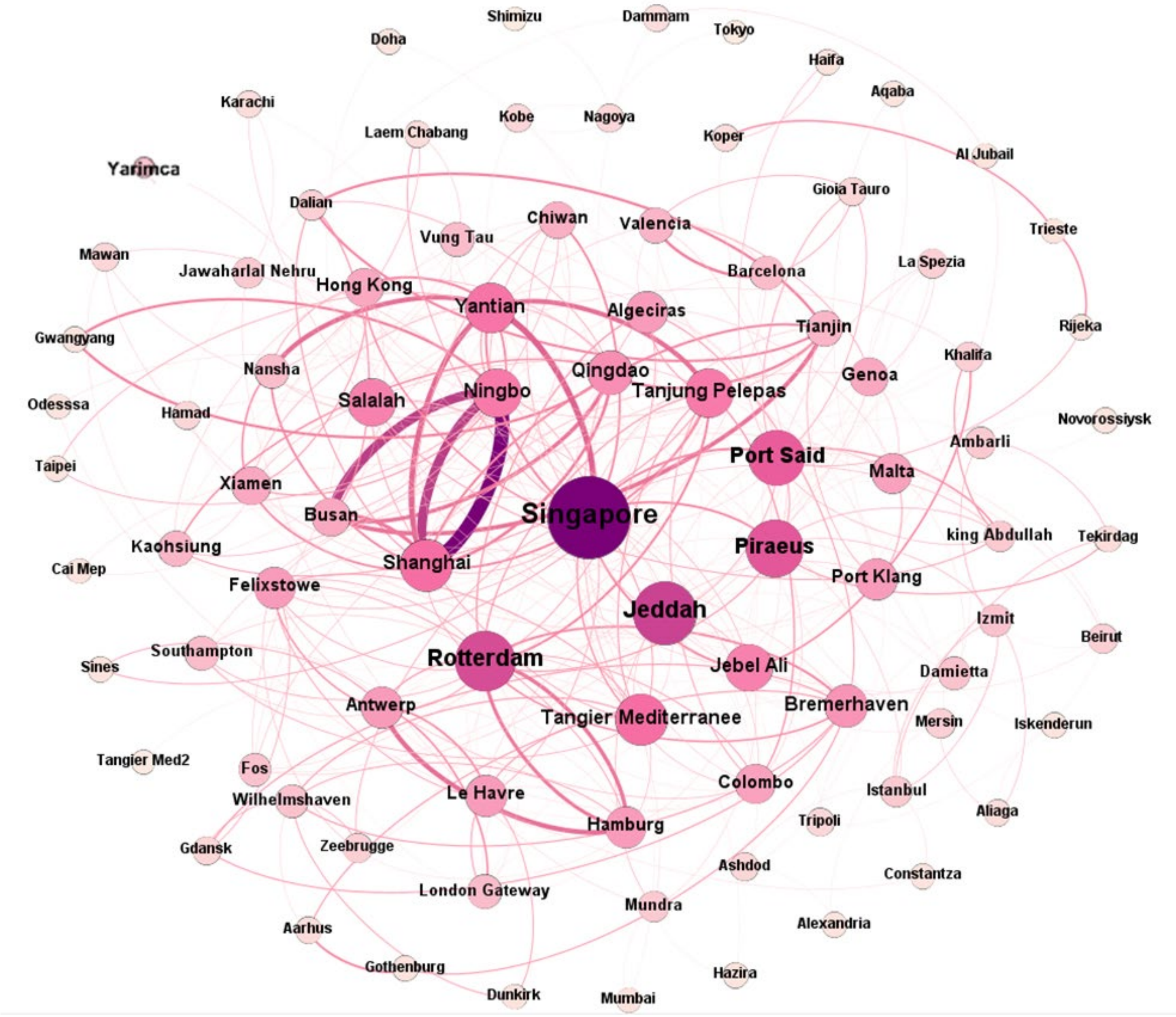


Figure 7.1 Topological diagram of the CSN considering node degree

*The size of nodes varies according to the number of connections and the size of links varies according to carried TEUs.

(Source: Author based on containers movements information from five shipping companies, as introduced in Section 6.3.2)

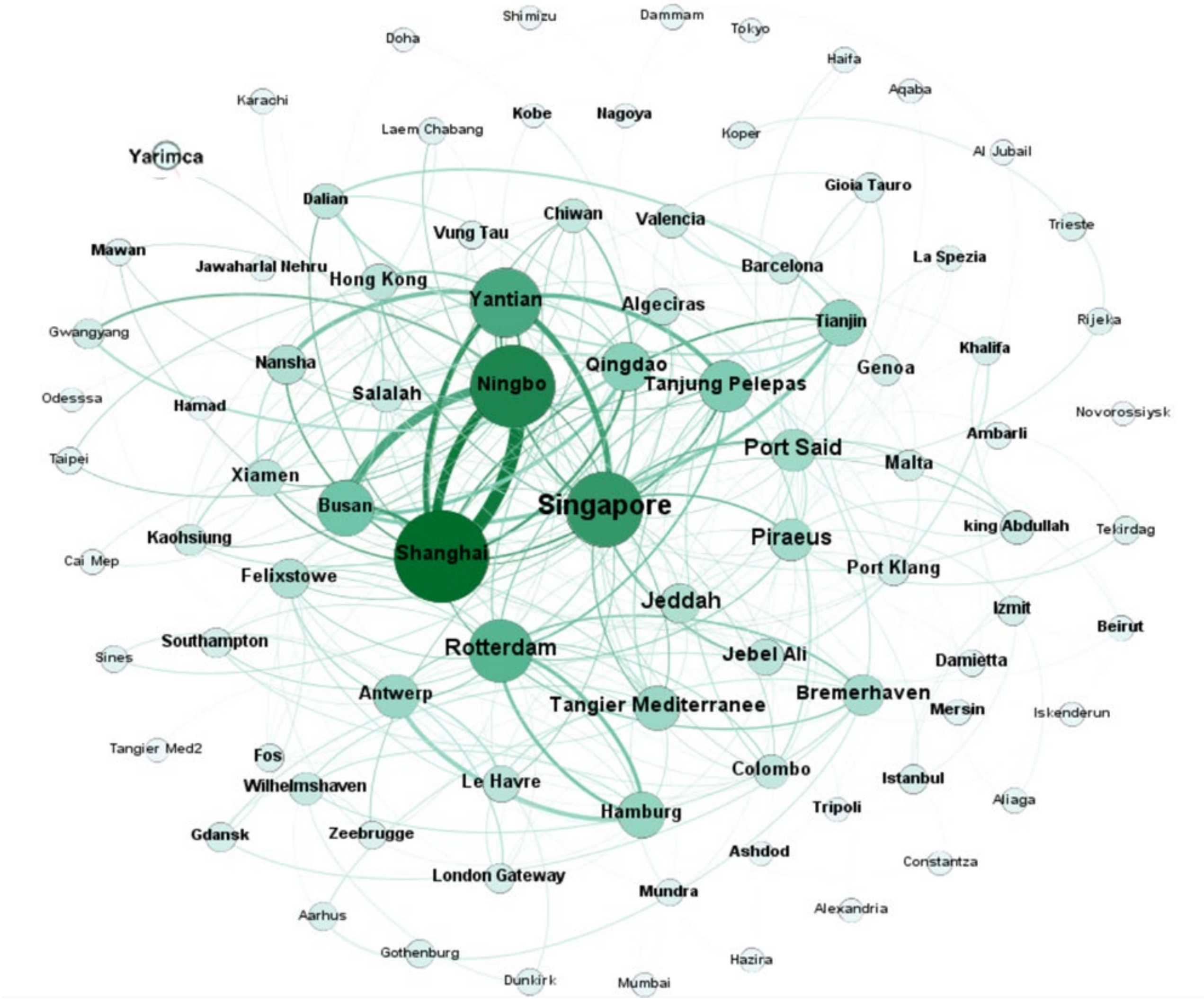


Figure 7.2 Topological diagram of the CSN considering node weight

*The size of nodes varies according to the total weight of links to and from the node and the size of links varies according to carried TEUs.

(Source: Author based on containers movements information from five shipping companies, as introduced in Section 6.3.2)

7.3 Results from the analysis of connectivity reliability

Network analysis-related metrics derived from complex network analysis and graph theory were applied to assess the connectivity and characteristics of the CSN. The metrics and formulas were justified in detail in Chapter 5, but the explanations of formulas are included again in the following sections for ease of understanding.

7.3.1 Analysis of connectivity based on topology structure

The average path length was defined as the number of links along the shortest paths for all the node pairs in the network. The average path length (APL) of the CSN was 3.479, which meant that every node in the CSN could reach any other nodes in the network within three to four steps only. On average, routes between port pairs comprised 3 to 4 stops/transits at intermediate ports. The average path length indicated the difficulty before arriving to the destination port, that is, the smaller the APL, the fewer transhipment times were required between two nodes.

Network diameter was defined as the shortest path length between the most distant node pairs in the network. The diameter of the CSN was 8, which represented the longest route in the CSN among all the node pairs, comprising of 8 stops.

The clustering coefficient was defined as the degree to which a node and its neighbours tend to cluster together. The clustering coefficient of the CSN was 0.272, which indicated that the clustered degree of nodes in the network was relatively high. A larger clustering coefficient indicates a greater prevalence of direct links connecting various nodes. This implies that the network exhibits a higher degree and reduced dependency on a single hub port. Consequently, larger clustering coefficient values are associated with improved connectivity and reliability.

In order to validate the findings of the CSN, a random network with the same number of nodes and $p=0.5$ was generated. The results in Table 7.1 show that the network diameter was the same as with the random network, and the APL of CSN (3.479) was slightly higher than the random network with the same scale (3.099). The reason can be attributed to the characteristics of the CSN in comparison to other types of networks. Due to the limitation of geography-related factors, capacity of ports, ship size etc., the configuration of the shipping network and the selection of ports would be affected. For example, strings between East Asia and West Europe are required to pass through the Malacca Strait, the Suez Canal and the

Strait of Gibraltar to reach their destination ports. These geographical constraints and port service barriers necessitate multiple transhipments along the string, resulting in a higher APL in the CSN as compared to other transport networks. However, the clustering coefficient of the CSN (0.272) was significantly larger compared with the random network (0.025). Following Barabási *et al.* (2002) and Ducruet and Zaidi (2012), the short average path length and high clustering coefficient indicated that the CSN was a small-world network – ports in the network were topologically close to each other – topologically, here, means that ships could reach to their destination port within a small number of steps (fewer transhipment times).

	Formula	**CSN**	**Random network**
Nodes		89	89
APL	APL= $\frac{1}{\frac{1}{2}n(n-1)}\sum_{i>j} d_{ij}$	3.479	3.099
Clustering coefficient	$C_i = \frac{L_i}{k_i(k_i-1)/_2}$	0.272	0.025
Diameter	$D = MAXd_{ij}$	8	8

Table 7.1 Comparison between the CSN and a random network

7.3.2 Analysis of connectivity based on node degree

The degree of the node refers to the number of links in which the node is directly connected with other nodes, which can be understood as the "connections" of the node. More specifically, as stated in Section 6.3.3, the CSN in this research was supposed to be a directed network, with links to and from the node. In agreement with the identification of network direction, degree of the node was divided into in-degree and out-degree. The in-degree and out-degree represent the number of links connected to and from the port, respectively. Table 7.2 shows the ranking of the top 20 ports with highest degree based on the calculation results.

Rank	Port	Total degree	In-degree	Out-degree
1	Singapore	41	19	22
2	Jeddah	28	15	13
3	Rotterdam	26	13	13
4	Piraeus	24	11	13
5	Port Said	23	11	12
6	Tangier Mediterranee	20	11	9
7	Shanghai	20	10	10
8	Yantian	19	9	10
9	Tanjung Pelepas	18	9	9
10	Ningbo	18	7	11
11	Salalah	17	7	10
12	Jebel Ali	17	7	10
13	Qingdao	15	10	5
14	Bremerhaven	14	7	7
15	Felixstowe	13	7	6
16	Antwerp	13	5	8
17	Hamburg	13	8	5
18	Le Havre	13	6	7
19	Algeciras	13	6	7
20	Port Klang	13	6	7

Table 7.2 Calculation of the top 20 ports with the highest degree.

The Singapore port had the highest degree, 41 (in-degree = 19; out-degree = 22), which was significantly higher than other ports. This meant that there was a significantly high number of ports connected with Singapore and most of the strings in the CSN needed to tranship from Singapore. Followed by Jeddah (28), Rotterdam (26), Piraeus (24) and Port Said (23). These ports were well connected among the CSN and were important to the network configuration, hence, placing them in the centre of Figure 7.1. In turn, Shimizu and Tokyo were at the bottom of the ranking, as ports in Japan were less connected in the CSN.

The correlation between in-degree and out-degree was positive and highly correlated with the correlation coefficient = 0.915, and significant at the p=0.01 level (Figure 7.3). The highly correlated relationship between in-degree and out-degree indicated that the ports with many inbound connections tended to also have similar outbound connections, and vice versa. There was a strong reciprocal relationship among ports in the CSN and a higher probability of forming bidirectional links between two nodes. This phenomenon contributed to the emergence of similar in-degree and out-degree distributions. Seven ports appeared in all of the three top 10 rankings in Table 7.2: Singapore, Jeddah, Rotterdam, Piraeus, Port Said, Shanghai and Yantian, which means that these ports had both significantly higher import and export relations with other ports within the CSN.

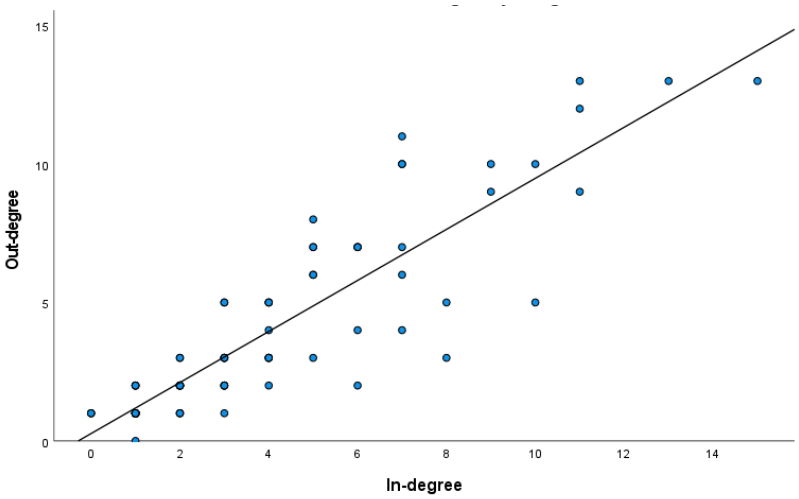


Figure 7.3 Correlation results between in-degree and out-degree.

However, there were still different cases, e.g., Qingdao (China) had a higher in-degree (10), and the out-degree (5) was only half of the in-degree, which showed the imbalance of import and export container trading, similar with Hamburg. Salalah and Jebel Ali had a higher out-degree (10) compared with the in-degree (7). The results of in-degree and out-degree firstly indicated the function of the port as an importer or exporter. Compared with the role of being an exporter, ports with a higher in-degree often served as importers within the CSN, e.g., Qingdao. On the contrary, the ports with a higher out-degree were more likely to function as exporters within the network, e.g., Jebel Ali. Another inference drawn from the results is that network configuration at the planning stage remains an influencing factor on network connectivity. Ports frequently assuming the role of destination node within the string had a higher inbound degree compared to ports functioning as origin nodes (a higher out-degree).

What stands out in the results of network degree analysis is that the degree distribution varied widely between different nodes. Figure 7.4 shows the distribution map of 10 ports with the highest degree. An examination of the map unveils a well-distributed pattern of noes along the trade connecting Asia and Europe. Three of the nodes are located in East Asia, two in Southeast Asia, two in West Asia, one in Southern Europe, and the remaining two were suited along Western Europe.

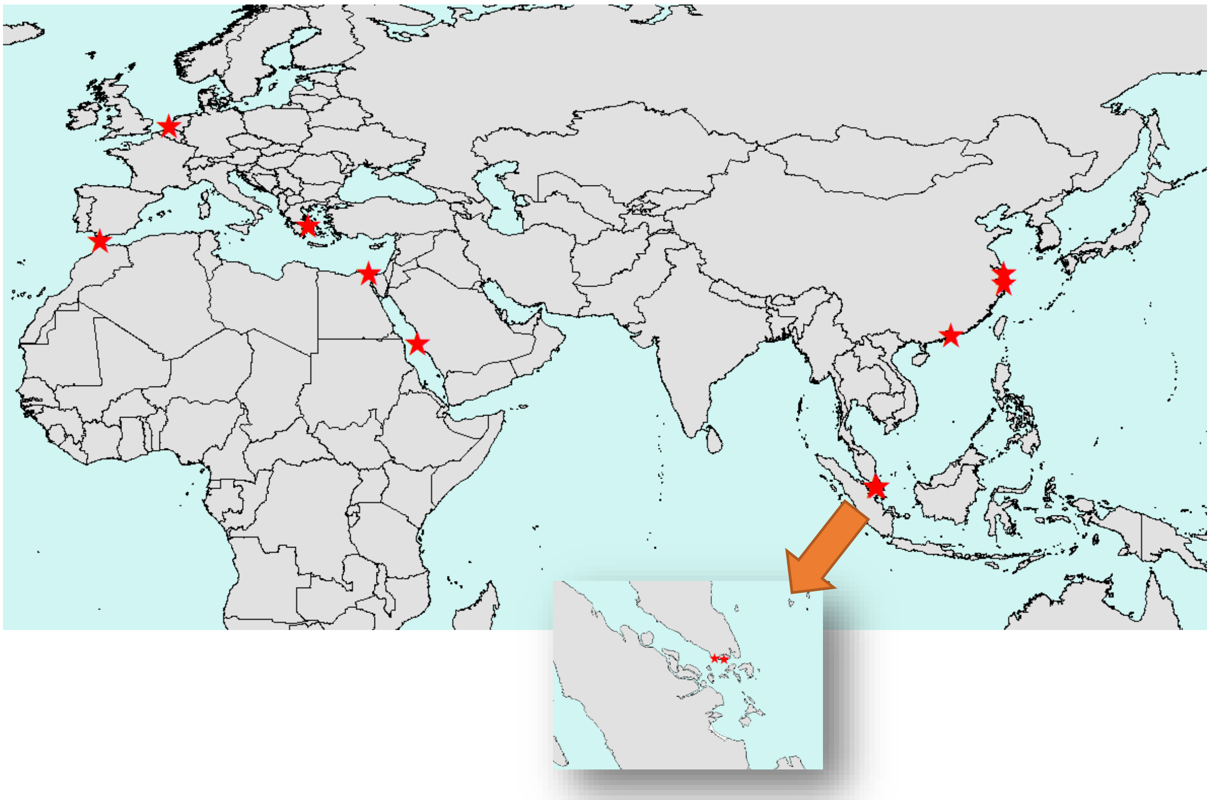


Figure 7.4 Distribution map for the top 10 ports with the highest degree
(Source: Author elaboration based on ArcGIS)

The literature review in Chapter 2, and interviews in Chapter 4, have already identified the influencing factors to network reliability, with a specific concern on connectivity. These factors could help explain the distribution of nodes when considering node degree. In line with the position of the nodes, nodes with a higher degree were not randomly distributed. Geography-related issues are one of the determinants to degree distribution. These nodes depended on the important position in the CSN, especially around the Malacca Strait, the Suez Canal and the Strait of Gibraltar. As previously mentioned, ships need to transfer through several important canals and straits before reaching their destination ports. Ports positioned in key strategic locations, such as Singapore, Port Said and Tangier Mediterranee assume a pivotal role in the CSN. Therefore, it comes as no surprise to observe that these ports have a higher degree of connectivity. Infrastructure availability, together with facilitation of transport access, could also be identified as a crucial factor. Take the port of

Singapore for example (with significantly higher degree). Public authorities in Singapore exploited the opportunity to become the centre of global maritime by developing world-class transportation handling facilities, and also establishing their information and electronics components (Slack and Gouvernal, 2016). Chapter 9 provides a deeper analysis for understanding the relationship between port performance and network reliability. Meanwhile, different functions of ports associated with their hinterlands and forelands also affect the degree (Ducruet, 2022). This has been explained in the analysis of in-degree and out-degree. The function of ports decides the role as an importer or exporter.

Although ports have different degrees in the rankings, it is important to point out that the CSN was highly connected. The average degree of the network was 8.022, which means that each port in the network was directly serviced by an average of 8 links (including in-bound and out-bound). This is also one of the reasons that explain the higher clustering coefficient compared with random network analysed in Section 7.3.1. The average degree also resulted in a shorter APL – ships only need to transit for 3 to 4 stops to their destinations on average within the network.

As shown in Figure 7.5, from the view of the entire shipping network, the total degree distribution of nodes within the CSN was skewed to the left, the frequent scores were clustered at the lower degree and the tail pointed to the positive scores. Most of the ports had a total degree of between 0 and10, occupying the proportion of 70.5%. Nodes with a degree of 2 had the highest proportion (21.6%). Among the nodes with a degree higher than 10, nodes with a degree of 13 had the highest proportion (6.8%). Ports with higher degrees increase the average degree of the overall network. The highest degree of the CSN achieved 41 (Singapore), significantly higher than other nodes, followed by a degree of 28 (Jeddah). Degree distribution varied widely between different nodes.

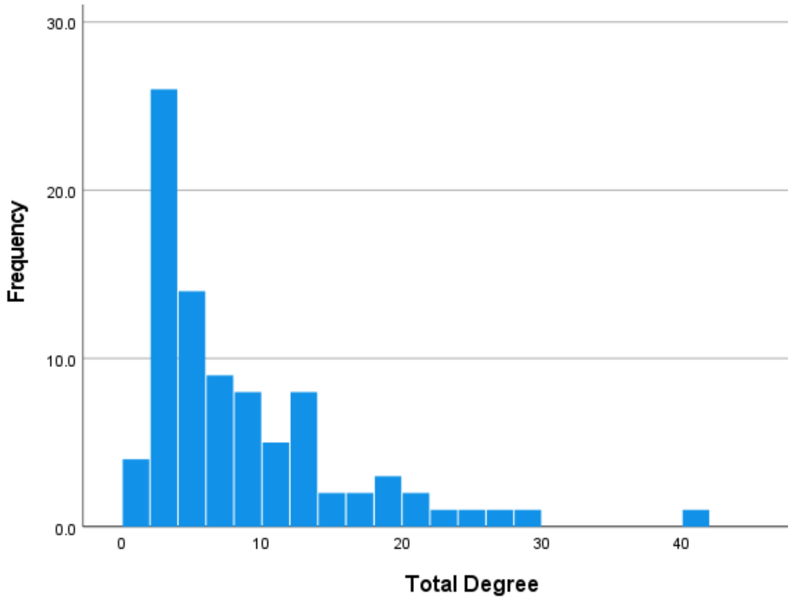
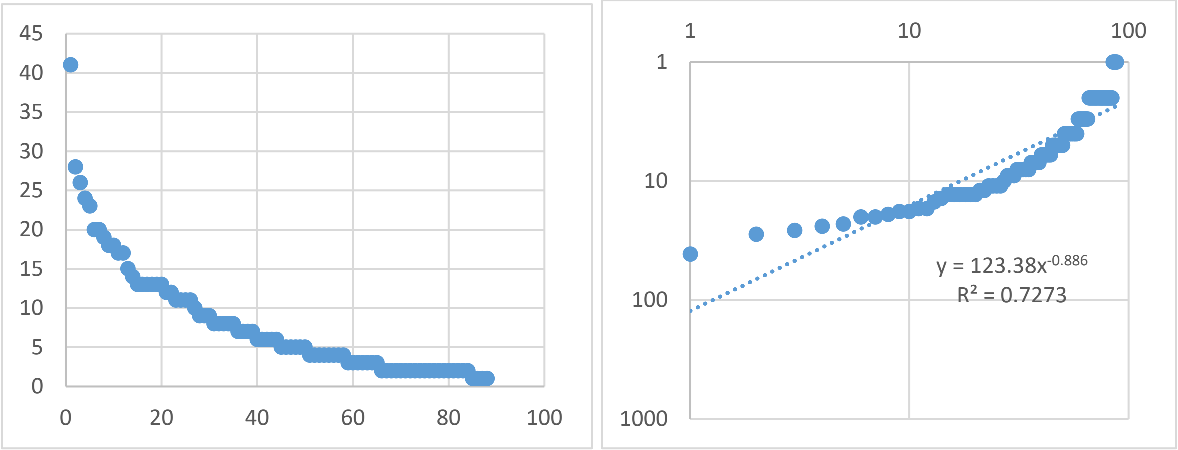


Figure 7.5 Distribution of total degree within the CSN
(Source: Author's analysis based on node degree)

The identification of the network with the power-law degree distribution was recognised as a scale-free network in the field of complex network theory, introduced by Barabási *et al.* (2000). To assess whether the degree distribution between Asia and Europe (Figure 7.6 (a)) fulfilled the scale-free property, the research conducted a test to determine if it fit the power-law distribution. Figure 7.6 (b) shows the result plotted on a log-log scale for the shipping network, revealing a fitting curve of the degree distribution that followed the power-law distribution with R^2=0.7273, therefore, fulfilling the scale-free property. In a scale-free network, with the increase of node degree, the probability value decreases, implying that there are fewer ports with a higher degree while more ports with a lower degree value in the network exist.



(a) (b)

Figure 7.6 (a) Scatter plot of node degree. (b) Log-log power-law fitting curve.
(Source: Author's analysis based on node degree)

The results of network connectivity considering network degree reveal that the CSN exhibits two characteristics: small-world and scale-free. This observation implies that the shipping network is highly connected, while also displaying a pattern that few ports have a higher degree value, and more ports have a lower degree value. This is in line with the findings of the literature review and the complex network theory. The configuration of the shipping network tends to follow the hub-spoke network structure, and it relies more on the hub ports, potentially leading to decreased network reliability. The network structure will be further developed in the next section.

The connectivity and clustering within the network can indeed have implications for network reliability. From one perspective, higher connectivity implies a greater number of available routes. This in turn, can help reduce the vulnerability arising from disruptions on any given route. However, as a consequence of being highly connected, interdependency of ports arises. Interdependency of connected ports makes the network more susceptible to disruptions. Any disturbance happening in one node can affect other nodes, especially those nodes with a higher degree. This issue will be discussed in the next chapter.

7.3.3 Analysis of connectivity based on weight

In contrast to the analysis based on the degree of nodes, the analysis in this section takes into account the weight of nodes and links (Figure 7.2). The results present a different topology graph with different ranking and distribution. According to Section 6.3.3, the weight of the link between port i and port j is the sum of all the services deployed on the link, measured in TEUs, and the weight of the node (port) refers to the total weight of the links to and from port *I*, which includes both the export link (departure from port *i*) and the import link (arrival at port *i*).

7.3.3.1 Weight of node

Table 7.3 presents the ranking of ports according to the weight of the nodes in the network together with the ranking of degree developed in Section 7.3.2. The top 15% of ports (12) among all the 89 ports, including (number in brackets is the percentage of their respective values within the total TEUs of the network) Shanghai (8.21%), Ningbo (7.01%), Singapore (6.09%), Yantian (5.31%), Rotterdam (4.69%), Busan (3.81%), Tanjung Pelepas (3.27%), Qingdao (3.01%), Hamburg (2.65%), Tianjin (2.62%), Antwerp (2.47%), and Tangier Mediterranee (2.43%), concentrated half of the total value (51.57%) in the CSN. Notably, ports in Asia played a more substantial role in terms of TEUs compared with European ports. Among the top 10 ports, eight were situated in Asia, with five of them being located in China. Two ports in Europe had higher weight in the network: Rotterdam (4.69%) and Hamburg (2.65%). In contrast, the bottom 15% of ports only accounted for 0.71% of the total TEUs. A total of 14 nodes possessed trade weight values surpassing the average weight of nodes (7,778,592.36 TEUs).

Rank	Port	Share total TEUs (%)	Port	Total degree
1	Shanghai	8.21%	Singapore	41
2	Ningbo	7.01%	Jeddah	28
3	Singapore	6.09%	Rotterdam	26
4	Yantian	5.31%	Piraeus	24
5	Rotterdam	4.69%	Port Said	23
6	Busan	3.81%	Tangier Mediterranee	20
7	Tanjung Pelepas	3.27%	Shanghai	20
8	Qingdao	3.01%	Yantian	19
9	Hamburg	2.65%	Tanjung Pelepas	18
10	Tianjin	2.62%	Ningbo	18
11	Antwerp	2.47%	Salalah	17
12	Tangier Mediterranee	2.43%	Jebel Ali	17
13	Port Said	2.32%	Qingdao	15
14	Piraeus	2.20%	Bremerhaven	14
15	Bremerhaven	2.08%	Felixstowe	13
16	Jeddah	1.85%	Antwerp	13
17	Nansha	1.84%	Hamburg	13
18	Felixstowe	1.83%	Le Havre	13
19	Xiamen	1.59%	Algeciras	13
20	Le Havre	1.51%	Port Klang	13

Table 7.3 Weight, degree and ranking of the top nodes within the network.
(Source: Author elaboration based on the calculation results)

Figure 7.7 shows the frequency distribution of weight. Similar to the analysis of node degree, the frequency distribution was positively skewed: a small number of ports accounted for a large share of TEUs within the container shipping network.

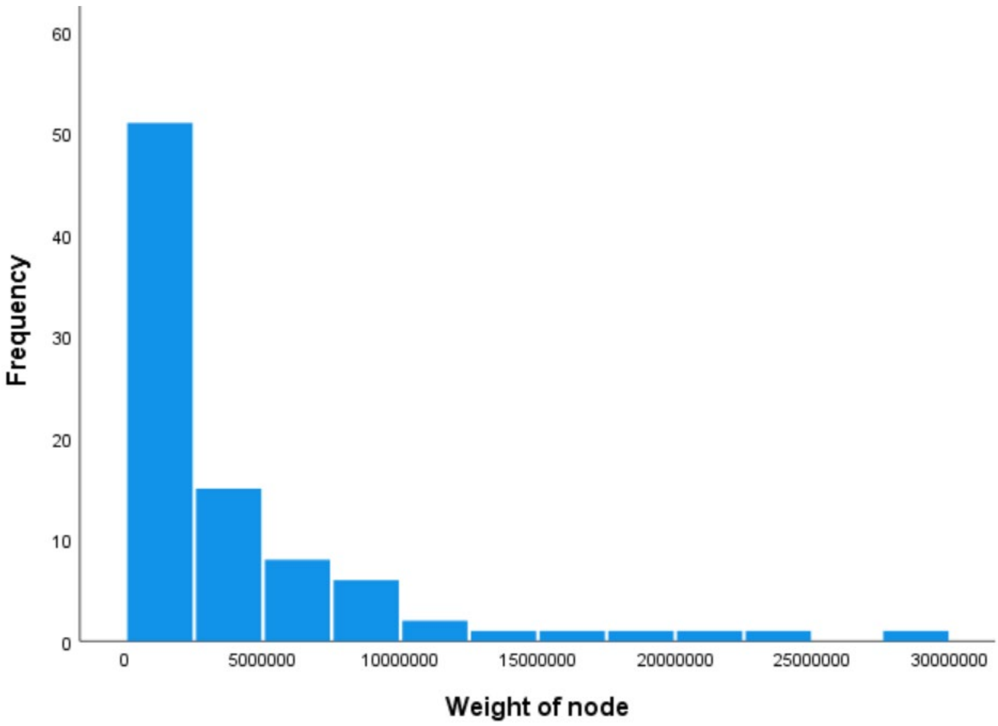


Figure 7.7 Frequency distribution of weighed nodes.

Compared with the ranking of ports based on their degree, the ranking of weight revealed a different result, which evidenced the difference between topology configurations. Figure 7.8 shows the distribution map of the nodes with the highest weight. In contrast to the distribution map of nodes with the highest degree, nodes with highest weight were not evenly distributed in strategic positions, e.g., canals and straits. The nodes were concentrated in East Asia and Western Europe. Combining the results with Table 7.4, ports from China accounted for more than 35% of the total TEUs within the network. Singapore – the second ranking county in the table, accounted for 6.09%, and Germany – the third ranking country, accounted for 5.84%. The total TEUs from China were almost five times higher than the second largest country. What dropped from the analysis was that the bigger the economy, the larger the weight of the node was. Compared with the degree distribution, the ranking of weighted nodes was calculated based on the number of TEUs deployed on the link, which was more related with the trade value and GDP of the city or country. There is also evidence from the global trading network (De Benedictis and Tajoli, 2011) that richer countries tend to have a higher weight and occupy a more central position within the network. According to Serrano and Boguñá (2003), due to the globalisation process and in the absence of barriers, including geographic, economic and technical constraints, the bigger the economy is, the value of the trade is larger and the weight in the network is higher. As a result, bigger countries such as China and Korea in Asia, Netherlands and Germany in Europe tend to hold more trade value and occupy a more central position in the map of the trade between Asia and Europe.

Furthermore, transport infrastructure and market access are essential requirements for ports (Slack and Gouvernal, 2016), especially for the nodes that have geographic proximity and share the same market. As evidenced from the ranking of ports, a correlation exists between the position of a port within the major markets and its weight, e.g., Shanghai is situated in the major market of China as well as the world, resulting in its highest weight among all the nodes. Yantian emerged as the only port from southern China within the top 10 ports. Interestingly, other ports like Nansha and Xiamen, though closer to it geographically, ranked considerably lower than Yantian. This result underscores the findings discussed in the literature review in Chapter 2, the selection of ports depends on many influencing factors, and different approaches to assess it. The infrastructure availability for logistics connectivity aligns with the size of the market and is closely associated with their hinterlands and forelands. Meanwhile, in the case of important transhipment hubs – the ports with a high degree, e.g., Jeddah, have a lack of access to substantial markets, resulting in a comparatively lower weight despite their high degree centrality.

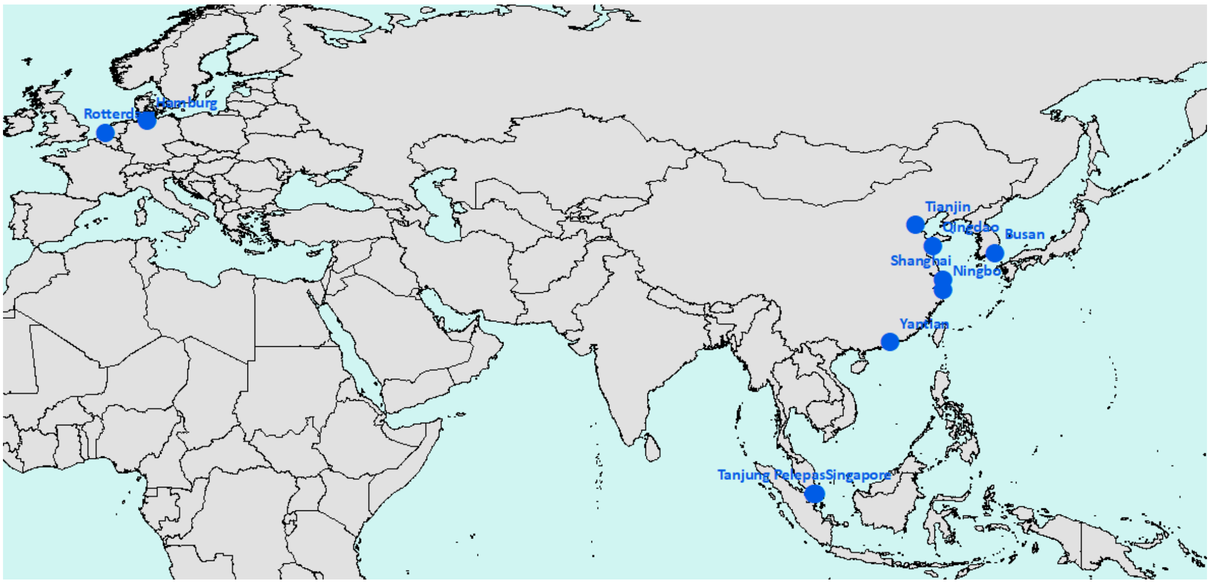


Figure 7.8 Distribution of top 10 weighted nodes
(Source: Author elaboration based on ArcGIS)

Rank	Country	% of total TEUs
1	China	35.26%
2	Singapore	6.09%
3	Germany	5.84%
4	Netherlands	4.69%
5	Korea	4.62%
6	Malaysia	4.13%
7	Spain	3.49%
8	United Kingdom	3.23%
9	Saudi Arabia	3.14%
10	Belgium	2.99%

Table 7.4 Rank of the Top 10 countries with the highest weight.

(Source: Author elaboration based on the analysis of weight)

7.3.3.2 Weight of link

In addition to the weight of the nodes in the network, the weight of the link refers to the cumulative cargo capacity of the ship traveling on that link and the frequency of the strings (section 6.3.3), that is, the sum of all the services deployed on the link (measured in TEUs). The analysis of weighted links in this section indicates the main links within the CSN. The distribution of weighted links (Figure 7.9) was similar to the distribution of weighted nodes. The frequency distribution of weighted links indicated that containers were concentrated on a few links only. A few weighted links accounted for a large share of TEUs in the CSN, while most of the links were weak and occupied little value.

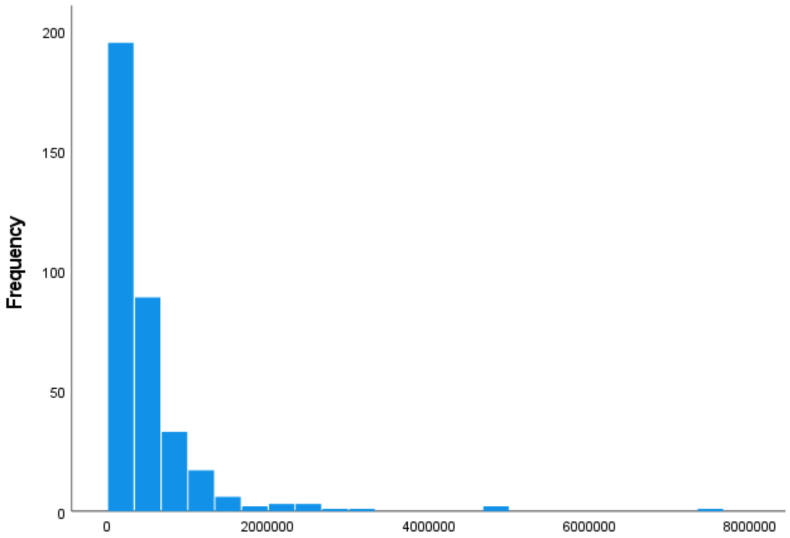


Figure 7.9 Frequency distribution of weighted links.

More specifically, Figure 7.10 shows the important links with the highest weight in the CSN. The top 20 links with the highest weight collectively account for more than 30% of the total weight within the network.

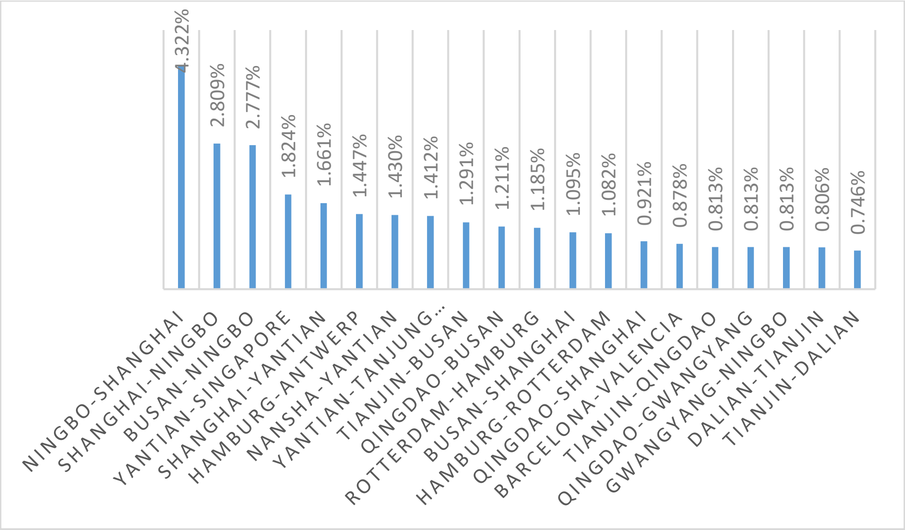


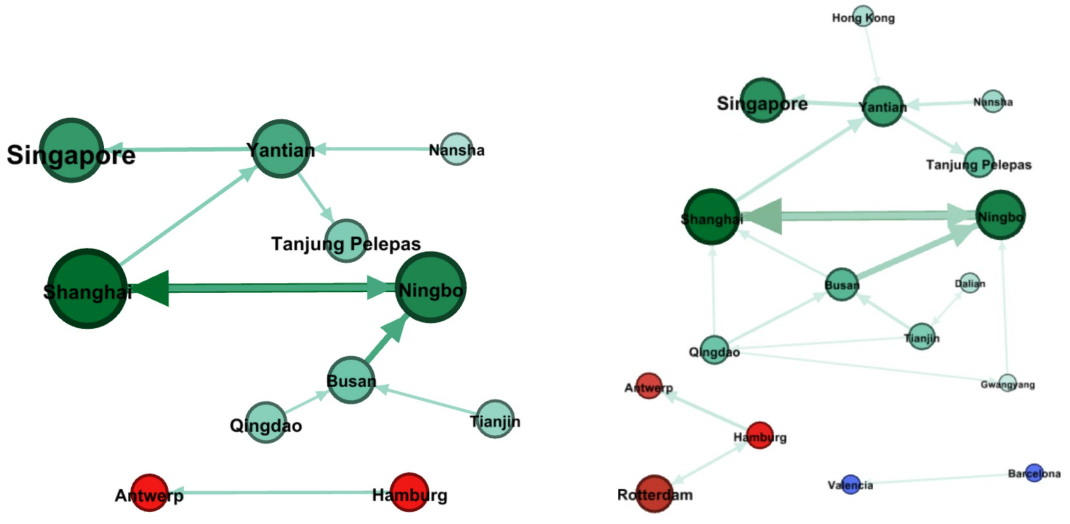
Figure 7.10 Ranking of links with the highest weight.
(Source: Author elaboration based on the calculation results)

The weight of the link represents the trade flow along the CSN, with the most valuable links occurring only between a few ports. It is interesting to discover the importance of the most valuable links and nodes in the network. This sheds light on the structure of the network and the interdependence of these nodes, particularly when analysing the vulnerability of the network. A separate analysis of the CSN based on different total weighted links in the network is shown in Figure 7.11.

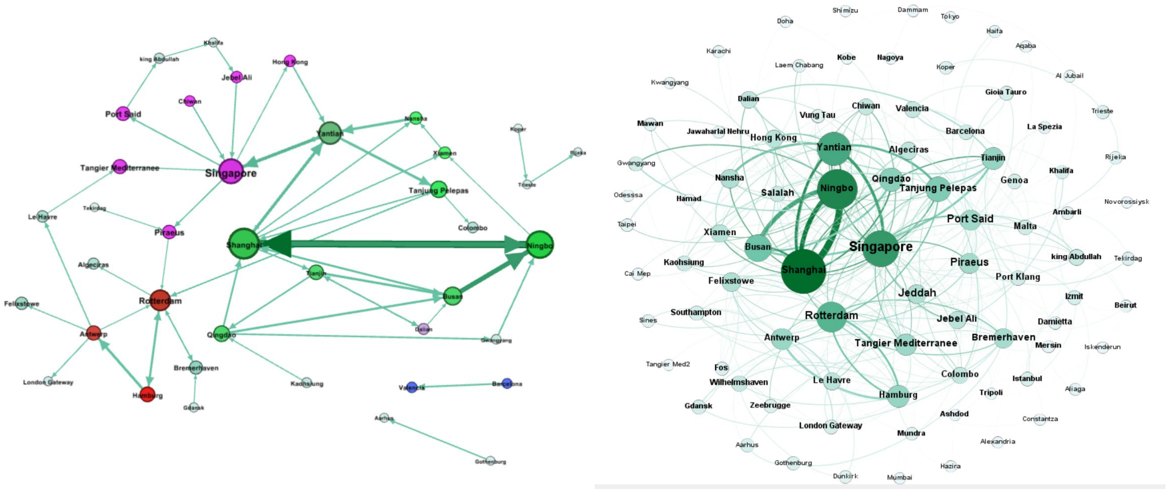
Figure (a) shows the links that occupied 20% of the total weight (TEUs) within the CSN. This visualisation encompasses only ten links out of a total of 353 links, along with 11 nodes from a pool of 89 nodes. These nodes could be divided into two parts: the Asia region and the Europe region. In each region, there were several hub nodes connecting to several spoke nodes. The hub node Yantian, established connections with Tanjung Pelepas, Nansha and Singapore. Likewise, the hub node Busan, connected Qingdao, Tianjin and Ningbo. Additionally, the hub node Shanghai, connected Yantian, Busan and Ningbo. In the Europe sector, Hamburg connected Antwerp and Rotterdam. The results were in line with the findings derived from the earlier-discussed ranking of nodes and links: (1) The CSN had several hub nodes, and (2) These hub nodes concentrated most of the container TEUs in the network.

As the total weight of the network increased to 30% (Figure b), several additional nodes were added in, yet the link count remained only at 19 (out of a total of 353 links). The hub nodes identified in Figure (a) retained their hub status in this new configuration. Moreover, new links emerged that were connected to the original hub nodes (Yantian, Busan, Tianjin, Shanghai, and Hamburg), thereby incorporating fresh spoke nodes into the network, including Dalian, Hong Kong and Gwangyang. Furthermore, certain nodes that initially appeared as spoke nodes in Figure (a) transitioned to becoming hub nodes in Figure (b), for example, node Qingdao.

As the total weight of the links increased to 50% (Figure c), a notable expansion of links and nodes connecting existing nodes appeared. This expansion gave rise to the emergence of new clusters, comprising nodes around Saudi Arabia, United Arab Emirates, Spain, and Western Europe. Consequently, a pattern of connections between these clusters began to form, contributing to a more connected and integrated network. This stage of development saw the interlinking of nodes situated alongside China and those clustered around Singapore. Additionally, node Tanjung Pelepas connected Rotterdam, Shanghai and Yantian. However, the number of links remained relatively low (totalling 57). This number represented only 16.15% of all possible links in the network. In the CSN, only a few strong links coexisted, with the majority being weak links.



(a) 20% of the TEUs (b) 30% of the TEUs



(c) 50% of the TEUs (d) 100% of the TEUs

Figure 7.11 CSN with total weight of link at 20%, 30%, 50% and 100%.

*The size of the nodes and links varied according to the weight of the nodes and links. Nodes and links are coloured according to the connected cluster they belong to.

(Source: Network simulation results, visualised by Gephi)

The development of the shipping network with hub nodes and links showed a hub-spoke network structure, and a small number of hub nodes connected most of the other feeder nodes in the network. The hub-spoke network structure and port hierarchies analysed earlier presented a “rich club” phenomenon (Ducruet and Notteboom 2012). This phenomenon is further evidenced through the analysis of weighted links – 1% of links (four) concentrated

12% of the weight within the network, and 15% of links concentrated over half of the total weight (50%) within the network.

As illuminated in the systematic literature review presented in Chapter 2, a large number of papers has evidenced and analysed the hub-spoke networks that are quite prevalent in maritime shipping networks. This prevailing paradigm has particularly garnered attention in addressing network design problems, wherein the allocation of hub ports, the activation of links, and the routing of predetermined cargo consignments through the network are generated to optimise cost-based (or service-based) objectives. The economy of scale presented by the hub-spoke network structure is exploited by concentrating cargo flow on few links with larger ships, thereby mitigating the costs (Gelareh *et al.*, 2010). However, the transhipment operations at the hub port increase the cost of loading and unloading the containers and also the waiting time in port. Compared with direct service, the repeated processes for loading and unloading in hub nodes and feeder nodes also increases the risk of facing disruptions and unexpected events. In accordance with the results from the analysis of the network, as a consequence of concentration on a few links and nodes, the economy of scale offered by the hub-spoke network structure is accompanied by a higher vulnerability to the network configuration due to the complexity of the network structure and transhipment of containers. The impact of network interdependency and the actions for improving network resilience are discussed in the next chapter.

7.3.3.3 Correlation analysis between degree and weight of nodes in CSN

After calculating the degree and weight of nodes and links in the network, it is essential to undertake a comparative analysis in order to discover the differences between these two kinds of metrics and their consequential implications on the positioning and functional role of nodes within the network.

The Pearson's correlation coefficient between node degree and weight was positive, with a correlation coefficient of $r = .778$, indicating that, to some extent, ports with more links connecting to other ports (a higher node degree) also have higher weight (Figure 7.12).

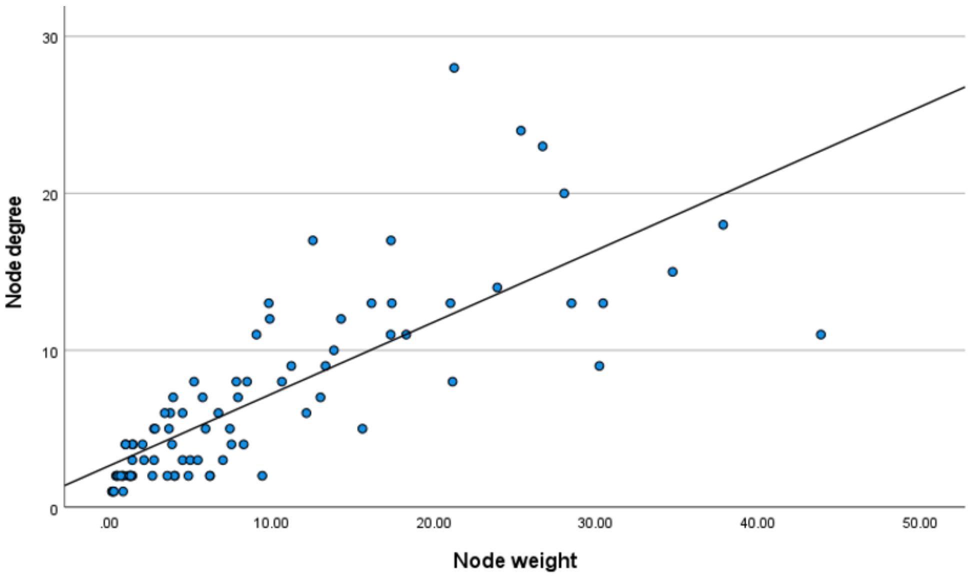


Figure 7.12 Correlation coefficient between node degree and weight

The correlation relationship could be further analysed based on the ranking of the nodes (as outlined in Table 7.3). When considering the top 10 ports, six nodes were involved in both of the two categories (high degree and high weight): Shanghai, Ningbo, Singapore, Yantian, Rotterdam, and Tanjung Pelepas. The nodes with a higher weight (top five) were all involved in the top degree group. As analysed in the previous sections, the weight of a node was largely contingent on the trade volume of the links, thereby relating to the economic size, while the degree of ports was more influenced by its geographic location. Nevertheless, the analysis showed that the factors influencing a port's role within the network are diverse, meanwhile, the port with the higher connectivity typically contributed multiple functions to the network.

The role of ports within the network could be further distinguished by the combination of the node degree and weight. Figure 7.13 shows the results with four categories:

- Feeder port (low degree and low weight)
- Local hub port (low degree and high weight)
- Transhipment port (high degree and low weight)
- Regional hub port (high degree and high weight)

Given the Qingdao port's intermediate degree and weight values compared to all other ports, it was strategically chosen as the division port – classifying the four categories. The ports with both high degree and high weight were regarded as the regional hub ports, which included six ports: Singapore, Rotterdam, Shanghai, Ningbo, Yantian, and Tanjung Pelepas. These ports play a pivotal role in facilitating transhipment due to the highly connected links to other ports especially within their respective regions. The extensive infrastructure and service availability in these ports enable them to efficiently handle larger container ships and manage the distribution of containers. For each region, there were several ports selected: Rotterdam in Western Europe, three Chinese ports in East Asia and two ports in Southeast Asia. Therefore, these ports were recognised as regional hub ports.

Despite possessing a substantial weight in container volume, the Busan port exhibited a comparatively lower degree of connections within the network, thus, regarding it as a local hub port. The Busan port, recognised as one of the most important ports in South Korea, serves as a pivotal junction for accommodating a large number of containers originating from Europe and diverse regions within the Asia hinterland. However, the position of the Busan port was at the end of the string between Asia and Europe, and usually, it was selected as either an originating or destination port. This specific geographical positioning of Busan underscores its role as a local hub port, which is connected with the hinterland by multimodal transport modes.

Six ports were identified as transhipment ports with a higher degree, but a lower weight, including Jeddah, Piraeus, Port Said, Jebel Ali, Tangier Mediterranee and Salalah. These ports serve as transhipment points due to their strategic positioning within the network and their efficient service operations; however, their hinterland may not exhibit substantial demand. The selection of these transhipment ports is also underscored by their high closeness centrality – a concept elaborated upon in next section.

Most of the ports in the CSN were regarded as feeder ports, characterised by both low degree and low weight. This classification aligns with the hub-spoke network structure, where fewer ports with a higher degree while more ports with a lower degree and a small number of ports, accounted for a large share of TEUs within the shipping network.

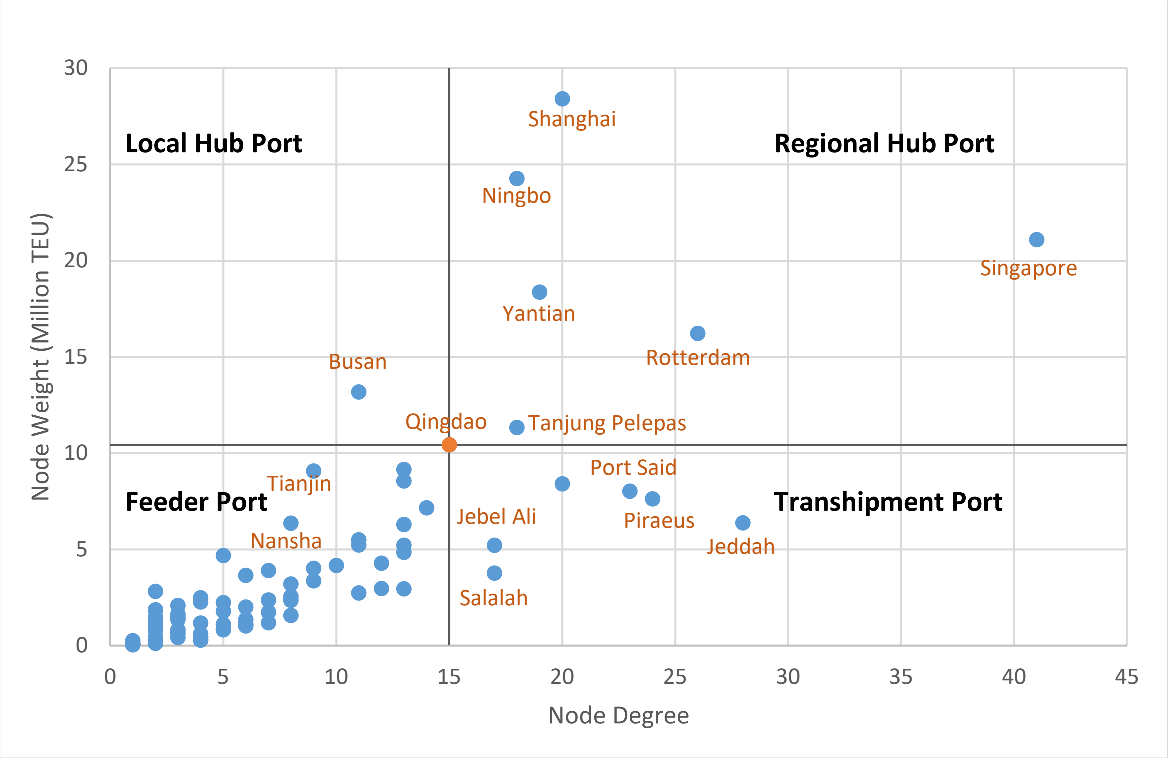


Figure 7.13 Distinguishing the role of ports within the network
(Source: Author elaboration based on node degree and weight)

Distinguishing the role of ports within the network is essential for analysing and recognising the important nodes in the context of network connectivity reliability. The regional hub ports were supposed to be the most important ports in the network. If these ports fail or face congestions, the accessibility of the network would be affected severely. The reliability of transhipment ports would affect the ports that are directly connected with them, often assuming a level of importance that is, to some extent, comparable to that of regional hub ports. However, there are still differences between two roles: when a port with a higher degree is not accessible, a great number of interconnected ports could experience delay or congestion. If a port with a higher weight, indicating greater container capacity, is not accessible, then a large quantity of containers would be stuck in ports. The local hub port was essential to the container trades due to their high handling capacity, making the reliability of the port crucial for maintaining efficient hinterland connectivity. Moreover, considering other themes of network reliability, such as resilience, the function of ports could help recognise the region that requires longer time to recover from disruptions.

The average degree of the network was 8.022, and 34.1% of the nodes (30) were over the average degree. Conversely, only 13 nodes (14.8%) exceeded the average weight of the nodes. This discrepancy between degree and weight highlights the concentration of container volume within a limited number of ports in the CSN, which serves as a driving factor influencing the overall network structure, notably, the hub-spoke pattern. This is also the reason why the researcher assumed the container shipping network to be a weighted and directed network.

7.3.4 Analysis of connectivity based on centrality-related metrics

7.3.4.1 Closeness centrality

Aside from degree centrality, which has already been discussed in section 7.3.2, centrality-related metrics, such as closeness centrality and betweenness centrality can also be used to identify ports' positions and accessibility within the network configuration. The degree of nodes considers the position of nodes in the network by assessing the direct links to other nodes among the networks. The **closeness centrality** calculated the average farness (inverse distance) from a given starting node to all other nodes (shortest path length) in the network, measured by the sum of the shortest paths between all pairs of nodes (Section 5.4). The closeness centrality showed the intensity of the links and the accessibility among the networks. Nodes with higher closeness centrality are topologically closer to other ports in the network since they have the shortest distance to all other nodes, and they are more likely to establish connections with other nodes since they can reach other nodes within a few steps. This allows these nodes to achieve better accessibility, and they are usually selected as transhipment nodes in the network. The degree of a node only considers the links that directly connect with the node; while closeness centrality serves to address the gap by considering the entirety of possible routes in the network, which refers to the path of voyage(s) between any pair of nodes in the network.

Figure 7.14 shows the closeness centrality distribution of nodes in the network. From the frequency distribution figure of closeness centrality, the distribution was not skewed significantly, and the mode of the frequency concentrates in the middle of the dataset. From the entire network configuration, the closeness centrality of most of the nodes was relatively similar and only a few nodes that had a lower value showed that the network was highly accessible and connected, while the independence of the nodes was relatively low. Relatively high closeness centrality for the nodes in the network indicated that it was easy to reach other nodes, and there was only a small topological distance between different routes among the network. This conclusion could be connected with the result of APL and node degree. The

APL of this network was 3.479, the routes between port pairs comprised on average three to four stops or transits at intermediate ports.

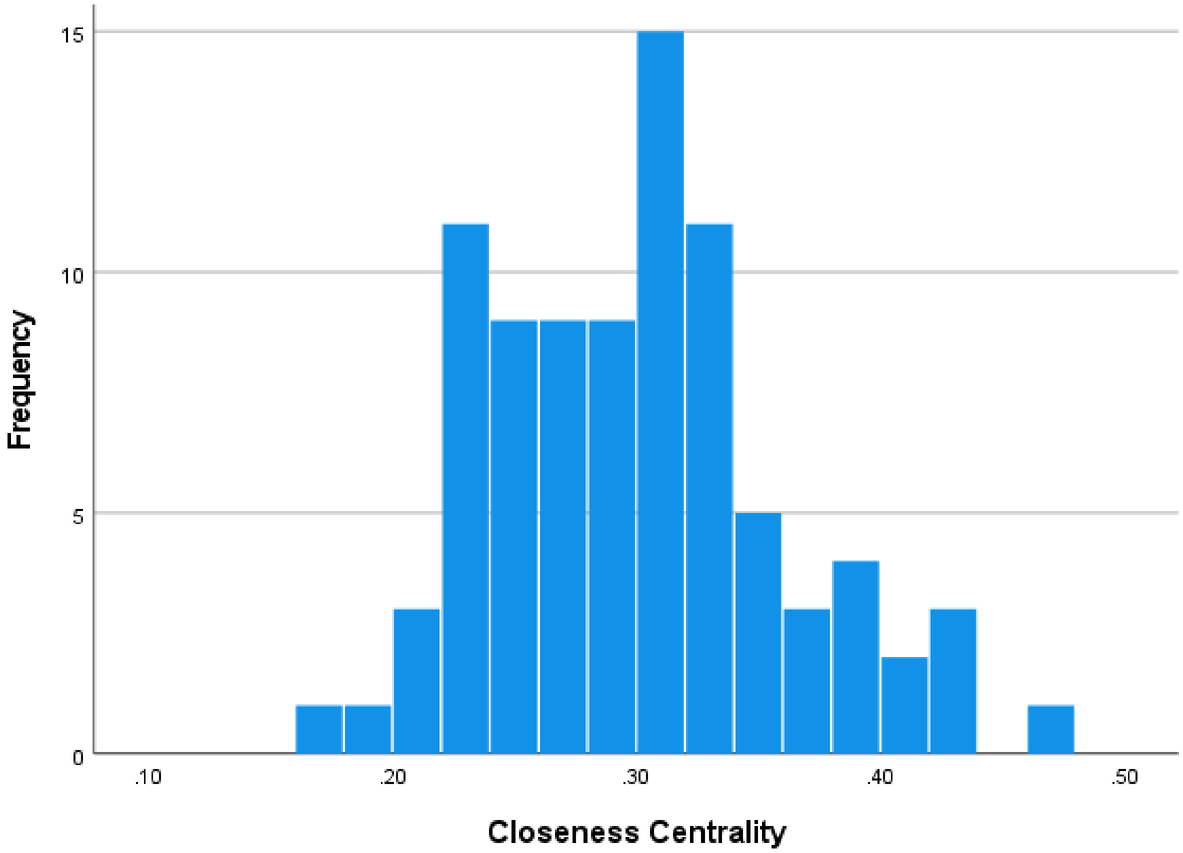


Figure 7.14 Closeness centrality of nodes

Singapore, Piraeus, Jeddah, Port Said, Salalah, Algeciras, Rotterdam, Tangier Mediterranee, Jebel Ali, and Tanjung Pelepas were the top 10 ports with the highest closeness centrality and their distribution is illustrated in Figure 7.15. Most of the nodes with high closeness centrality were located alongside the main canals and straits, e.g., the Malacca Strait, which indicated that ports with better geographical conditions tended to be more accessible and highly connected with other ports. Ports in West Asia had a higher closeness centrality, which could be attributed to the strategic positioning of this region, it lied along the midpoint of the trade between Asia and Europe. This geographical location allowed ports in West Asia to be chosen as transhipment nodes before reaching their destination ports.

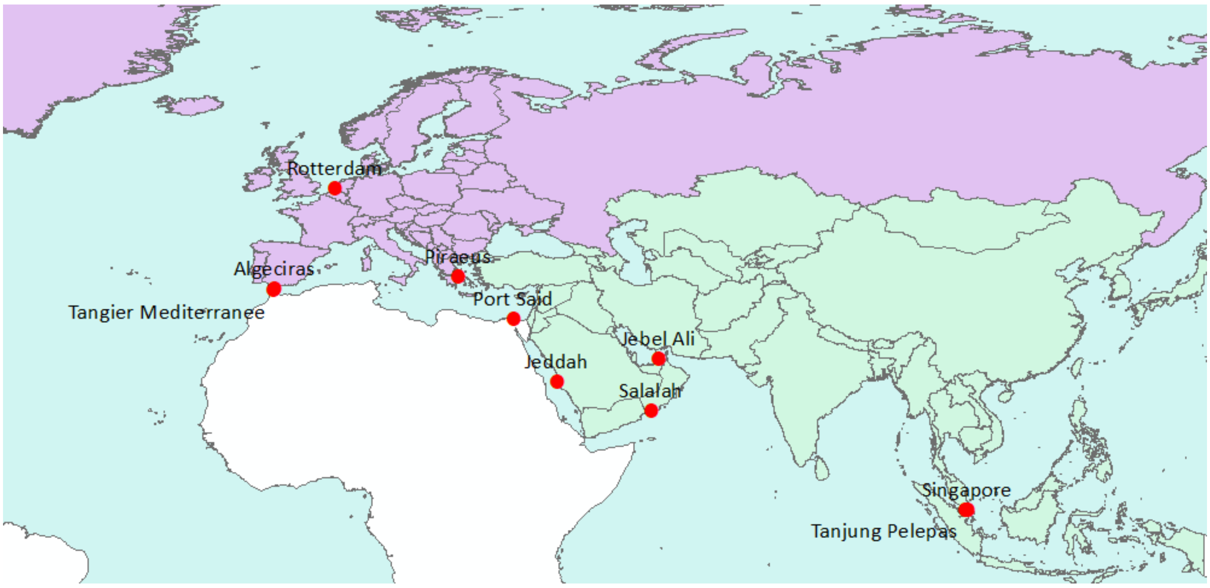


Figure 7.15 Distribution of ports with a high closeness centrality
(Source: Author elaboration based on ArcGIS)

As shown in Figure 7.16, the correlation coefficient between degree of node and closeness centrality was 0.771, p=0.01 meaning that nodes with more direct links with other nodes are also topologically closer to the rest of the nodes in the network.

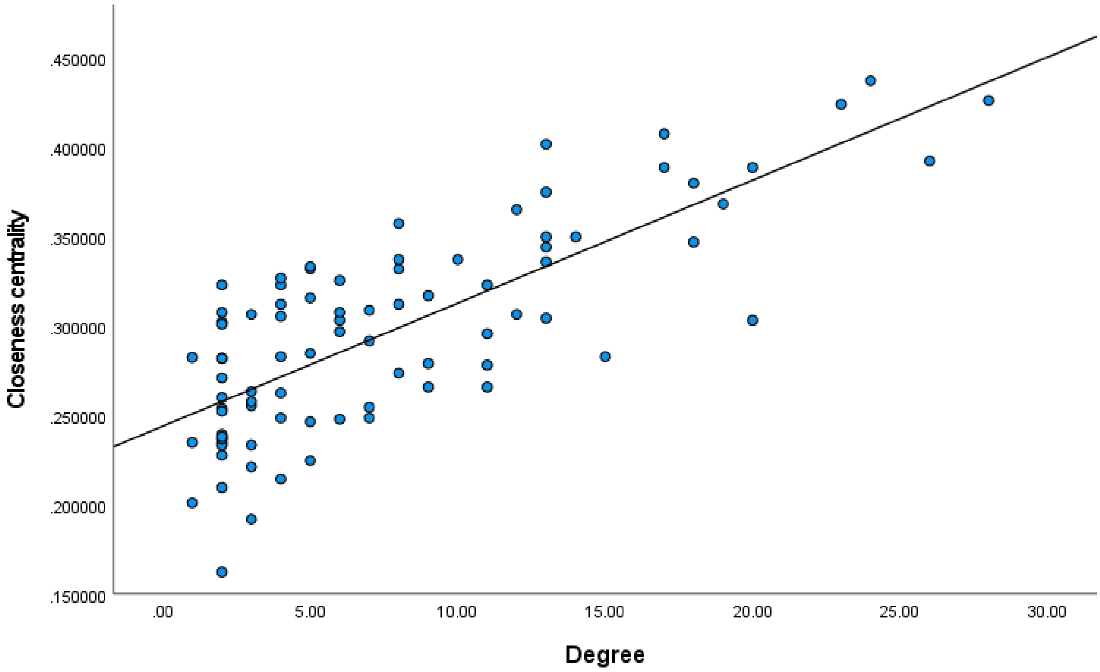


Figure 7.16 Correlation between degree and closeness centrality

7.3.4.2 Betweenness centrality

Betweenness centrality calculates the importance of a node in terms of how often it falls along the shortest paths between node pairs – the number of shortest paths that pass through the node. The role of ports that can be regarded as “hub” in the network refers to nodes with high transhipment capability, engendering a substantial concentration of the shortest paths that transfer through them. Nodes with higher betweenness centrality could be regarded as hub points in the network since they are involved in most of the shortest paths. The betweenness centrality frequency distribution (Figure 7.17) reveals a positively skewed pattern, contrasting with the distribution of closeness centrality. The ports were clustered at the lower end of the scale, with only a few ports displaying high scores. Singapore significantly stood out as the port with the highest score, which signifies its pivotal role as the most important hub node in the network configuration. The score of Singapore was phenomenally higher than other ports, which corresponded with the results of node degree. The outcome was further corroborated by Figure 7.18. The correlation coefficient of betweenness centrality and node degree is very high (0.827, p=0.01). Ports with higher direct connections also tend to be hub nodes.

In addition to Singapore – Jeddah, Piraeus and Port Said also had a high score, but then it dropped dramatically to port Jebel Ali. The betweenness centrality of 11 ports was 0, which means that these ports did not lie on any of the shortest paths. There was a significant difference between each port concerning betweenness centrality. The network depends on a few ports as hub ports to tranship and most of the ports in the network are feeder ports. The network depends on the connection between the hub ports and feeder ports, and the development of all the nodes is unbalanced. The result could be intricately linked to the earlier analysis about hub-spoke network structure.

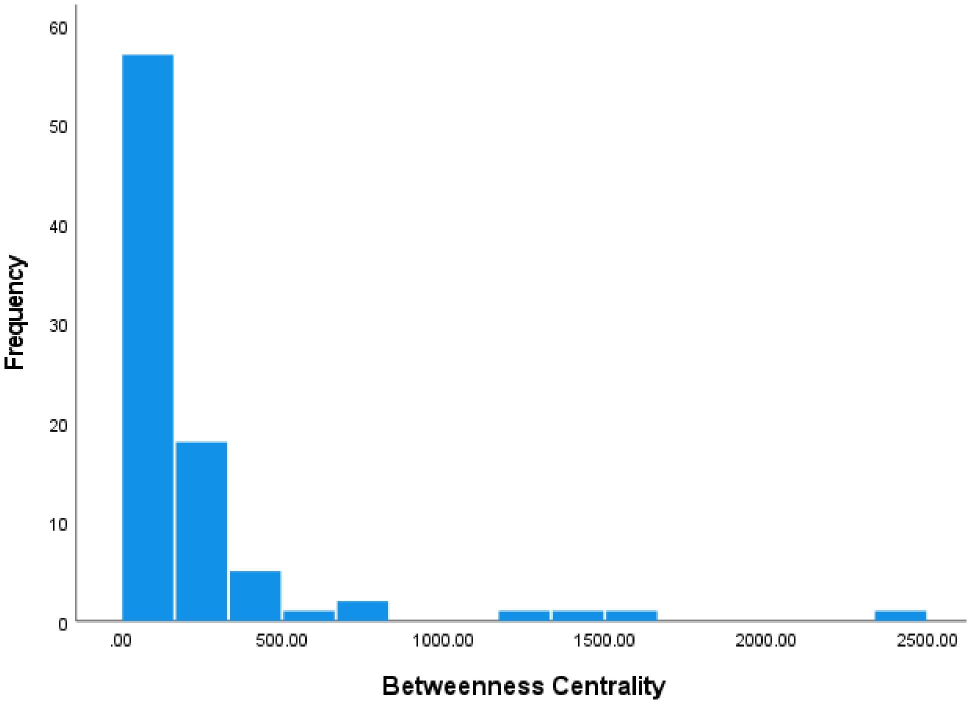


Figure 7.17 Betweenness centrality of nodes.

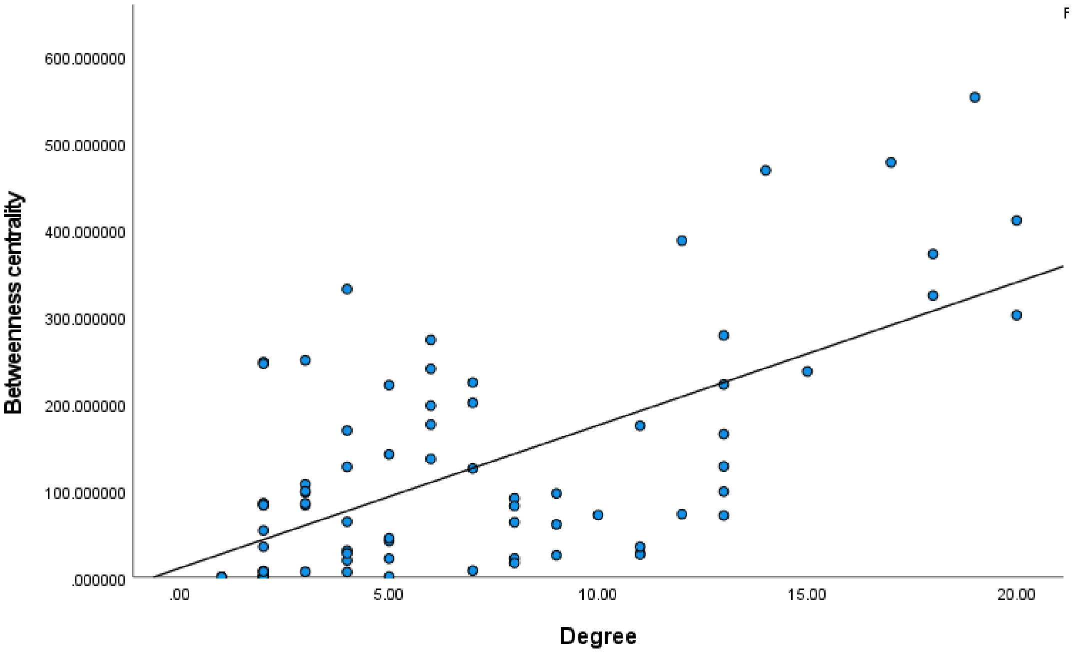


Figure 7.18 Correlation relationship between betweenness centrality and node degree.

As shown in Figure 7.19, the correlation between closeness and betweenness centrality exhibited a moderate relationship, with a correlation coefficient of 0.619 (p=0.01). This finding implies that nodes possessing greater connectivity with other nodes in the network can be considered as an important hub node in the network.

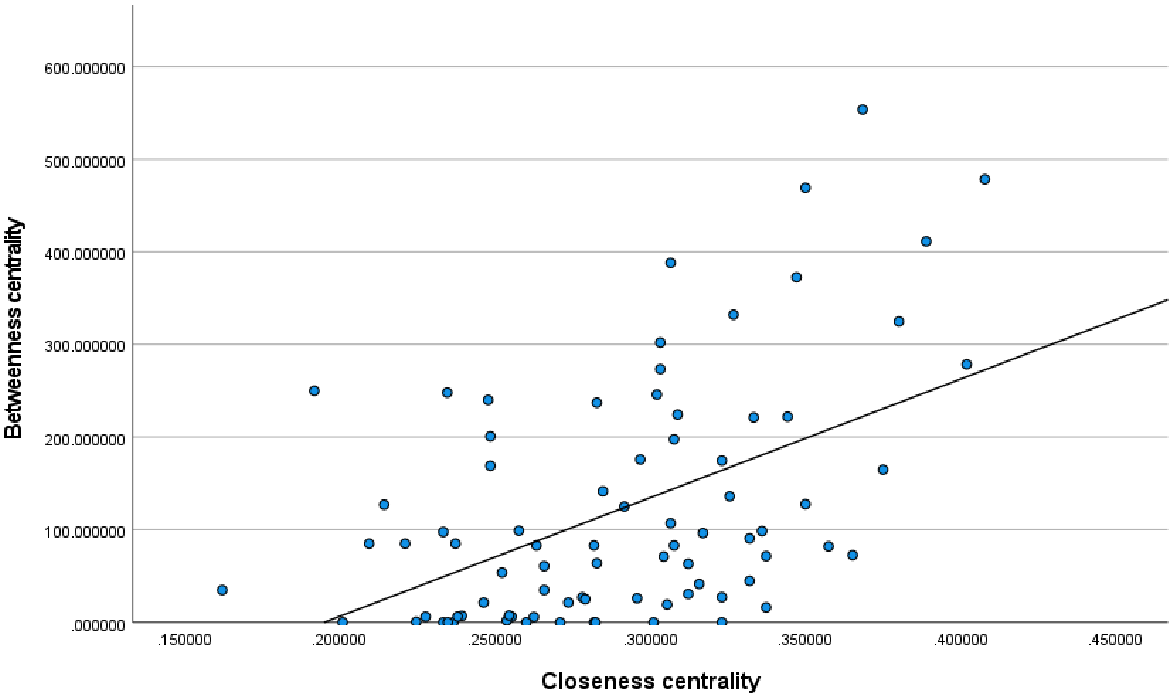


Figure 7.19 Correlation between closeness and betweenness centrality.

In the context of shipping networks, four centrality-related metrics are typically analysed: degree centrality, betweenness centrality, closeness centrality and eigenvector centrality. This section analysed the betweenness and closeness centrality of the CSN, with a specific focus on investigating the role of ports within the network. Degree centrality, as discussed in Section 7.3.2, refers to the number of direct connections associated with a node. Unlike degree centrality which weights links equally, eigenvector centrality takes into account not only the number of connections but also the importance of those connections. However, the research has conducted an analysis based on the weight of the nodes and links to assess the importance of connections and identify the role of ports based on a combination of weight and degree. Additionally, eigenvector centrality is essential for understanding the network's resilience and vulnerability to disruptions, offering insights into how changes or disruptions to critical nodes can impact the overall functionality and stability of the CSN. However, the research intends to assess network vulnerability and resilience through simulating attacks, aiming to provide more accurate and realistic results. Consequently, the analysis of eigenvector centrality was not included in this research, but it could be a subject for further investigation in future research.

7.4 Conclusion

The basic function of the container shipping network is to transport containers from origin ports to destination ports. The reliability depends on whether the containers could reach their destination ports. Therefore, a fundamental requirement of a shipping network is to ensure the accessibility across different nodes within the network, which aligns with the substantiation provided in the literature review. The connectivity of the shipping network is an important indicator when assessing the reliability of the shipping network.

The use of network analysis in this chapter provides insights on both the configuration of container shipping and the role of nodes within the network. This research built a directed and weighted CSN with 89 nodes and 353 links. A thorough analysis of connectivity reliability was conducted by using metrics including: degree, weight, closeness centrality and betweenness centrality. The network analysis showed that the CSN was highly connected, dense, and clustered, and ships can reach their destination port within a small number of steps, however, different nodes held different roles within the network. Moreover, the distribution of degree and weight showed the development of a hub-spoke network structure, a number of hub nodes played a critical role and concentrated most of the other feeder nodes in the network. Higher connectivity increases the accessibility of the CSN, as it implies a greater number of available routes. However, it is imperative to acknowledge that a small number of ports accounted for a large share of the market within the network, which makes the network more vulnerable and much weaker, especially when facing disruptions. Following the network configuration of the CSN and the role of ports within the network identified in this chapter, Chapter 8 will further explore the network configuration reliability – the vulnerability of the network and the ability to recover from disruptions.

Chapter 8. Analysis of the network configuration reliability

8.1 Introduction

High connectivity reliability contributes to enhancing the accessibility of the CSN; however, the high interconnection of the CSN introduces a noteworthy consideration: any shock, decision or disruption affect not only the port itself, but also other nodes within the network. The impact of disruptions, e.g., port congestion, could propagate through the network even when the node pairs are not directly connected. This chapter explores the extent to which disruptions can affect the network's reliability – the theme of network configuration reliability – by simulating attacks to the network. Section 8.2 introduces the research design procedures for simulations. Section 8.3 starts to analyse the impact of nodes' failures in order to give insight on whether the network could be affected by disruptions or risks. Additionally, this section investigates whether the network could perform well even when parts of the system have failed. Section 8.4 summarises the findings in this chapter.

8.2 Research design for network simulation

In order to assess the vulnerability of the network under disruptions, the research project simulated attacks to the network as a means of exploration. Upon conducting a thorough analysis of disruptions in Asia and Europe, the attacks undertaken in this research project could be divided into two categories based on their underlying causes and resulting effects: random attacks and intentional attacks.

Random attacks encompass disruptions such as natural disasters and ship incidents. Within the context of the CSN, the occurrence of random attacks is characterised by a uniform probability across all network nodes. This probability remains consistent; it doesn't depend on the role of port, infrastructure or position in the network. For example, a natural disaster (e.g., typhon or hurricane) would imply the shutdown of ports, and ships would need to stop and wait at the anchorage which would lead to a brief failure of the nodes and directly connected links. Other natural disasters (e.g., earthquake and tsunami) would also imply the shutdown of nodes and directly connected links, but for a longer time due to the damage to the infrastructure. In addition to natural disasters, the random failure of ships is also a kind of random attack to the network. In March 2021, the Suez Canal was blocked for six days after the grounding of Ever Given – a 20,000 TEU container ship. These kinds of attacks usually occur in ports or in canals crowded with ships, culminating in blockages of port, canal and global freight flow.

Intentional attacks encompass a range of disruptions, including terrorist attacks, war, workers' strikes and so on. These kinds of attacks usually target important nodes in the network, such as the hub ports and ports in important geographic locations. When intentional attacks occur, their impact propagates throughout the network, influencing all the strings related to the port and necessitating a reroute of the port of call. Both random attacks and intentional attacks would imply the shutdown of ports. This, in turn, could make the nodes or links in the network fail and disappear from the planned rotation.

This research project simulated attacks to the network, that is, simulated the removal of a specific node accompanied with its directed in-bound and out-bound links. In light of the two types of attacks, this research project was simulated from two perspectives. For a random attack, an equitable probability was assigned to every node within the network. The simulation of a random attack is to assess the reliability of the network when facing random disruptions, which entails the random removal of nodes from the network, aiming to discover the accessibility of the network when facing natural disasters and other randomly generated disruptions. For an intentional attack, the probability of each node being attacked varies based on the role of ports within the network. The simulation of intentional attacks is designed to assess the reliability of the network while taking into account the hub-spoke network structure and the interdependency on the hub nodes in the network. In the intentional simulation, the targeted nodes were selected based on their ranking in terms of both degree and weight within the CSN: (i) by highest node weight ranking, and (ii) by highest node degree ranking.

The evaluation and analysis of the simulation results are based on the metrics including average degree of the network, network efficiency and relative size of the maximal connected subgraph (Table 8.1), each shedding light on different facets of the network's behaviour.

Metric	Definition
Network average degree	The average number of links in which the node in the network is directly connected with other nodes.
Network efficiency	A measure of how efficiently the network exchanges information (along the shortest path). The efficiency between two nodes refers to the reciprocal of path length.
Relative size of the maximal connected subgraph	The maximal subgraph* when the connected network is facing disruptions. (*The network will split into several subgraphs when nodes fail. The maximal subgraph refers to a connected subgraph to which no more nodes can be added.)

Table 8.1 Metrics for network simulation in this research

As analysed in the previous sections, **network average degree** refers to the average number of links in which the node in the network is directly connected with other nodes. The failure of a node will lead to the failure of multiple links that are directly connected with this node. The failure of these links may lead to the failure of several new nodes that are directly connected with these links. Then, the network will split into several subgraphs, and the connected subgraph to which no more nodes can be added is called the **maximal connected subgraph**, that is, the maximal subgraph when the connected network is facing disruptions. The relative size of the maximal connected subgraph could be used to discover the impact of the attack; it could represent the clustering of nodes in the network. **Network efficiency** is a metric to assess how efficiently the network exchanges information, that is, the farther two nodes are in the network, the less efficient their communication will be. As elaborated in section 7.3.1, the path length between a node pair is determined by the number of links along the shortest path connecting them within the network. This concept aligns with the definition of network efficiency, which indicates that the efficiency of a node pair is inversely correlated with its path length. The average efficiency of the network is computed as the average efficiency across all pairs of nodes (Eq.8.1).

Network efficiency:

$$E = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{8.1}$$

Where E refers to the average network efficiency; n denotes all the nodes in the network; and d_{ij} refers to the shortest path length between node i and j.

Attacks were simulated on all the nodes in the CSN (in total 89 nodes), and the impact of the attacks are discussed in the following sections.

8.3 Results from the analysis of network configuration reliability

The analysis of network configuration (as presented in the previous sections), along with the literature review, showed that the CSN was highly connected. Moreover, the network was clustered, and it depended on certain important nodes and links in the network, which was due to the hub-spoke network structure, as well as the network characteristics (small-world and scale-free). The assessment of connectivity reliability, combined with the new set of risks – disruptions to the network – highlight another theme identified in this project: network configuration reliability. Network configuration reliability here refers to whether the network could be affected by the disruptions and the ability of the network to perform well even when parts of the network have failed. The CSN connects two major global economies. In the event of disruptions, particularly if attacks target multiple nodes within the network, there exists the risk of a cascading effect that could severely affect international container shipping on a global scale, and ports in the network and their hinterlands would be affected to various degrees.

This section is going to investigate whether the network characteristics analysed above could increase or decrease the vulnerability and resilience of the network. In addition, the role of ports according to network analysis metrics may either help the CSN recover or may not. More specifically, network simulation is applied to analyse: (i) the impact of disruptions to the network; (ii) the identification of important nodes within the network; (iii) the propagation effect due to the network connectivity; and (iv) the ability of the network to recover from disruptions.

8.3.1 Simulation results discussion

The research project simulated attacks to the network from three perspectives: random attack, intentional attack according to node degree and intentional attack according to node weight. Figure 8.1, Figure 8.2 and Figure 8.3 show the graphic representation of simulation results. These figures offer an impactful portrayal of the measured metrics as they evolve following the simulated attacks.

In the context of random attacks, a discernible and consistent trend emerges across the metrics. The average degree of the network, the size of the maximal connected subgraph and the network efficiency exhibit a steady decline. Compared with a random attack, the metrics showed a more pronounced decline under intentional attacks according to node degree and weight. The impact is most remarkable in the size of the maximal connected subgraph, a metric intricately tied to the presence of isolated nodes in the network. This remarkable decline accentuates the vulnerability of the network to intentional attacks, magnifying the influence of the targeted disruptions on the network performance. That is, the container shipping network is relatively resilient when facing disruptions like weather, natural disasters, and vessel incidents. The network would be severely affected when facing target attacks, particularly during the initial stages of such attacks, resulting in a significant and rapid decline in performance. The following analysis will delve into the specific results for each individual metric.

8.3.1.1 Results based on network degree

Figure 8.1 presents the trend for network average degree when facing attacks. As shown in the figure, the average degree decreased rapidly under three kinds of attacks and was affected the most by the attacks according to node degree. Compared with the other two intentional attacks, the curve for the random attack decreased gradually. Attacks according to node degree had the most effects to the network configuration compared with attacks according to weight.

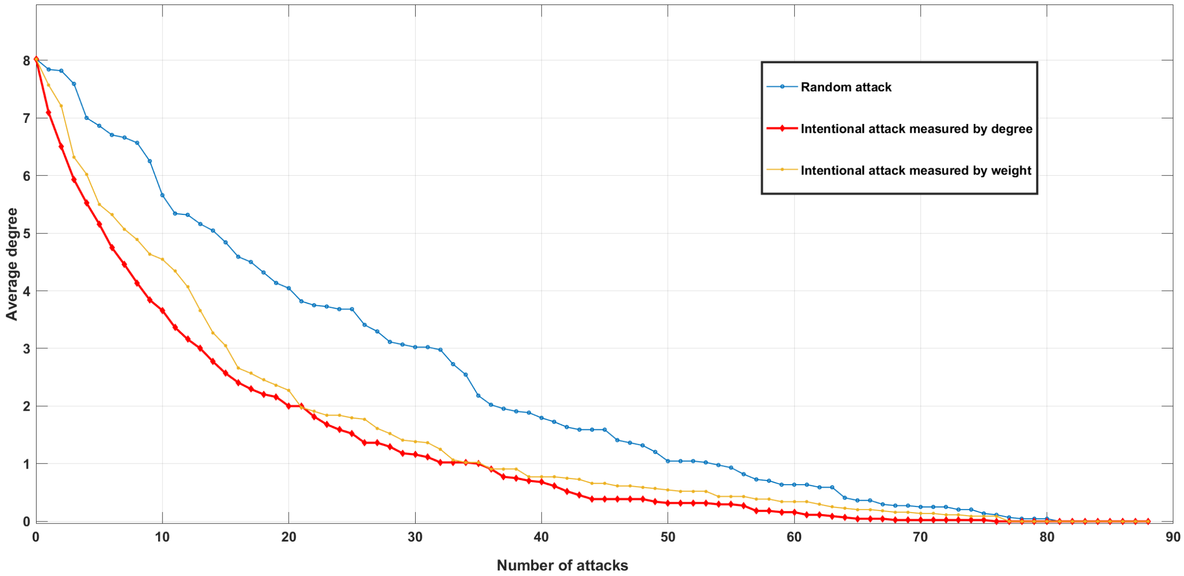


Figure 8.1 Simulation results based on network average degree.

The influence of attacks on nodes with higher value was notably pronounced. Table 8.2 specifically focuses on the simulation results of the first 15 attacks, which provides a representation of the evolving trend in response to these attacks. The average degree of the network without attacks was 8.022 (the result from Chapter 7). The average degree dropped sharply when facing the first several attacks according to degree then remained steady. The difference between a random attack and an attack according to degree reached the maximum (2.43) when the attacked nodes increased to 8, the two values were 6.57 and 4.14. The researcher used the **change rate** (Eq. 8.2) to investigate the impact of attacks:

$$\Delta D = \left(1 - \frac{D^*}{D}\right) \times 100\% \tag{8.2}$$

Where ΔD denotes the change rate of network average degree, D and D^* denote the average degree value after and before the node is interrupted.

When considering from the perspective of node degree, a significant disruption occurred when the node with the highest degree (Singapore) failed. This resulted in a decline in the average degree, which decreased to 7.1 – a reduction of 11.61% as computed by Eq. 8.2. The result reveals that the first nine attacks precipitated a remarkable 52.12% average degree reduction, demonstrating that they were 2.56 times greater than the random attacks. The decline continued until the average degree reached 0, as 75 nodes encountered targeted attacks. When averaged across two instances, the average change rate of network degree under an intentional attack measured by node degree, was 1.46 times higher compared to random attacks.

Failed nodes	Random Attack	Attack according to degree	Attack according to weight
0	8.022	8.022	8.022
1	7.84	7.09	7.57
2	7.82	6.5	7.20
3	7.59	5.93	6.32
4	7	5.52	6.02
5	6.86	5.16	5.5
6	6.70	4.75	5.32
7	6.66	4.45	5.07
8	6.57	4.14	4.89
9	6.25	3.84	4.64
10	5.66	3.66	4.55
11	5.34	3.36	4.34
12	5.32	3.16	4.07
13	5.16	3	3.66
14	5.05	2.77	3.27
15	4.84	2.57	3.05

Table 8.2 Average network degree in response to the initial 15 attacks

The curve in response to attacks measured by node weight exhibited a similar trend to that of attacks measured by node degree, yet with less impact. The first attack, targeting the node with the highest weight (Shanghai), led to a reduction in the network degree to 7.57, making a decrease of 5.67%. The impact was relatively milder compared to the effects observed in the attacks measured by node degree. Attacks on the top 13 nodes in the network resulted in an average degree of 3.66, signifying a 54.39% decline from the original value and 1.52 times greater than the effect of random attacks. On average, the change rate of network degree, as influenced by an intentional attack measured by weight, was 1.32 times higher than the random attacks. The most significant discrepancy between degree and weight emerged when the failed nodes numbered between 9 and 15, with 11 marking the peak difference. As the count of failed nodes reached 21, the gap between the two curves began to diminish, with convergence and overlap observed at various points.

Based on the preceding analysis, the degree of the network represented the connectivity reliability of the network, that is, how the nodes in the network are directly connected with other nodes. When facing disruptions, the network was less directly connected topologically due to the fact that ships need to transfer more times than usual to reach their destination port, the number of direct links in the network decreased. This is to say, a more pronounced reduction in network degree indicates a greater sensitivity of the network configuration reliability to the disruptions. When considering the three types of attacks, attacks according to node degree have the most serious impact to the network. In a broader context, the connectivity sensitivity of the CSN when facing intentional attacks was 1.46 times greater than the random attacks.

8.3.1.2 Results based on network efficiency

Compared with other measuring metrics, the curves for network efficiency exhibit a smoother trajectory and the difference between the impacts of the three types of attacks was relatively minimal in this context (Figure 8.2). Network efficiency refers to the complexity and difficulty in transport across the container shipping network. The efficiency depends on the path length between node pairs, with increased link counts along the shortest path being indicative of decreased network efficiency. In the event of attacks within the network, a ship is compelled to undergo more transfers along its string to its destination. These additional transfers serve as strategic detours in order to avoid the failed nodes by attacks. By taking these actions, the difficulties associated with container transportation increase, leading to a decrease in network efficiency.

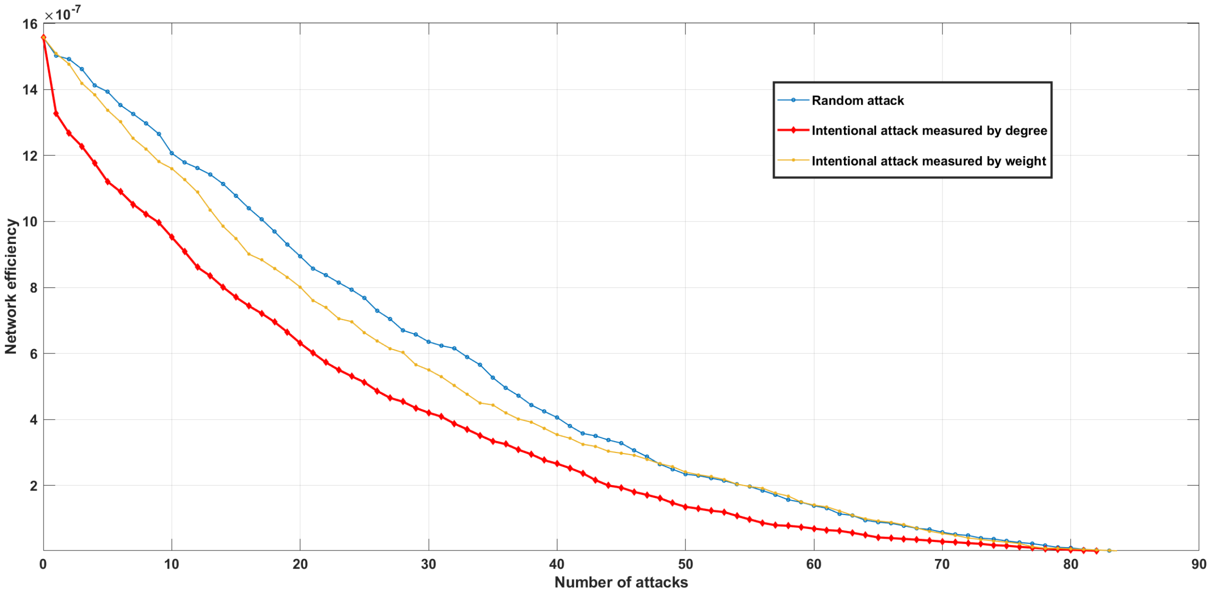


Figure 8.2 Simulation result based on network efficiency.

As depicted in Figure 8.2, the visual representation highlights a consistent downward trend in network efficiency when confronted with three types of attacks. The attack results based on node degree remains the most potent in terms of impact. Similar to the analysis of network average degree, this section adopted a change rate to investigate the effects of attacks:

$$\Delta E = \left(1 - \frac{E^*}{E}\right) \times 100\% \tag{8.3}$$

Where ΔE denotes the change rate of network efficiency, E and E^* denote the network efficiency value before and after the node is interrupted.

The change rate of network efficiency reflects the accessibility of the shipping network. The network was most affected by the attacks based on node degree. The first attack (Singapore) led to a 14.82% decrease in network efficiency. When the number of failed nodes reached to 17% (15), the network efficiency decreased by 50.54%. On average, the change rate of network efficiency in response to intentional attacks measured by node degree was 1.34 times greater than the random attacks.

The impact caused by the attacks measured by node weight was not significant compared with attack measured by node degree in the first several attacks. For instance, after the initial attack targeting Shanghai, the network efficiency decreased by only 3.16%; a result similar to that observed in random attacks. Further examination reveals that attacks to the top 10 ports with higher weight produced a modest reduction of 25.5%; a smaller decline when contrasted with the effects of attacks based on node degree. A few specific attacks stood out due to their more significant impact (over 3%) on network efficiency, including the first attack (Shanghai), the third attack (Singapore), the seventh attack (Tanjung Pelepas), the thirteenth attack (Port said) and the fourteenth attack (Piraeus). Remarkably, these nodes possessed higher degree, indicating that the nodes with higher degree were more essential to the network's efficiency. The difference between random attacks and attacks measured by weight was also not relatively significant, with the average decline rate standing at 1.07 times greater than that of random attacks. Two curves started to overlap after the occurrence of 45 attacks.

8.3.1.3 Results based on maximal connected subgraph

The size of the maximal subgraph indicates how nodes are connected when facing disruptions. Specifically, it quantifies the extent to which nodes remain linked within the network under such circumstances. The relative size of the maximal connected subgraph, on the other hand, refers to the proportion of connected nodes after attacks in relation to the initial count of connected nodes before attacks (89 in this research). This metric offers a dynamic perspective on how the network endures through disruptions, by identifying the isolated nodes in the network to assess the impact of attacks.

Figure 8.3 shows the results based on the size of the maximal connected subgraph. In the context of random attacks, the relative size of the maximal connected subgraph presents a diagonal decline trend, reflecting the reduction in network connectivity as disruptions unfold. Attacks measured by degree and weight showed nearly identical results during the first several attacks on the highest ranked ports. This means that the attacks had a similar impact on network accessibility. Echoing the patterns observed in the other two metrics, attacks based on node degree exhibit the most substantial impact on network reliability.

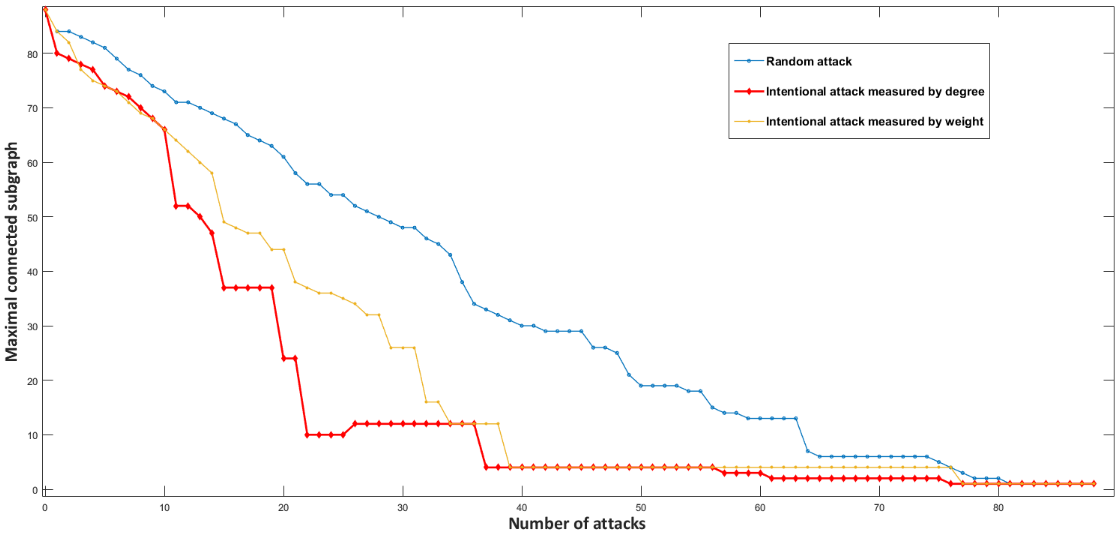


Figure 8.3 Simulation result based on the size of the maximal connected subgraph.

What is interesting in the analysis of the maximal connected subgraph is its ability to provide insights into the progressive pattern of network failure. This metric essentially serves as a visual representation of the network's accessibility, showing how the network configuration transforms in response to disruptions. The initial size of the maximal connected subgraph, comprised of 89 nodes, can be viewed as the core framework of the CSN. This size signifies a fully connected network, wherein ships can arrive at all the nodes in the network either directly or by transhipment.

The impact of attacks measured by degree emerges as being the most impactful to the network. Therefore, the research project employed this metric (measured by degree) to investigate the progression of network failure (Figure 8.3). When the number of attacks reached 11% (ten times), the maximal connected subgraph exhibited a gradual and consistent reduction. On average, each additional attack corresponded to a 2.5% decrease in the size of the subgraph. Despite that the percentage of attacks achieved 11%, resulting in approximately a quarter of the nodes being affected, the integrity of the network remained at more than 70%. This result illustrated that even in the face of a considerable percentage of attacks, the shipping network would retain its accessibility. The central core of the network, though limited in its performance, continued to function.

The subsequent stage encompasses attack percentages ranging from 11% to 17%, corresponding to 11 to 15 attacks. As the number of attacks came to 17%, a significant shift in the results was observed: the size of the maximal connected subgraph experienced a sharp and drastic decline, plummeting from 75% to 42% directly. The main body of the network decreased by more than 50%, which indicated that half of the nodes in the network could not reach each other within the network. The connectivity, accessibility and transhipment ability were all highly affected. Meanwhile, the results of the maximal connected subgraph had continually been on a rapidly decreasing trend, and the ability decreased sharply and continually. From this result, it could be investigated that when the intentional attacks to 15 nodes within the container shipping network happened, the entire shipping network was not connected in all regions, so the network partially failed. By this we mean that the network was not connected, the ships needed to transfer more times than usual to reach their destination port, and some nodes cannot reach to other nodes within the network.

The last turning point was when the number of attacks reached 36 (equivalent to 40%). The value faced the second cliff fall, and the size of the maximal connected subgraph decreased directly to around 10%, which means that only around 10% of the entire shipping network was still connected. Meanwhile, the decline trend gradually levelled off and reduced to 0 after 40% of the nodes in the network were attacked. It could be concluded from this result that when the number of intentional attacks to the CSN reached 40% and above, the shipping network has completely failed and no longer had the ability to transport containers between different regions.

In accordance with the results of the maximal connected subgraph, the reliability of the network configuration depended on how many ports were connected after the disruptions. If the number of affected ports was less than 10, the container transportation on the CSN could still work as usual, but the performance would be limited or operated at a reduced efficiency. If the number of affected ports was around 15, the CSN would partly fail. If the number of affected ports exceeded 36, then the CSN would not be able to afford normal container transportation. Take one example here – the impact of COVID-19 highly affected many ports around the world. The closure of ports and the lockdowns in the hinterland were qualified as node failure within the network. If the pandemic led to the total failure of 15 ports, then all container transportation in the CSN would be affected. Encountering such situations is indeed uncommon, even during the pandemic period, only a limited number of ports experienced closures at the same time. However, restricted port activities or partial closures of ports could also act as a failure of nodes within the network. From the other perspective, if the stakeholders are able to implement measures that minimize the impact and ensure that the number of affected ports remains below 10, the overall configuration of the shipping network may not severely impede container transportation. In addition, the results of network vulnerability, especially the procedures of network failure cast light on the specialisation of ports within the network. The next section will introduce the classification of the important nodes in the network.

8.3.1.4 The role of ports in the network – considering network vulnerability

According to the procedure of network failures analysed in the last section (Section 8.3.1.3), the CSN would be partly failed when the number of attacked ports reaches 17%, and it would be totally failed when the number of attacked ports reaches 40%. Building upon the analysis of nodes' positions within the network and considering their functions (as explored in earlier sections, e.g., closeness centrality and betweenness centrality), this section provides an added dimension for classifying nodes based on their impact to disruptions. In addition to analysing the entire network and individual ports, this research also aims to assess the reliability of specific regions within the network. The CSN was partitioned into six regions: East Asia, Southeast Asia, South Asia, Middle East, Southern Europe and Western Europe. All the nodes were categorised into their respective region based on their position within the network.

All the nodes are divided into three domains (Figure 8.4) according to the network failure procedures:

- The first domain comprises ports with the highest degree (top 17%). These ports were supposed to be the most important hub nodes within the network, which could directly affect the connectivity and the efficiency of container transportation. Disruptions occurring in these key ports hold the potential to inflict a substantial impact on the entire network. The list of ports in this domain is shown in Table 8.3

Rank	Port	Regional position	Rank	Port	Regional position
1	Singapore	Southeast Asia	9	Ningbo	East Asia
2	Jeddah	Middle East	10	Tanjung Pelepas	Southeast Asia
3	Rotterdam	Western Europe	11	Jebel Ali	Middle East
4	Piraeus	Southern Europe	12	Salalah	Middle East
5	Port Said	Middle East	13	Qingdao	East Asia
6	Tangier Mediterranee	Southern Europe[3]	14	Bremerhaven	Western Europe
7	Shanghai	East Asia	15	Hamburg	Western Europe
8	Yantian	East Asia			

Table 8.3 List of ports in first domain

(Source: Author elaboration based on the simulation results)

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[3] Tangier Mediteerranee is a Moroccan port, located at the Strait of Gibraltar and is regarded as the largest port in Africa. To facilitate the regional analysis of the CSN configuration, Tangier Mediteerranee is involved in the Southern Europe region for further examination.

- The second domain encompasses ports ranked between 18% and 40%. These ports were typically designated as transhipment points or regional hub nodes. While they may exhibit comparatively lower levels of connectivity and influence compared to the nodes in the first domain, their significance to the network's overall connectivity, particularly within specific regional sectors, remains noteworthy. The list of ports in this domain is shown in Table 8.4.

Rank	Port	Regional position	Rank	Port	Regional position
16	Antwerp	Western Europe	27	Chiwan	East Asia
17	Felixstowe	Western Europe	28	Tianjin	East Asia
18	Le Havre	Southern Europe	29	Valencia	Southern Europe
19	Algeciras	Southern Europe	30	Kaohsiung	East Asia
20	Port Klang	Southeast Asia	31	Nansha	East Asia
21	Colombo	South Asia	32	Barcelona	Southern Europe
22	Malta	Southern Europe	33	Southampton	Western Europe
23	Busan	East Asia	34	London Gateway	Western Europe
24	Xiamen	East Asia	35	Vung Tau	Southeast Asia
25	Hong Kong	East Asia	36	Wilhelmshaven	Western Europe
26	Genoa	Southern Europe			

Table 8.4 List of ports in second domain.

(Source: Author elaboration based on the simulation results)

- The last domain encompasses ports ranked beyond 40%. These ports were supposed to be the feeder ports, facilitating connections among spoke links in the network. Usually, these ports don't assume transhipment points or other functional roles. In other words, their impact on the vulnerability of the entire shipping network is relatively limited. The list of ports is shown in Appendix 3.

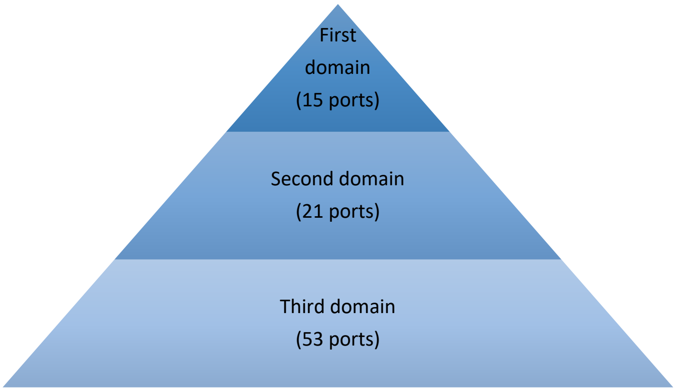


Figure 8.4 Specialisation of ports within the network
(Source: Author elaboration based on the number of ports in each domain)

To summarise, the progression of network failure depends on how many nodes in the network are subjected to disruptions. The procedure can be divided into three stages, with ports in the network being classified in accordance with the divided stages. Due to the different roles of ports within the shipping network, the impact of attacks on the port varied. The impact of disruptions in hub nodes is greater compared to feeder nodes. Ports in the first domain highly affected the vulnerability of the CSN, followed by ports in the second domain. Therefore, the protection of recognised important ports in the first two domains could guarantee and increase the reliability of the entire container shipping network to some extent.

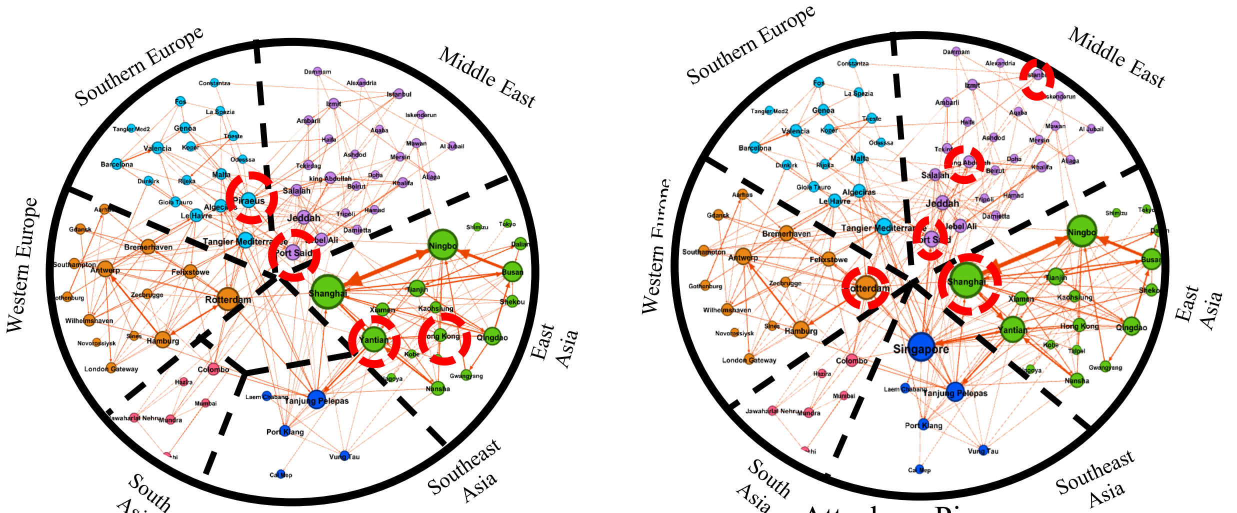
8.3.2 The impact of attacks to the network

This section develops the impact of specific nodes within the network, to understand how the network would be affected by disruptions and the dependency between nodes.

8.3.2.1 Impact of node failure

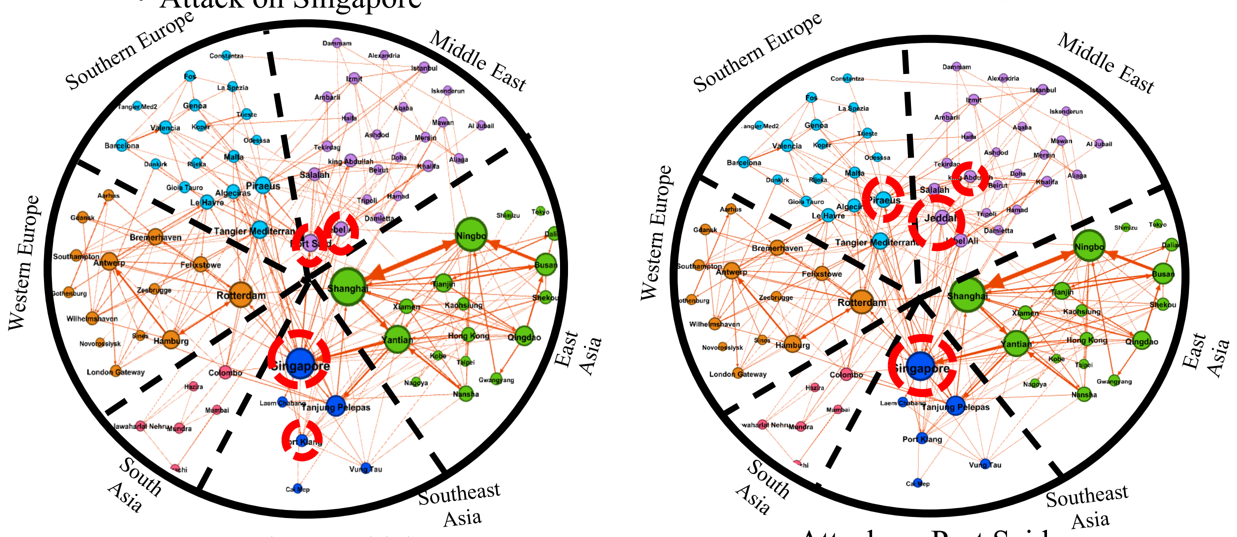
This research simulated attacks to six ports separately to investigate their impact on the network. Five ports with the highest centrality related value (degree, closeness centrality and betweenness centrality) were selected: Singapore, Piraeus, Jeddah, Port Said and Rotterdam. Although attacks measured by node degree had the most effects to the network configuration compared with attacks measured by weight, Shanghai port (with the highest weight) showed high importance to the CSN. Thus, six ports were selected for simulation. Furthermore, it is noteworthy that these six ports represented five different regions of the shipping network – Singapore from Southeast Asia; Piraeus from Southern Europe; Jeddah and Port Said from Middle East; Rotterdam from Western Europe and Shanghai from East Asia. These ports not only contribute to the entire network configuration but also assume vital roles in facilitating regional reliability. Similar to the simulation method employed in Section 8.3, this section investigates the impact of node failure specifically and graphically, especially focusing on the impact to the entire shipping network. The impact of the attack on each node was studied and detailed below. Figure 8.5 gathers the graphic results of attacks to the six selected ports.

Before delving into the analysis results, it is pertinent to recall the network connectivity analysis results developed in Chapter 7: the original average degree of the network was 8.022, the clustering coefficient was 0.272, the average path length was 3.479, the graph density was 0.046, the network diameter was 8, and there were 353 links in total.



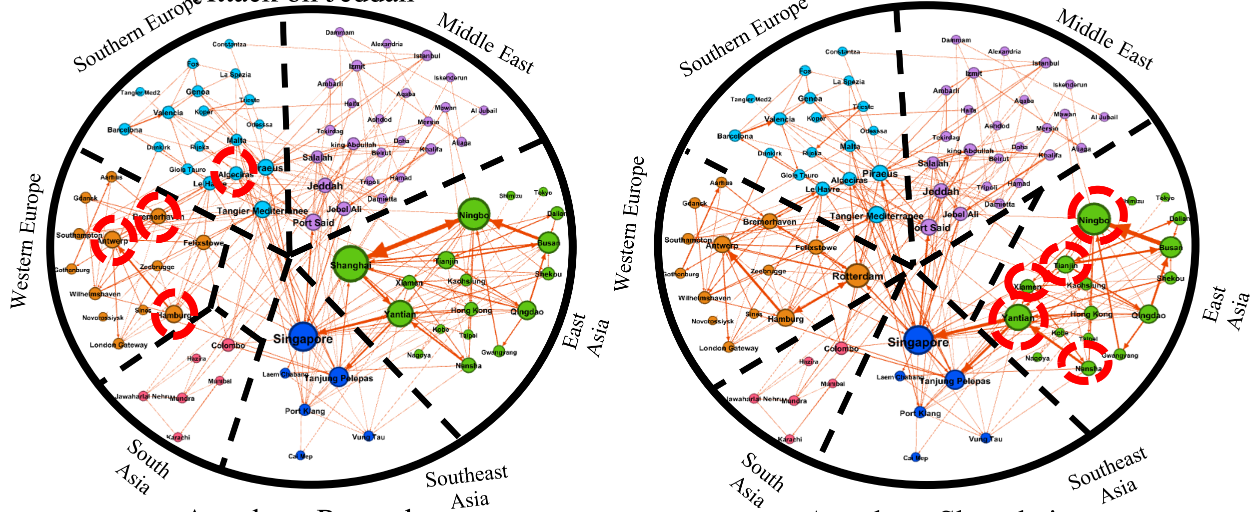
Attack on Singapore

Attack on Piraeus



Attack on Jeddah

Attack on Port Said



Attack on Rotterdam

Attack on Shanghai

Figure 8.5 Attacks on the six selected ports

*The red circles represent the most affected ports

(Source: Author based on the topological diagram of the CSN analysed in Chapter 7, and visualised by Gephi)

- Singapore

Singapore had a degree of 41 (in-degree 19, out-degree 22). The degree value was significantly higher than other nodes within the network and was also emerged as the foremost node in terms of betweenness centrality and closeness centrality. The weight of Singapore was only lower than Shanghai and Ningbo. There is no doubt that Singapore was the most important hub node within the CSN. Furthermore, the combination of high degree and low clustering coefficient of Singapore represented that there are a number of ports that highly depend on Singapore and are directly connected with it.

In the case of the attack on Singapore, the CSN experienced a contraction, resulting in a loss of over 12% of links. The average degree of the network also witnessed a decline, with nodes within the network now being connected directly, with an average of 3 nodes (used to be 4). The attack on Singapore did not affect the density very much, and the network diameter remained the same. In total, 27 ports within the network were affected by the attack on Singapore. More specifically, 19 links to and from Yantian, and 7 links in Piraeus and Port Said, 6 links in Hong Kong and Chiwan, were the most affected ports. This vividly illustrates that the consequences of an attack on Singapore extend beyond its immediate region, affecting not only ports in close proximity but also those in distant regions directly linked to it. As a critical global hub node, the impact of such an attack demonstrated the interdependence of ports across different regions within the network.

- Piraeus

The attacks on Piraeus led to a discernible thinning of the network connections, resulting in a 12.5% increase in the network diameter due to the decrease of only around 7% of links. Although the links that were affected by attacks on Piraeus were not significantly high, Piraeus is supposed to be an important transhipment hub in the shipping network, the affected nodes varied in all the other regions. In total 17 ports were directly affected. The most affected ports were Singapore (6 links), Port Said (5 links), Rotterdam (4 links) and king Abdullah (3 links). Similar to the result of Singapore, the attack on important transhipment hub nodes not only affected their own region but also nodes in other regions.

- Jeddah

Jeddah is one of the most important hub nodes in the Middle East with the role of transhipment. Similar to the simulation results of Piraeus, attacks targeting Jeddah precipitated an 8% reduction of the links, accompanied by a decline in the average degree. The removal of links also engendered a decrease of around 7% in the clustering coefficient, resulting in the regions in the network becoming smaller. A total of 19 ports were affected by Jeddah, with a notable concentration of impacts in European regions. Among the affected ports, Port Said emerged as the most impacted, with 8 links connected with it, followed by Port Klang, Singapore, Mundra and Tangier Mediterranee. Jeddah acts as the role of a regional transhipment hub, which connects Southeast Asia with Europe.

- Port Said

The attack on Port Said triggered a contraction of the network, resulting in a loss of approximately 7% of links. Paradoxically, this reduction in size was accompanied by a denser web of connections, as evidenced by a clustering coefficient increase of around 3%. The attack on Port Said affected limited ports compared with other selected ports, affecting a total of 14 ports in the network. Jeddah was the most affected (8 links), followed by Singapore (7 links), Piraeus (5 links) and King Abdullah (5 links). Port Said, akin to Jeddah, holds the role of a regional hub, and is situated in proximity to the Suez Canal, functioning as a transhipment point. If the links were cut off due to the attacks on Port Said, the connectivity of the network could be affected. However, there were still other ports, e.g., Jeddah shared the same role as a transhipment point in this region, which was more reliable to the resilience of the network, so the degree and density of the network were not highly affected in this simulation.

- Rotterdam

Rotterdam, as one of the most important nodes in Europe, impacted particularly on the connectivity to European ports. With the attack on Rotterdam, 8% of the links were lost. Rotterdam was the only port among the selected ports where the network diameter increased from 8 to 9. This alteration implied that the network was less densely connected, as the shortest path length between the most distant node pairs in the network increased. This proved the high dependence of other directly connected ports with Rotterdam. Nonetheless, the ports directly connected to Rotterdam were less likely to be connected to each other.

A total of 15 directly connected ports were affected. Reflecting its significance as a hub node in Europe, the ports within the European region were impacted the most. Ports like Hamburg experienced substantial repercussions, followed by Bremerhaven, Antwerp and Felixstowe. The impacted ports proved the role of Rotterdam as a regional hub, demonstrating its instrumental function in connecting European ports within the network.

- Shanghai

Shanghai had the highest weight among all the nodes in the network, with a degree of 20 (in-degree 20, out-degree 20). This suggested that compared with other selected ports, a greater number of containers would be stuck or affected if an attack were to target Shanghai. The result of centrality-related metrics confirms its central role within the CSN, portraying Shanghai as a crucial hub node. Compared with other nodes in East Asia, it has a lower coefficient result (0.24), signifying that its neighbours are less connected. This highlights Shanghai's role as a "bridge" within the region, where the ports in East Asia highly depend on the Shanghai port.

The attack on Shanghai decreased 6% of the links within the network, which is relatively moderate compared to other nodes. However, the attack isolated one node from the network, the node was not initially connected with the CSN. The density and clustering coefficient were slightly affected. The impact on Shanghai showed a different feature: fewer directly affected nodes but a high frequency of links. The attack on Shanghai directly affected only 13 ports, but the link between Shanghai and Ningbo was repeated 59 times, implying that there were 59 links affected by the attack. The frequency was followed by Yantian (18 times), Qingdao (8 times), Nansha (6 times) and Xiamen (5 times). From the perspective of geographical distribution, Shanghai is located at the end of the trade between Asia and Europe, making it relatively distant from the centre of the network. As a result, the ports directly affected by the attack on Shanghai were concentrated in a specific region, i.e., Eastern China.

The simulation conducted on the entire shipping network, as analysed in Section 8.3.1.3, revealed the failure procedure when there were attacks on the network. In addition to assessing the vulnerability of the CSN, the analysis provided insights into the specialisation of ports within the network. The impact of disruptions in hub nodes showed a greater impact than that in feeder nodes. The ports in the first domain, consisting of highly connected hub nodes, had a greater impact on the vulnerability of the CSN, followed by the ports in the second domain. The subsequent simulations on six important nodes in the network further proved and reach to the conclusion that the impact of attacks on ports varied based on their roles within the network. For example, Rotterdam was a critically important node to ports in Europe, while its impact was comparatively limited for Asian ports, and Shanghai exhibited a contrasting pattern. Both of the ports could be recognised as regional hub nodes. Singapore was one of the most influential global nodes within the network, which connected ports from different regions. Moreover, the weight of the links associated with Singapore was also substantial. Compared with Singapore, Jeddah and Port Said were also recognised as important hub nodes for transhipment but with less impact to disruptions due to their weight. Upon analysing the findings, the researcher observed that a contributing factor to the comparatively lesser impact was the distance between Jeddah and Port Said. These two ports are both located near the Suez Canal, indicating their similar functions within the network. The similar ranking of betweenness centrality and closeness centrality also proved this conclusion.

The definition of network configuration reliability refers to whether the network could be affected by disruptions and the ability of the network to perform well even when parts of the network have failed. The findings presented in this section showed the varied impact of disruptions based on the roles of individual nodes. Meanwhile, it also cast light on the improvement of resilience within the network. The focus of the next section (8.3.3) will be placed on improving network configuration reliability by considering the ports with the same function in each region.

8.3.2.2 Impact of passage failure

There is no doubt that ports constitute the main part of the shipping network, simulating disruptions in ports – attacks to nodes – plays an important role in assessing the extent of vulnerability and network configuration reliability of the container shipping network. In addition to nodes, important passages, such as the Malacca Strait, the Suez Canal and the Taiwan Strait are also pivotal to network reliability, especially after disruptions, e.g., the blockage of the Suez Canal in March 2021 by the container ship *Ever Given.* As illustrated in Figure 8.6, passages connect the core regions within the shipping network. Any disruption that hinders the proper functioning of these passages can have a profound impact on the global container shipping network (Liu *et al.*, 2018; Wu *et al.*, 2019).

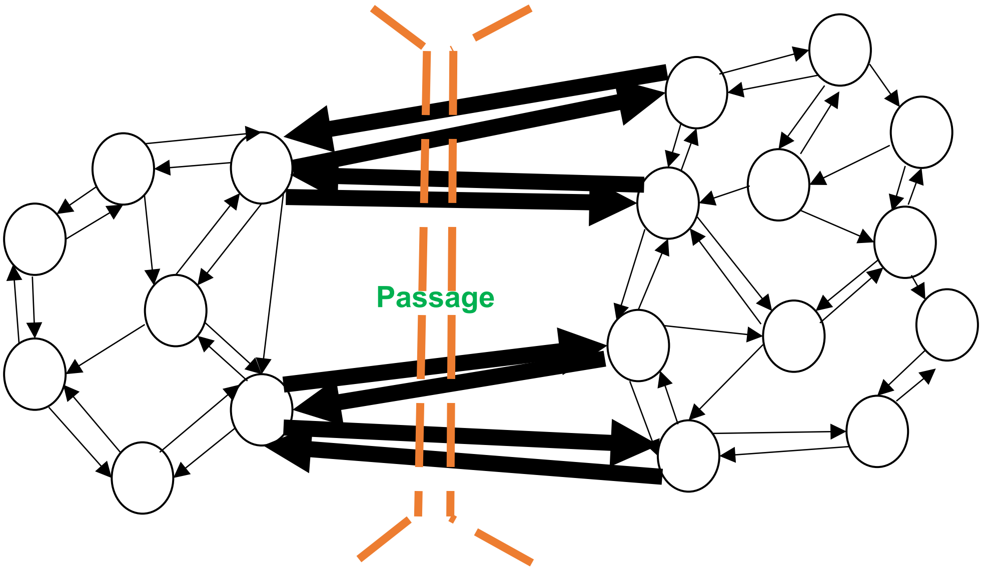


Figure 8.6 Concept diagram of shipping passage

What is simulated in this section is the failure of the Suez Canal and the Taiwan Strait, to assess the impact on the CSN. The positions are shown on Figure 8.7.

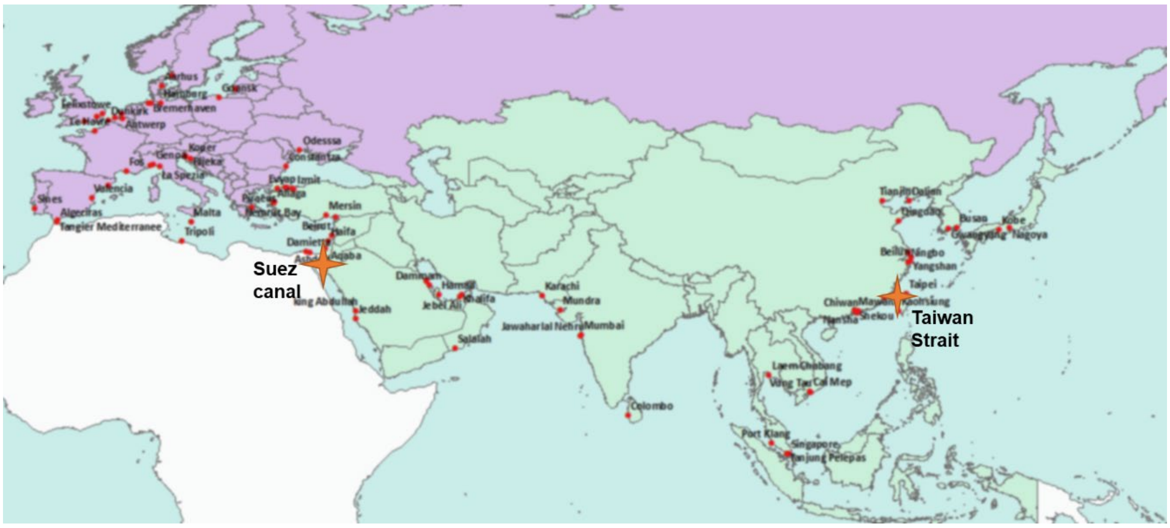


Figure 8.7 Position of the Taiwan Strait and the Suez Canal

*Orange stars represent the position of passages. Red points represent the nodes involved in the CSN.

(Source: Author elaboration based on ArcGIS)

- Taiwan Strait

The Taiwan Strait separates the Taiwan island and continental Asia, connects the east coast of Asia and Southeast Asia. Disruption or closure on the Taiwan Strait could have a major impact on container shipping strings between Asia and Europe especially the westbound strings from East China. Meanwhile, the Taiwan Strait is surrounded by several important hub ports such as Shanghai, Ningbo, Busan and Qingdao.

Among the 115 strings in this research project, 89 (77%) passed via the Taiwan Strait. The failure of the Taiwan Strait decreased the average degree of the network for around 8%. The attack on the Taiwan Strait cut off the connection between the east coast of China and Europe. As a consequence, the network diameter increased (8 to 9). Graph density and clustering coefficient both decreased about 7% which meant that the attack significantly reduced the number of links within the network. The network became much smaller, and ships needed more steps to reach to their destination.

The Taiwan Strait is the primary choice of routing for ships travelling between the east coast of China, South Korea and Japan, to Europe. If there is a disruption in this area, ships would usually choose to reroute via east of the Taiwan island and this alternative route typically adds three days to transit times. Taking the example of MSC's GRIFFIN Westbound string, it departs from Shanghai and makes calls along the way at Ningbo, Yantian, Singapore, Tanjung Pelepas, Port Said, Rotterdam and Antwerp, before finally arriving at Felixstowe with a voyage time usually around 37 days. The alternative route via east of the Taiwan island would add three more days on the voyage between Ningbo and Yantian. However, delays usually have knock-on effects to other nodes along the string, the entire duration could well be longer than 40 days. In addition, the alternative route (east of the Taiwan island) is more exposed to bad weather, especially during certain seasons (from June to October). The east coast of the island faces the open Pacific Ocean, which is prone to powerful weather disturbances, e.g., typhoons, which often make landfall on the eastern side of the island rendering the alternative route more vulnerable.

- Suez Canal

The Suez Canal lies in the west part of the CSN. It connects the Mediterranean Sea and the Red Sea through the Isthmus of Suez and divides Africa and Asia, which is also part of all the strings transported between the Indian Ocean and Mediterranean Sea.

Among the selected strings in this research project, all 115 strings in the CSN would be affected, as all the strings need to pass through the Suez Canal to reach their respective ports of call. More specifically, the average degree of the network decreased by around 11%, which was the most impacted result observed among all the simulations. Its graph density and clustering coefficient also decreased by 10% and 3.5%, respectively. Network diameter was severely affected as well (increased to 10), indicating a less densely connected network. The attack on the Suez Canal showed the highest degree of change on measuring metrics, underscoring the pivotal role of the Suez Canal to the shipping network. In this research project, we only considered the international container transportations, that is, the strings connecting different regions between Asia and Europe; for example, East Asia--Europe, Southeast Asia--Mediterranean and so on. So the failure of the Suez Canal had the greatest impact on the CSN.

When the Suez Canal fails, ships could choose to reroute or transport by other transport modes. If a ship chooses to reroute, it would need to navigate through the South Atlantic and South Indian Ocean, circumventing the Cape of Good Hope. This alternative would add approximately 3,500 nautical (n) miles to the journey. For example, the link between Shanghai and Rotterdam is 10,750 n miles (via the Suez Canal), the reroute journey is around 14,200 n miles, which increases more than 30%. Consequently, the extended journey would also increase the journey time by around 7 days, assuming the ship's speed of 20 knots. The carrier could also choose other transport modes – tranship in ports in Middle East – and then change to land transportation. However, as analysed in the previous sections, ports in this area are acted as feeder and transhipment nodes, and the capacity ability and operation ability of these ports may not satisfy the ships from hub nodes.

The Taiwan Strait and the Suez Canal are two of the most important passages – also can be regarded as nodes – within the CSN, which connect the east part and west part of the shipping network. If one or both of the nodes fail, almost all the strings among the shipping network would be unable to reach their destination ports. The shipping network would lose the function of transportation for quite some time. However, it should be noted that the aforementioned simulations primarily focused on assessing the network configuration reliability. The analysis did not take into account the potential impact on the number of containers affected by such attacks, as well as the additional waiting time. For example, as illustrated in Figure 8.8, the sequence of events during the Suez Canal failure in 2021 is depicted. It took six days to dislodge the *Ever Given*. The number of waiting ships increased, culminating at a peak of 367 ships on the sixth day, which almost doubled the average daily number under normal circumstances. Furthermore, the procedure proved that it needed around five days to restore normal operations and clear the backlog of ships awaiting passage through the canal due to disruptions. The researcher made a simple linear prediction here: if the Suez Canal was disrupted for 30 days, the accumulative waiting ships could reach around

1,655 and it would need about 27 days to recover. From one perspective, when taking into account the additional time, the impact of disruptions showed a greater impact. From the other perspective, the reliability of the network configuration not only depends on the network configuration itself (the quantity and quality of nodes and links), but also the performance of the network as well as the dependency of the selected nodes. Indeed, the reliability of the network might either be enhanced or weakened depending on how it performs. The performance analysis of the network is presented in the next chapter.

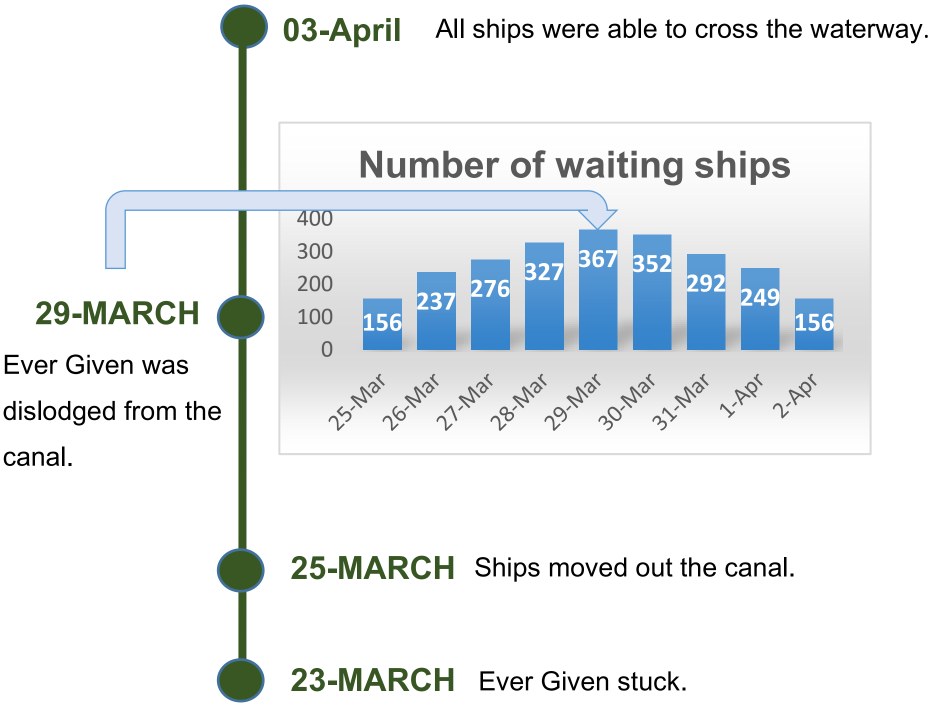


Figure 8.8 Suez Canal blockage in 2021
(Source: Author elaboration based on the news: https://porteconomicsmanagement.org/pemp/contents/part6/port-resilience/suez-canal-blockage-2021/)

According to the collected data for the CSN, disruptions would impact 89 strings passing through the Taiwan Strait and 115 strings passing through the Suez Canal. This corresponds to approximately 77% and 100 % of the entire network, respectively. The main passages in the network serve an important role in ensuring network configuration reliability. Consequently, the connectivity reliability would decline when the main passages within the network fail, and some of the passages could have a greater impact compared to other important ports, e.g., the Suez Canal exhibited the most considerable influence considering the network analysis metrics.

This research considered the impact of node failure and important passage failure. However, there are other disruptions that can affect the shipping network, such as the company-level disruptions. With the disruption of a shipping company, other companies may need to absorb its cargo volumes, resulting in a redistribution of cargo among different shipping lines and routes. This can alter the dynamics of existing shipping networks and may require adjustments in logistics and transportation strategies. Moreover, if a major shipping company experiences disruptions, the cargo that would typically flow through its routes might need to be rerouted through other ports and shipping lines. This redirection can lead to congestion at alternative ports, affecting efficiency and causing delays. Major disruptions at the company-level can even have broader implications for global trade, especially if the affected company handles a significant portion of trade in specific regions or industries. The impact of company-level disruptions could be a valuable area for further exploration in future research.

8.3.3 Network resilience

As introduced in Chapter 2, the reliability from the perspective of network configuration was defined as whether the network could be affected by disruptions or risks and the ability of the network to perform well even when parts of the system have failed. The ability to perform well when parts of the network have failed can be measured by network resilience. Different from the definitions proposed by Wu *et al.* (2019), Yuan *et al.* (2019) and Wan *et al.* (2018) – where resilience refers to the capacity of a system to return to its original state – the resilience in this research refers to the ability to absorb failures and promptly recover in the event of failures (Verschuur *et al.*, 2022). The definition is framed on the functional dynamics of the entire network.

The simulations of network vulnerability conducted in Section 8.3.1.3 showed that when the shipping network encountered attacks to more than 17% of nodes within the network, the CSN began to fail. Indeed, it is uncommon for disruptions to lead to so many nodes (over 17%) in the network failing or partly failing at the same time. Disruptions that commonly occur in the real world, such as weather, strikes and so on, typically impact only a few nodes in the network. In these attacks, the network has the ability to recover and adapt itself over a period of time by implementing various actions to mitigate the effects of the disruptions, which is recognised as the resilience in this research. Due to such reliability, the network could operate even when parts of the network have failed. This section investigates the resilience of the network – more specifically, the resilience of different regions within the network in order to assess the reliability of the entire shipping network.

8.3.3.1 Network resilience considering network configuration

Section 7.3.3 introduced the network configuration of the CSN – the hub-spoke network structure – a few weighted links accounted for a large share of TEUs in the container shipping network and higher weighted links took place between a few hub nodes. Figure 8.9 shows the distribution of ports of the CSN developed in this research. Upon further examination of the recognised hub nodes' position on the map, it can be observed that the current shipping network was not only a single hub-spoke network structure, but the hub-spoke network structure was developing into a multi hub-spoke network structure. For example, Shanghai and Ningbo ports in East Asia; Singapore and Tanjung Pelepas in Southeast Asia; Hamburg, Rotterdam and Antwerp in Western Europe and so on. These port pairs had similar rankings in terms of their degree, weight and centrality-related metrics, indicating their similar roles in the network. Moreover, these ports are located in close proximity and share the same hinterland region. Studies also indicated that it is difficult to develop a single hub-spoke network structure and promote a single hub for one region (Gilman, 1980; Wang and Wang, 2011).

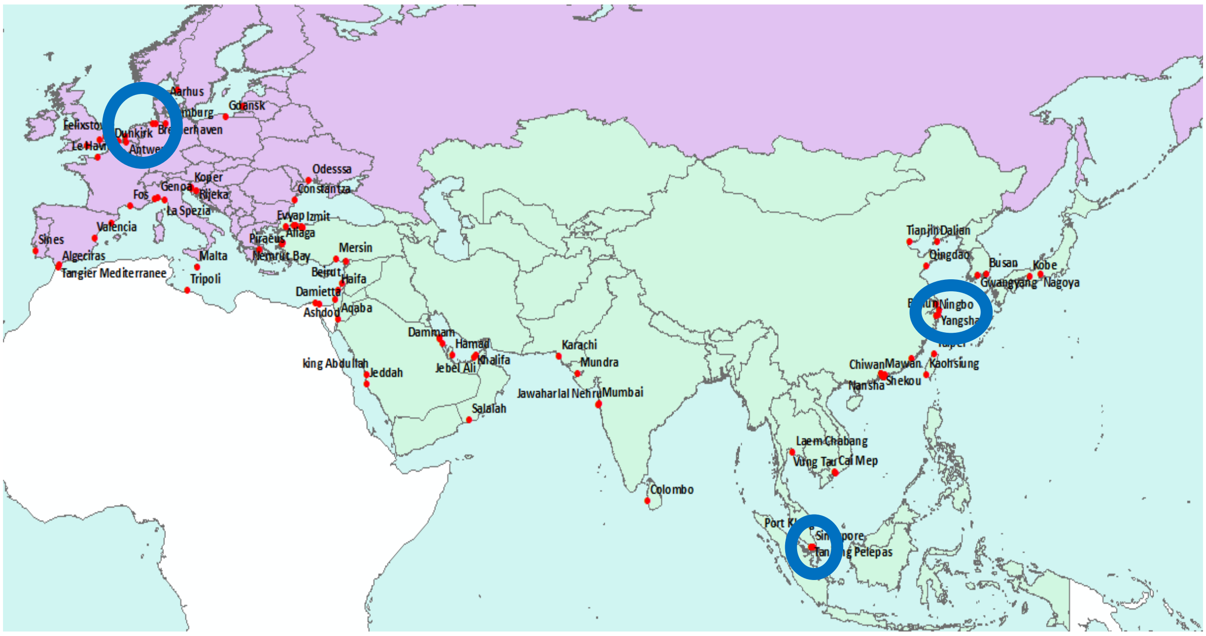


Figure 8.9 Distribution map of container ports on the selected strings.

(Source: Author elaboration based on ArcGIS)

One of the reasons that contributed to the emergence of a multi-hub network is that the shipping network is expected to divert containers from a congested port or a disrupted port to alternative hub nodes, which could reduce the costs and turnaround time. Such a network structure could enhance the network reliability in terms of network configuration: if one hub node fails, the other hub nodes could act as backup nodes until normal port operations are restored. For example (Figure 8.10), the ship CMA CGM Bali (14,812 TEUs) from COSCO AEM2 Westbound intended to make calls at Nansha then Yantian then head to Singapore. However, during that time, COVID-19 led to the closure of the Yantian port for several days. To adapt to this situation, the ship omitted Yantian and chose Shekou as a backup port. The new route was Nansha to Shekou, and then to Singapore.

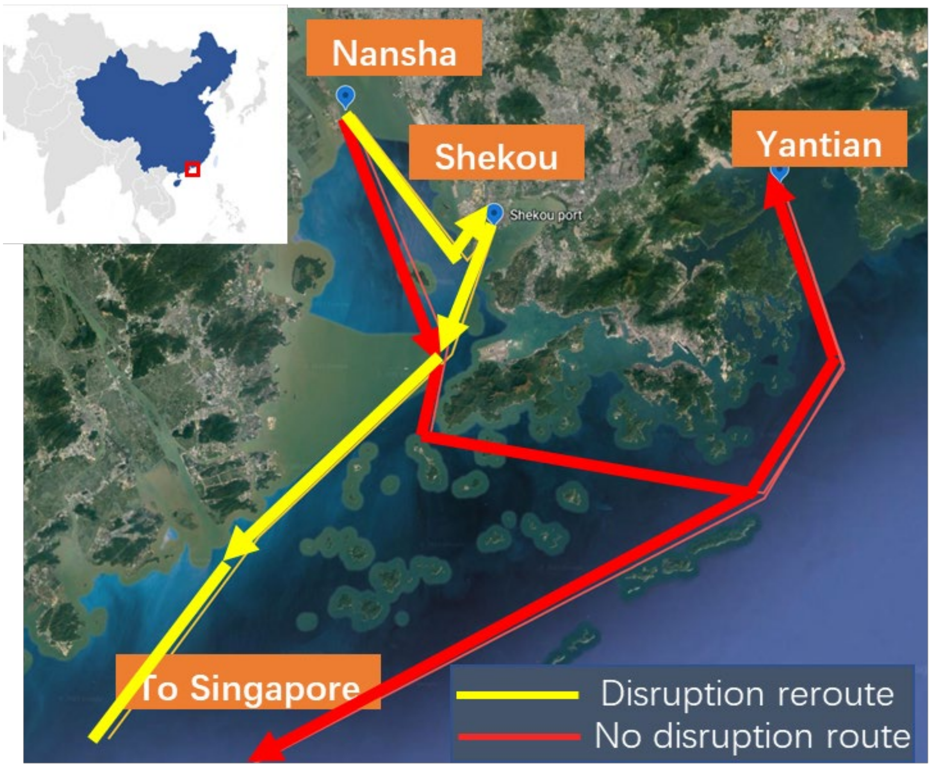


Figure 8.10 Route map for ship CMA CGM Bali

8.3.3.2 Regional resilience analysis

Section 8.3.2 simulated the failure procedure of the network and classified the ports according to the simulation results. 15 ports were identified as being the most affected ports to the vulnerability of the network, falling with the first domain, 21 ports were recognised as important transhipment nodes or regional hub nodes, exhibiting a comparatively lower impact on network vulnerability, and were grouped within the second domain. The other 53 ports were recognised as feeder nodes, comprising the third domain. Figure 8.11 shows the port's distribution of the three domains within the analysed network configuration.

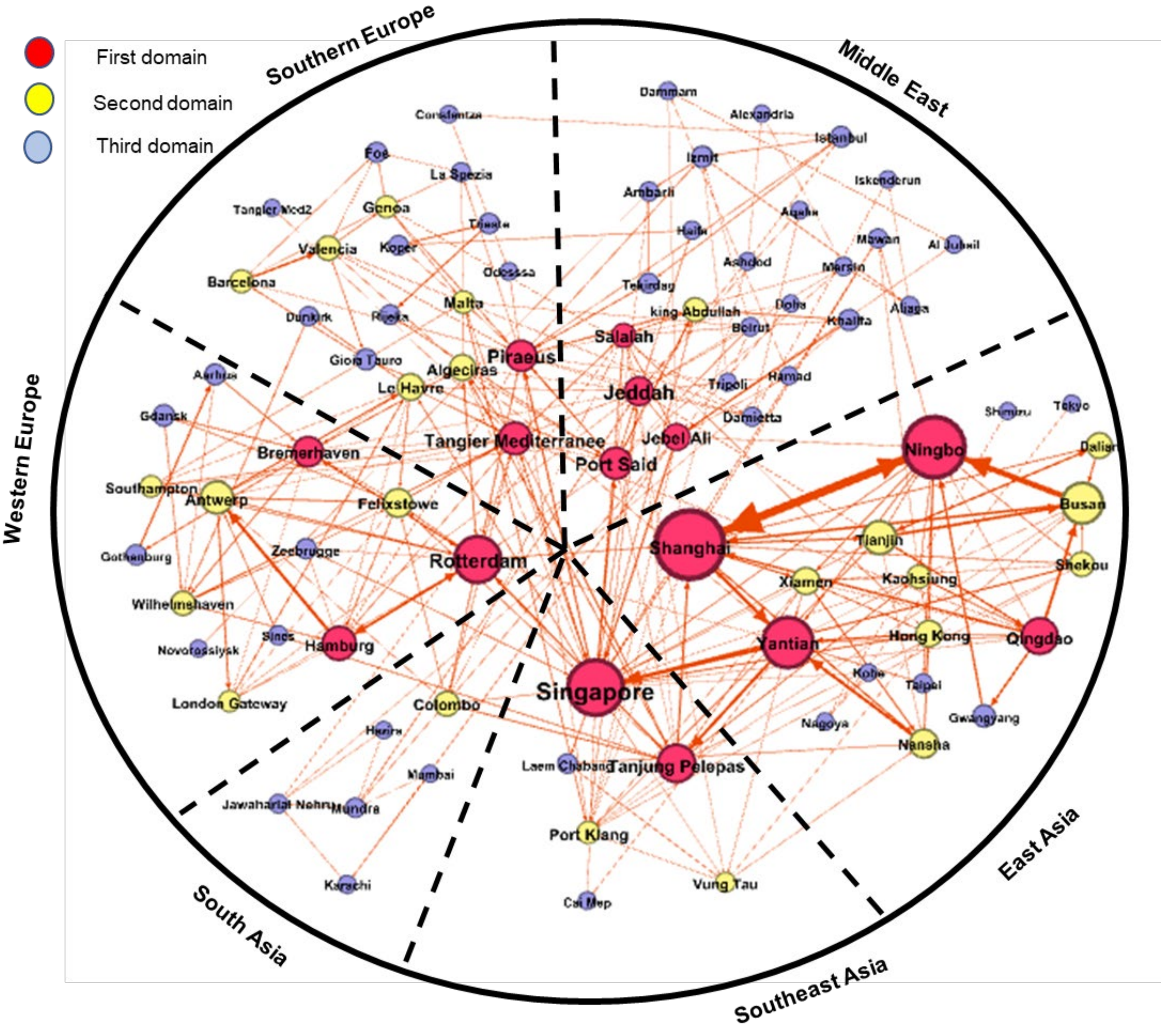


Figure 8.11 Classification of nodes within the network configuration in terms of vulnerability
(Source: Author based on the topological diagram of the CSN analysed in Chapter 7, and visualised by Gephi)

The example provided above, along with the analysis of network configuration, indicates that the resilience of a region within the container shipping network is influenced to some extent by the number of hub nodes in the first domain and second domain. This can be explained due to the resilience of one region depending on the availability of backup nodes to cover the containers from the disrupted node. In this context, a region endowed with a greater number of hub nodes is more likely to facilitate rerouting options, enhancing network resilience even if the hub node fails in that region. The role of a port within the network is important in determining the resilience while the ports that act as transhipment nodes or hub nodes are more useful for recovery.

In summary, the resilience of a given region, or to say, the ability to recover from disruptions from the perspective of network configuration depends on the number of backup nodes within that region. Additionally, the resilience ability is positively correlated with the number of ports from the first and second domains. The importance of these ports to network vulnerability and container transportation further represents their pivotal role in enhancing resilience. The resilience metric (R) of one region can be defined as:

$$R = \sum_{i=1}^{n} D_i \tag{7.4}$$

Where R refers to the resilience reliability of one region; i refers to the node from the first or second domain in the region; n refers to the total number of nodes from the first and second domains; and D_i refers to the degree score of the node. The highest degree is from Singapore and the score is equal to 1. Degree scores of other nodes are rescaled according to their distance from the highest score.

The CSN remained partitioned into six regions: East Asia, Southeast Asia, South Asia, Middle East, Southern Europe, and Western Europe. The results of the resilience metric are shown in Table 8.5.

	East Asia	**Southeast Asia**	**South Asia**	**Middle East**	**Southern Europe**	**Western Europe**
Number in first domain	4 (22.2%)	2 (33.3%)	0 (0%)	4 (16%)	2 (11.1%)	3 (21.4%)
Number in second domain	8 (44.4%)	2 (33.3%)	1 (16.7%)	1 (4%)	6 (33.3%)	5 (35.7%)
Resilience Metric	3.54	1.95	0.29	2.22	2.68	2.49

Table 8.5 Resilience metric of each region

In general, regions with more ports in the first and second domains have a wider array of potential backup ports available. As a result, regions with higher resilience scores possess the capacity to swiftly recover from disruptions within the shipping network. More specifically, the results show that the resilience of East Asia was the highest compared with other regions, which means that container shipping transportation in East Asia has the ability to recover quickly from disruptions. Western Europe, Southern Europe and Middle East had similar resilience results. Southeast Asia and South Asia had lower resilience ability. Therefore, the ports in these two areas cannot recover quickly from disruptions, and the network would fail when part of the nodes fail. Meanwhile, South Asia stood out as a potential weak point within the CSN. If the nodes in South Asia fail, then most of the strings that need to make calls in this region could struggle to find suitable backup ports. Consequently, the entire shipping network would experience prolonged recovery time in the aftermath of such disruptions. When conducting a comparative analysis of each region, the number of ports in the first domain and the structure of ports distribution between the first and second domain should also be considered.

- East Asia

East Asia had the highest resilience score, which is supposed to be the most reliable region when considering the network configuration. The rapid growth of China's economy and its expanding international container trading led to an increase in both the number and scale of Chinese ports. There were 12 selected ports in two domains, which contributed to the higher resilience score. The 12 ports accounted for 66.6% of all the ports in East Asia. This implies that more than half of the ports in East Asia can be recognised as important nodes to Asia-Europe container trading. Additionally, the availability of multiple ports of comparable scale provides ample options for backup ports, enhancing network resilience. Having the enough ports enabled the distribution of volume from any disrupted port, making it feasible to find a backup hub.

There were four ports in the first domain: Shanghai, Ningbo, Yantian and Qingdao. Shanghai and Ningbo shared the same hinterland, and had similar ranking of degree, weight and centrality. During the COVID-19 period, container shipping to East Asia highly depended on the Ningbo port due to the closure of the Shanghai port. Qingdao located in the Northeast Asia, the strings to Qingdao influence the Far East, South Korea and Japan. Although Qingdao was the only port in the first domain from Northeast Asia, it had three ports in the second domain to support it: Dalian, Tianjin and Busan. As with the case of Qingdao, Yantian faced a similar situation. Because Yantian is located in Southeast China, Xiamen, Shekou and Hong Kong were alternative ports to support Yantian.

- Southeast Asia

The relatively low resilience score of Southeast Asia can be primarily attributed to the scale of the region, as it comprised only four ports in two domains. The limited number of ports directly impacts the resilience ability of the region. Despite the relatively small number of ports, the proportion of ports in two domains was high, occupying 66.6% of all ports in the network. Most of the nodes in Southeast Asia could be recognised as important nodes, which also proved the importance of the shipping network in Southeast Asia to the entire network.

The structure in this region was resilient with two ports in the first domain (Singapore and Tanjung Pelepas) and two ports in the second domain (Port Klang and Vung Tau). The resilience of Southeast Asia was led by Singapore and Tanjung Pelepas. Compared with other regions, the lack of ports from the second domain led to the lower resilience ability. Furthermore, Singapore was recognised as one of the most important hubs, with the highest degree in the network. Its influence extends across a wide range of ports in both Asia and Europe. If there is a disruption in Singapore, it could pose considerable challenges for other ports in this region to find a suitable replacement for their pivotal function.

- South Asia

South Asia had the lowest resilience score. This can be attributed to the fact that only one port (Colombo) could be regarded as a hub port (second domain) in this region. Consequently, if there is a disruption in Colombo, South Asia would lose its ability as being a transhipment point within the shipping network. This region could be regarded as one of the most vulnerable regions in the entire shipping network.

- Middle East

The analysis of network connectivity reliability in Section 7.3.4 showed that several ports with the highest closeness centrality and betweenness centrality are located in the Middle East. This result gave rise to the fact that the ports in the Middle East were recognised as being the most important transhipment ports within the network configuration. However, compared with the role of this region, it had a relatively low resilience score. Firstly, the total number of nodes involved in two domains only accounted for a mere 20%, a considerably lower proportion compared to other important shipping regions. The number of feeder ports was high, but the feeder ports lacked the capacity to fulfil the role of backup hub to some extent. Furthermore, the ports from the second domain contributed much less to the resilience reliability in this region. Lack of ports from the second domain had a great impact on network resilience.

There were four ports selected as the leading hub nodes: Jeddah, Port Said, Jebel Ali and Salalah. Even though they are located in different directions, four ports in different areas of the Middle East, share the same hinterland and are relatively proximate to each other, so they could still be options as backup ports. Meanwhile, due to the high proportion of feeder ports, each hub node could be supported by several feeder ports, e.g., Jebel Ali could be supported by nearby feeder ports like Dubai and Abu Dhabi, enhancing the resilience of the entire region.

- Southern Europe

The resilience score in Southern Europe was the second highest among the six regions. As an international trade corridor, Southern Europe has become an important region in global container shipping. Hub nodes occupied 44.4% of its overall ports and ports from the second domain contributed more to resilience reliability, especially when comparing the result with the Middle East. Despite having only two ports in the first domain, Southern Europe achieved a substantial resilience score.

Piraeus and Tangier Mediterranean emerged as the hub nodes in this region. Interestingly, the coexistence of many countries in this region resulted in the emergence of a multi-hub network structure. For example, Valencia and Barcelona could act as backup ports for each other and they are linked with feeder ports.

- Western Europe

The resilience score and the structure of Western Europe are quite similar to Southern Europe: ports from the second domain contributed more to resilience reliability. However, the proportion of ports in the first domain is larger in Western Europe.

As the core region of Europe, Western Europe has three nodes from the first domain: Rotterdam, Bremerhaven and Hamburg. As the gateway of Europe, there is no doubt that Rotterdam plays a significant role within European ports. However, it was not always a single super hub port in Europe. With the development of container transportation, Antwerp nearby was developing as an important node with higher degree and weight. This contributed to the overall network resilience, as the interdependence and collaboration between these two hubs enable a more resilient multi-hub network structure. Bremerhaven and Hamburg acted as the second multi-hub system in this region. Three ports in UK – London Gateway, Felixstowe and Southampton – were involved in the second domain, which also made a contribution to the resilience reliability of this region.

8.4 Conclusion

This chapter investigated network configuration reliability, with a focus on network vulnerability and resilience. That is, to analyse the network configuration reliability considering whether the network could be affected by disruptions, along with the impact of disruptions and the ability to perform well even when parts of the network are disrupted. The result proves that the transportation ability of the CSN, when facing disruptions such as weather or sudden accidents of ship, is less affected compared with when facing disruptions such as terrorist attack, war, strike to specific ports. The results also cast light on the impact of disruptions to the entire network: the progress of network failure depends on how many nodes in the network are facing disruptions. The procedure can be divided into three stages: limited performance (when attacked nodes were below 11%), partly failed (17%) and totally failed (40%). The network was supposed to fail when the disruption affected more than 40% of the nodes within the network.

Meanwhile, due to the different roles of ports within the shipping network, the impact of attacks varied. Considering the role of ports identified from connectivity analysis, if disruptions happen in the nodes with higher weight, e.g., the Shanghai port, there will be more containers stuck in the port. If disruptions happen in the nodes with higher degree, e.g., the Singapore port, there will be more directly affected ports within the network. With the analysis of network vulnerability, the impact of disruptions in hub nodes is greater than in feeder nodes. Then, the researcher further developed the impact of attacks to several hub nodes and important passages in the network. The simulation of attacks to hub nodes also proves that the impact of attacks varied due to the role of ports. For most of the nodes in the network, the failure of nodes exerts an influence on other nodes, ripping through the entire shipping network, but the impact is limited. However, for some important nodes, e.g., the Suez Canal and the Singapore port, the failure would significantly affect the entire shipping network. From the network analysis and simulation results, it can be concluded that **the**

protection of recognised important nodes could guarantee the reliability of the entire container shipping network to some extent.

The research further developed the network configuration reliability from the perspective of resilience. Section 8.3.3 analysed the resilience of six regions within the network by calculating the resilience score, which depended upon the number of hub nodes within each region. East Asia was regarded as the most resilient region, followed by Southern Europe and Western Europe. The optimisation of network reliability in terms of network resilience includes the distribution of hub nodes and the selection of backup nodes, which could improve the resilience of the network by decreasing the time to recover from disruptions.

The next chapter will develop the last theme that should be taken into account when analysing network reliability: infrastructure reliability. Chapter 9 will investigate the performance of ports and weak points within the network. Meanwhile, combined with the results from network connectivity and configuration, it will investigate whether the performance of ports will be affected by the dependency on other nodes within the network. Chapter 9 will also consider the propagation effect from the perspective of network analysis and graph theory.

Chapter 9. Analysis of the infrastructure reliability

9.1 Introduction

This research project adopted a network analysis approach to assess the reliability of the container shipping network and built a directed and weighted network with 89 nodes and 353 weighted links. Building upon the framework established in this research, the last theme that should be taken into account is **infrastructure reliability**. As identified from both the interviews (Chapter 5) and the evidence gathered from the literature review (Chapter 2), the factors that affect infrastructure reliability encompass the capacity, efficiency and risks associated with the infrastructure and operations in ports, as well as the construction of hinterland and intermodal connection to the hinterland. Given the data availability and the scale of this research, the assessment of infrastructure reliability for the CSN in this chapter will be limited to the performance within ports.

Ports play a crucial role in guaranteeing the reliability of container services. This research project explores infrastructure reliability by examining the performance of ports, which is determined by whether consignees could receive their containers on time. For the ports that cannot provide reliable services, the researcher further investigates the underlying reasons for such unreliable port performance by analysing the berth time and anchorage time. The results from the network analysis in previous chapters have indicated the need for a more comprehensive approach to assess the network reliability, the researcher needed to consider not only the performance of the infrastructure but also the impact of network configuration. In the context of this chapter, the impact of network configuration refers to the extent to which the performance of a given port can be affected by other ports within the network; at the same time, the reciprocal influence of the port on others is due to the network connectivity and dependency. The research exploring the relationship between port performance and network configuration is still scarce.

Given the different metrics that were used in Chapter 7 and Chapter 8, this chapter explores the infrastructure reliability by building another Performance of the Container Shipping Network (PCSN), based on the identified CSN. Section 9.2 outlines the research design for analysing the performance of the network. Section 9.3 presents the result of network performance, encompassing the examination of nodes, links and strings within the network. Section 9.4 further examines the reasons that affect the performance from the perspective of port infrastructure reliability. Section 9.5 explores the propagation effect and dependency of ports by taking into account the network configuration. Section 9.6 presents two cases of ports and conducts a thorough analysis on their reliability within the network, considering three themes identified in this research. Finally, section 9.7 summarises the findings in this chapter.

9.2 Research design for analysing network performance

Chapter 7 and Chapter 8 focused on the construction of the container shipping network between Asia and Europe (CSN), which served as the foundation for understanding network connectivity reliability and configuration reliability. Specifically, the aim was to investigate whether the network was reliable enough to support normal operation and perform well under disruptions. The analysis sought to identify critical nodes and weak points within the network in order to enhance the overall reliability. Subsequently, the researcher proceeded to build the Performance of the Container Shipping Network (PCSN), building upon the design and analysis of the CSN. As introduced in Section 6.3.4, data for the ship performance database was obtained through the observation of selected ships' transportation processes. Due to the requirement of real-time data and the complexity of observing, the database was built based on the AIS data provided by the Sea/net Clarksons Research Portal. This data source provided insights into the berthing behaviour and waiting behaviour of container ships. In line with the available data from the CSN, a total of 86 ships were selected as the basis for constructing the PCSN (Section 6.3.3).

Containerisation has the characteristic of providing "just in time" performance. As stated in most of the research that focused on network reliability in other transport modes, time reliability has often been considered as one of the indicators for assessing reliability. Time reliability refers to the probability of successfully completing a trip between a given O-D pair within a specified time interval (Chen *et al.*, 2011; Prabhu Gaonkar *et al.*, 2013; Forozandeh *et al.*, 2019). In this chapter, we aim to develop port performance as a measure of time reliability, specifically focusing on the on-time performance of ships. The on-time rate has been a challenge in container shipping, especially considering the recent significant decrease in the on-time rate. Thus, variations in time reliability have become a popular approach to compute reliability. Two metrics, on-time rate and average delay are employed to evaluate network performance.

After analysing the performance of the network, this research extends its investigation to explore the infrastructure reliability in ports, which directly affect the performance of those ports. More specifically, the analysis included the time at berth, the time at anchorage and ship trajectory. The research method built upon the work of AbuAlhaol *et al.* (2018), which used the turnaround time and number of ships in port to assess the congestion of ports. What's new in this research project is that different from the work of AbuAlhaol *et al.* (2018), the turnaround time is divided by the time at berth and the time at anchorage. Time at berth, thereby, reflects the infrastructure utilisation and efficiency within the port. Additionally, the time at anchorage is considered, serving as a significant factor in measuring port congestion and capturing the time lost within the port. In agreement with the division of turnaround time, the container transportation process is divided based on three points: departure, at anchorage and at berth. The turnaround time was represented by the sum of the waiting time and the berthing time.

Meanwhile, with the network configuration and the dependency between nodes identified in Chapter 7 and Chapter 8, this research further explores the propagation effect by taking into account the links within the network. Unlike the previous analyses that primarily focused on the individual port performance, this study considers the relationship between nodes within the network. By doing this, it acknowledges the dependency between nodes, recognising that the performance of one node can be influenced by the nodes that are directly connected to it, as well as the ports within the same string. The propagation effect was also adopted when analysing the vulnerability and connectivity of the entire shipping network. Higher connectivity and hub-spoke network structure make the network highly affected by disruptions. Any disruption happening in one node could affect other nodes. Consequently, the analysis of network performance should take into account the dependency and potential propagation effects within the network.

9.3 Performance of the container shipping network.

According to the reasons stated above, one of the most direct indicators for evaluating the PCSN is time reliability, which refers to the actual on-time performance of individual container ships. Time reliability is one of the most important issues for shipping companies and customers, and it also serves as a key measure within transportation reliability analysis in other transport modes. The following sections will present an analysis of the performance of the entire shipping network, individual carriers (shipping companies), strings and specific hub links based on the observed ship movements.

9.3.1 Metrics for assessing network performance

Basically, two metrics were calculated to assess the network performance: on-time rate and average delay. In line with the calculation method utilised in the Global Liner Performance report, the definition of "**on time**" has in accordance with the widely used calendar-day definition, been settled as the arrival day within plus or minus 1 calendar day from the proforma schedule. That is, if the actual arrival date is same or plus/minus 1 calendar day compared with the planned schedule, then the ship is said to have arrived "on time". Although it is more accurate to assess the delay on an hour basis, it should be noted that some shipping companies only provide their schedules on a calendar day basis. Hence, in this research project, the on-time rate and delay were calculated on the calendar day basis. Typically, the arrival time provided by the shipping companies refers to the time to berth. The observation of port time in this research included both the time at anchorage and the time at berth, we used the time at berth to estimate the on-time performance. The on-time rate was determined by considering the number of on-time ships in relation to the total number of services within the designated scope.

In the context of this research, the term "delay" refers to the number of calendar days between the planned schedule and the actual arrival (to berth) of ships, including both later than the plan and earlier than the plan. The assessment of delay typically focuses on the average delay, which was calculated as the simple arithmetic mean of the delays observed for individual ship arrivals at ports. The performance of one carrier was calculated based on all the port calls of the carrier. The actual performance of the string was more complicated, taking the ship CMA CGM Bali on string AEM2 Westbound from COSCO for example (Table 9.1). The calculation of delay days for each link within the string followed the "on-time" standard, considering the actual arrival date as either being the same or minus 1 calendar day of the scheduled date. In this case, the first five links of this string were supposed to be on time with no delay days. The link from Shekou to Singapore arrived one day later than the schedule date but was still supposed to be on time with no delay days. The delays were generated on the last two links from Singapore to Malta and Malta to Valencia. The ship experienced a delay of 4 days in Malta and 5 days in Valencia respectively compared with the planned schedule.

Departure Port	Scheduled Departure	Actual Departure	Arrival Port	Scheduled Arrival	Actual Arrival	Delay (days)
Qingdao	10-Dec-2021	10-Dec-2021	**Busan**	12-Dec-2021	12-Dec-2021	0
Busan	13-Dec-2021	13-Dec-2021	**Shanghai**	17-Dec-2021	17-Dec-2021	0
Shanghai	19-Dec-2021	18-Dec-2021	**Nansha**	21-Dec-2021	21-Dec-2021	0
Nansha	21-Dec-2021	22-Dec-2021	**Shekou**	22-Dec-2021	22-Dec-2021	0
Shekou	22-Dec-2021	23-Dec-2021	**Singapore**	25-Dec-2021	26-Dec-2021	0
Singapore	26-Dec-2021	28-Dec-2021	**Malta**	08-Jan-2022	13-Jan-2022	4
Malta	09-Jan-2022	15-Jan-2022	**Valencia**	11-Jan-2022	17-Jan-2022	5

Table 9.1 Timetable for the string AEM2 Westbound

Following the standard of average delay, the average delay of the link refers to the number of calendar days between the planned schedule and the actual arrival (plus/minus 1 calendar day is not taken into account). Each string consists of several links, and the average delay of each string is calculated by summing all the cumulative delay days in each link and dividing it by the total number of links within the string. For instance, in the provided example (Table 9.1), the cumulative delay of the string was 9 days across 7 links. Similarly, the average delay of the shipping network is computed by the sum of all the delay days that were generated across all links and then divided by the total number of links in the network.

The measuring approach for the delay of the string and the entire network highlighted the fact that the performance of nodes depends not only on their own characteristics but also on the connectivity with other nodes. The purpose of analysing infrastructure from the perspective of network configuration enables insights into the impact of dependency and propagation effects within the network, shedding light on a broader understanding of infrastructure reliability.

9.3.2 Performance of links

The observed database comprised a total of 86 ships belonging to 86 different strings (one ship per string) and the selection procedures were stated in Section 6.3.4. Within the 86 strings, there were 599 links, among which 568 links were operated as scheduled, while 31 links chose to reroute or omit the origin port of call, and thus were not considered when assessing the performance of links. To summarise, 568 links from 86 strings (five shipping companies) constituted the PCSN and were used to investigate the network performance in this research. More specifically, the AIS data of 86 ships within the network in the period of

1 November 2021 – 31 January 2022 was captured to analyse the network performance. This necessitated observing the different AIS position and movement signals of each of the 86 sample ships every day over the three-month period.

The on-time rate of the selected 568 links was only 39.26%. The on-time rate was low, which gave an insight into the bad performance of the PCSN. In comparison, the on-time rate of the global container shipping network during the same time period was reported as 35.8% for the year 2021, provided by Sea-Intelligence. While the on-time rate of the PCSN was slightly higher than the global average, it still remained a low score. This result emphasises that the performance of the container shipping network was not reliable enough, as the carriers were facing serious delay on the entire network scale. Inefficient reliability within the shipping network can be particularly detrimental when facing disruptions as analysed in network vulnerability. Therefore, the forthcoming analysis will primarily focus on examining the **average delay** results, providing further insights into the network performance.

- Links

The average length of links among the network was found to be 6.23 days. The average delay days of all the links among the network (568) was 2.88 days. This implies that each ship, on average, experienced a waiting time of approximately three days at each port of call. Figure 9.1 shows the frequency distribution of delays in each link. What stands out in the figure is that 39.2% of the links managed to arrive on time without any delay days. Roughly half of the links either arrived on time or with one delay day. Over 80% of the links delayed less than 5 days. However, still a small portion of links (7%) encountered delays exceeding ten days. Moreover, six links delayed longer than 20 days.

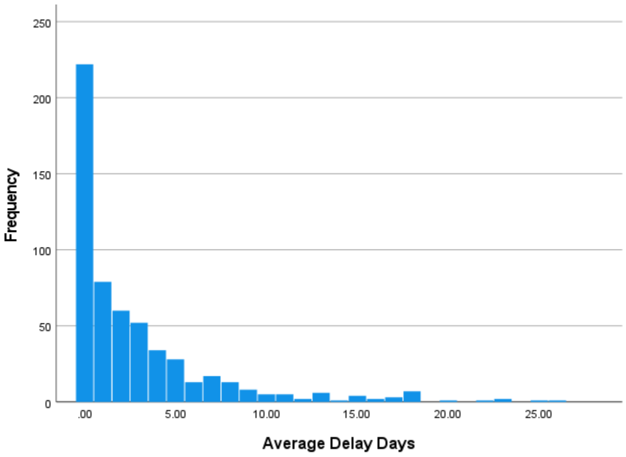


Figure 9.1 Average delay of links in the network

According to the data provided by Sea-Intelligence, the average delay across the global shipping network was 7.72 days in November 2021 and 7.95 days in January 2022. When comparing with the global scale, the on-time rate of the PCSN was similar; however, the average delay days was shorter (1 day less). Despite the overall lack of reliability in the network, ships did not need to wait for such a long time in each port of call on average compared with the global scale.

During the observation, 6 links had long delay days (longer than 20 days), including: CSCL Venus in Piraeus, which was attributed to the strike in Piraeus; Texas Triumph in Shanghai, due to the COVID-19 restriction in China; Ever Grade in Rotterdam, encountered a long time on the voyage to Rotterdam; COSCO Shipping Solar in Piraeus, faced congestion-related issues, likely stemming from the strike; and HMM Algeciras in Antwerp and Rotterdam, with the delay in Antwerp being a consequence of a delay at its origin port, Rotterdam. In summary, the reasons for such a long-time delay were typically caused by disruptions within the network, and with delays generated in the origin port having a knock-on effect on subsequent ports of call.

In Chapter 7, the connectivity reliability of the CSN was examined. The analysis revealed a hub-spoke network structure, wherein a few weighted links accounted for a large share of TEUs in the container shipping networks. Figure 9.2 shows the ranking of the top 15 hub links according to their weight, along with the average delay of the links. Among these 15 links, Tianjin to Busan had the best performance with no time delay, followed by Hamburg to Rotterdam and Nansha to Yantian. The average delay of the remaining important links was over one day. Shanghai to Yantian and Rotterdam to Hamburg had the longest average delay around four days. Throughout the three-month observation period, the link – Shanghai to Yantian – had the weight of 2,875,108 TEUs and the link – Rotterdam to Hamburg – had a weight of 1,872,322 TEUs which indicated that a large number of containers were subjected to delays of around four days. Seven of the 15 links were longer than the average delay of the network (2.88 days): Shanghai--Ningbo; Busan--Ningbo; Shanghai--Yantian; Hamburg--Antwerp; Yantian--Tanjung Pelepas; Qingdao--Busan and Rotterdam--Hamburg. What is striking in this figure is that these hub links accounted for a large share of containers within the network, yet the performance of these links was not as efficient as their important position. With the decreasing reliability of these links, the more containers would be affected.

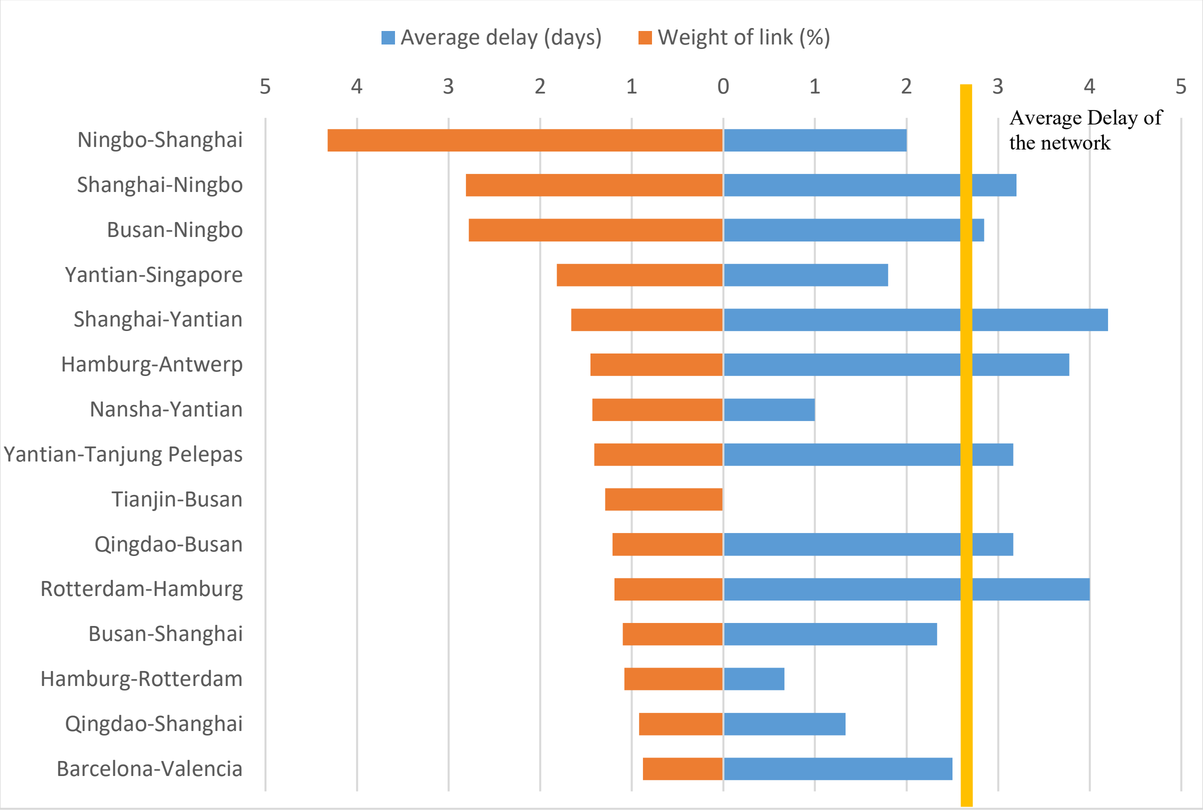


Figure 9.2 Weight and average delay of top 15 links.

- Carriers

The selection of carriers in this research project focused on five major players in the container shipping industry: Maersk, MSC, CMA CGM, COSCO and Hapag-Llyod. Collectively, these carriers accounted for approximately 65 percent of the global container shipping market. The market share was based on the overall TEU capacity deployed on liner trades around the world. The time reliability of each carrier was decided by whether a carrier was engaged in a service or not. If a carrier was engaged in a service, its performance was calculated based on all the links operated by that carrier. However, it is important to note that some of the strings in the shipping networks were jointly operated by more than one carrier. For example, carrier A may provide a service comprising a specific number of port pairs on competing carrier B's string. For these strings, both carriers would receive the same performance results for those services. Figure 9.3 shows the results of average delay and on-time rate of five shipping companies.

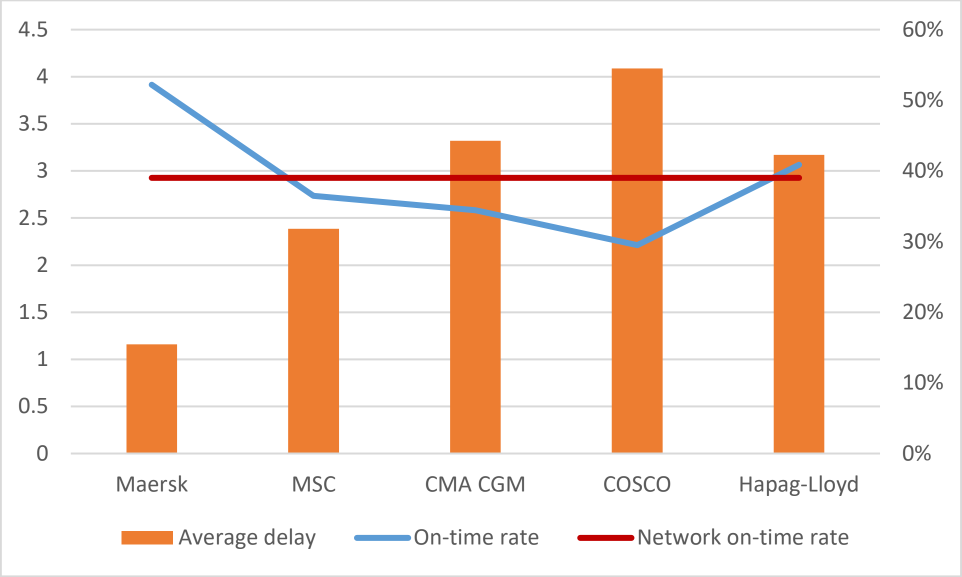


Figure 9.3 Average delay and on-time rate for the five shipping companies

Maersk emerged as the most reliable carrier with the highest on-time rate and the lowest average delay days, on-time performance was 52.2% and average delay was 1.16 days. Followed by Hapag-Lloyd and MSC with an on-time performance of 40.9% and 36.5%, average delay of 3.17 days and 2.39 days, respectively. CMA CGM had an on-time performance of 34.4% and an average delay of 3.32 days. Among the five carriers, COSCO was the most unreliable carrier, with an on-time performance of only 29.5% and an average delay of 4.09 days.

Comparing these carrier performances with the overall network performance, the on-time rate of MSC, CMA CGM and COSCO were all below the on-time performance of the network. Similarly, in terms of average delay, both Maersk and MSC demonstrated lower average delay days than the average delay across the entire shipping network. Although the on-time performance of MSC was not very high, the average delay was quite shorter compared with other carriers (except Maersk). In contrast, Hapag-Lloyd, had a higher on-time performance but longer delays.

9.3.3 Performance of strings

The previous section described the performance of each link within the network, which gave insights into the time reliability of each link and the carriers operating on those links. This analysis aligns with the understanding of network reliability, wherein the nodes and links are integral components of the network configuration, considering their connectivity and the propagation effect of delays. The earlier analysis on the average delay proved that some of the delays were propagated from the previous links. What's new in this research is to further investigate the delay of the string, to explore the differences and comparisons between the performance of links from a micro-level and the entire shipping network from a macro-level. This investigation also cast light on one of the reasons for an unreliable network – the propagation effect within the network. Furthermore, the analysis of network resilience in Chapter 8 showed that the network was quite resilient to some extent due to the actions that carriers took to recover from disruptions. The performance of strings could show the ability of the ships or carriers to catch up with the original schedule, which reflected the ability to recover from disruptions from the perspective of network resilience.

Delay of the string in this project was defined as the delay of the last link within the string. It represented the final performance of ships upon reaching their destination port, taking into account the overall shipping performance. Again, the database included 86 strings from five shipping companies. Figure 9.4 shows the frequency distribution of the delay of the string. The average time length of the strings was found to be 43.36 days. The average delay for each string was 6.45 days. The longest delay appeared in the string French Asia Line 6 Westbound from CMA CGM for 26 days. The average delay of the links, as discussed in the last section was 2.88 days. The result of the average delay of the string (6.45 days) was much longer than the result of the links (2.88 days).

These findings highlight two important considerations when assessing the reliability of container shipping networks. Firstly, the commercial indices for container shipping performance usually measure only the average delay of individual links, which is not accurate enough to capture the reliability of the entire network, as it does not account for the accumulative delay generated across other nodes within the string. Secondly, when measuring the impact of congestion or disruptions, the accumulative delay of the string, i.e., the propagation effect should also be taken into account. Take the blockage of the Suez Canal in 2021, which was introduced in Chapter 8, for example. It took five days to clear and recover from its disruptions; however, for the ships that passed through the canal, it caused a much longer delay than five days in their subsequent ports of call which enhance the importance of assessing the reliability from the entire framework rather than considering only one factor.

Meanwhile, around 19.8% of strings arrived on time to their destination port without any delay, among which, 6 strings arrived on time at the final port but with delays in other ports of call along the string. This observation demonstrates the resilience of the networks, and it will be further discussed in this section.

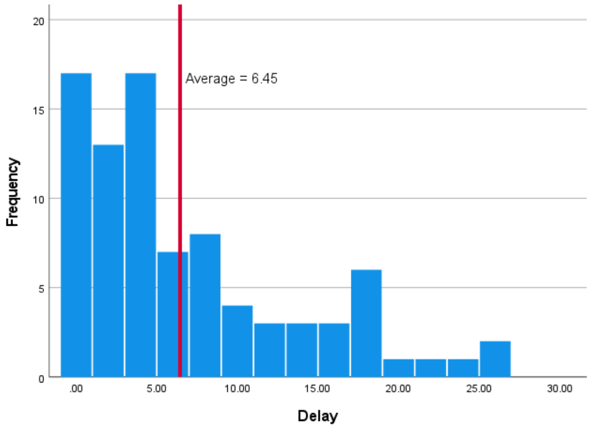


Figure 9.4 Frequency distribution of the delay of the string

Figure 9.5 shows the delay of the strings in five shipping companies. The ranking of the five carriers was the same as the ranking of average delay. Maersk had the shortest delay of the string, followed by MSC, Hapag-Lloyd, CMA CGM and COSCO.

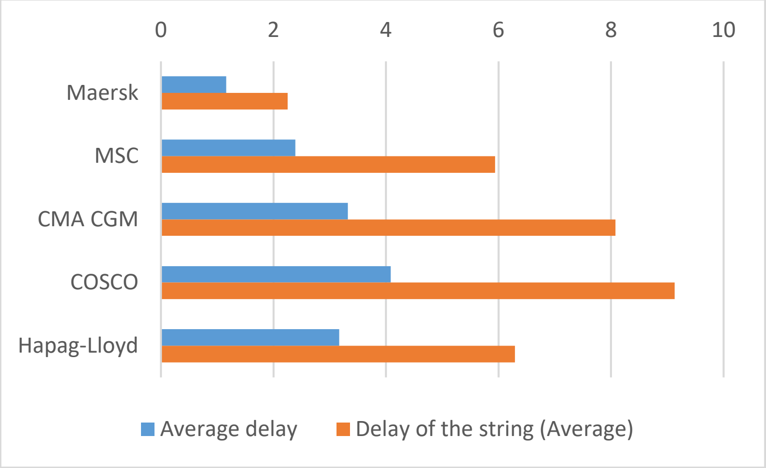


Figure 9.5 Delay of the string in five shipping companies
(Source: Author elaboration based on the average delay results)

With the analysis on the reasons of delay, the strings could be categorised into three domains: increase, decrease and remain. The first domain "increase", which represents the delay of the string, is due to the accumulation of the delay that generates in the previous links. The propagation effects coupled with the network connectivity leads to the spread of congestions, thereby increasing the delay within the string. The second domain "decrease", refers to the strings in which the longest delay is observed in one of the links. However, carriers or ships take actions to recover and catch up the schedule; thus, reducing the delay generated by subsequent nodes within the string. This domain reflects the ability of carriers or ships to effectively recover from disruptions and mitigate the impact of delays. The last domain is where the delay of the string remains the same after initially occurring in one of the links. This domain also includes some strings where the performance of individual links within the string may be slightly different, but the performance of the last link aligns with the majority of the links within the string. The strings falling within this domain could be regarded as less capable but still reliable in any event. Figure 9.6 shows the number of strings with each domain.

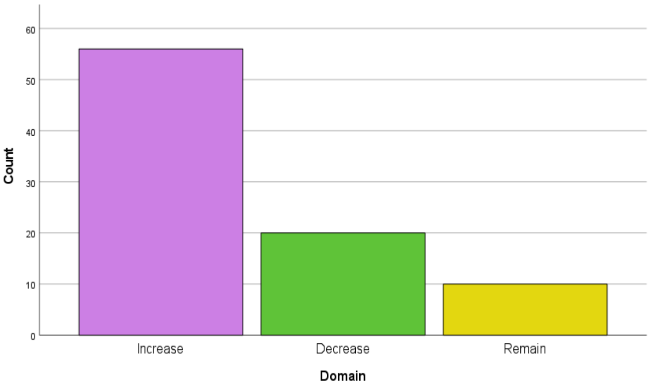


Figure 9.6 Grouping according to the three domains generated by delay of the string.

- Increase

What stands out in Figure 9.6 is the number of strings in the first domain. Approximately 65% of the strings were classified into the first domain, indicating that the spread of delay was still one of the most obvious influencing factors to the performance of the shipping network. Most of the strings were affected by the delays generated in the previous links. The performance of these links within the string usually showed a gradual increase. Take the string Med Express Westbound from CMA CGM for example (Table 9.2), the ship Xin Pu Dong experienced a delay starting from the port of Malta, which then increased gradually until the end of the string. The observation suggested that for most of the strings in the shipping network, the performance reliability is determined not only by the individual performance of each port but also by the configuration of the network – how the nodes are connected in the network and whether the string includes many ports that are vulnerable.

Departure Port	Scheduled Departure	Actual Departure	Arrival Port	Scheduled Arrival	Actual Arrival	Delay (days)
Valencia	15-Dec-2021	15-Dec-2021	**Barcelona**	15-Dec-2021	16-Dec-2021	0
Barcelona	16-Dec-2021	16-Dec-2021	**Genoa**	17-Dec-2021	18-Dec-2021	0
Genoa	18-Dec-2021	19-Dec-2021	**Malta**	20-Dec-2021	22-Dec-2021	1
Malta	21-Dec-2021	23-Dec-2021	**Damietta**	23-Dec-2021	26-Dec-2021	2
Damietta	24-Dec-2021	27-Dec-2021	**Aqaba**	26-Dec-2021	29-Dec-2021	2
Aqaba	27-Dec-2021	29-Dec-2021	**Jeddah**	28-Dec-2021	01-Jan-2022	3

Table 9.2 Timetable for string Med Express Westbound

- Decrease

As shown in Figure 9.6, 23.3% of the links showed a gradual decrease in delay within the string. This domain represents strings where delays initially occurred at one or more ports of call but were subsequently mitigated through actions taken by the ships to catch up the schedule. The example is shown in Table 9.3, FE2 Eastbound operated by Hapag-Lloyd. So, the overall trend within the string displayed a gradual decrease. The analysis in this research project focused only on strings that made calls to the planned ports. During the observation, 31 links were chosen to either reroute or omit the origin port of call due to the disruptions generated within the network. Although these links were not involved when calculating the time reliability (on-time rate), they were involved in this section as omitting or rerouting were actions that a carrier could choose to increase the reliability.

Departure Port	Scheduled Departure	Actual Departure	Arrival Port	Scheduled Arrival	Actual Arrival	Delay (days)
Southampton	19-Dec-2021	20-Dec-2021	**Le Havre**	21-Dec-2021	23-Dec-2021	1
Le Havre	22-Dec-2021	26-Dec-2021	**Hamburg**	27-Dec-2021	28-Dec-2021	0
Hamburg	31-Dec-2021	31-Dec-2021	**Rotterdam**	01-Jan-2022	03-Jan-2022	1
Rotterdam	05-Jan-2022	07-Jan-2022	**Singapore**	26-Jan-2022	30-Jan-2022	3
Singapore	27-Jan-2022	01-Feb-2022	**Shanghai**	08-Feb-2022	08-Feb-2022	0
Shanghai	10-Feb-2022	10-Feb-2022	**Ningbo**	10-Feb-2022	11-Feb-2022	0
Ningbo	12-Feb-2022	12-Feb-2022	**Nansha**	14-Feb-2022	15-Feb-2022	0

Table 9.3 Timetable for the string FE2 Eastbound

More specifically, the performance of each carrier in this domain varied, which represented the ability of different carriers to recover from disruptions to some extent. As shown in Figure 9.7, across the 20 strings in this domain, Maersk accounted for 45% of the strings, followed by CMA CGM (25%), Hapag-Lloyd (20%), COSCO (10%) and no strings involving MSC. It can be estimated from this result that Maersk demonstrated a relatively better ability to recover from delay compared with other carriers. The actions that the carriers take, including speeding up on the voyage to the next port after a generated delay, omit one of the following ports and decrease the waiting time at anchorage. For example, the ship Mette Maersk from Maersk, was delayed for three days in Wilhelmshaven port. Firstly, it decreased the turnaround time in Wilhelmshaven, and it was only two days delayed when it departed from Wilhelmshaven. Then, the delay days were kept to the next port of call: Tangier Mediterranee. It started to speed up on the voyage from Tangier Mediterranee to

Tanjung Pelepas. It arrived only one day behind the schedule which could supposed to be arrive on time. Meanwhile, it only took one hour from anchorage to berth in Tanjung Pelepas, which made the ship departed on time from Tanjung Pelepas. According to the literature review, in terms of connectivity from the perspective of supply chain management, as well as the evidence from the interviews, the reliability of the network highly depends on the information sharing ability and the communications. A reliable carrier has the ability to catch up the schedule and provide better performance.

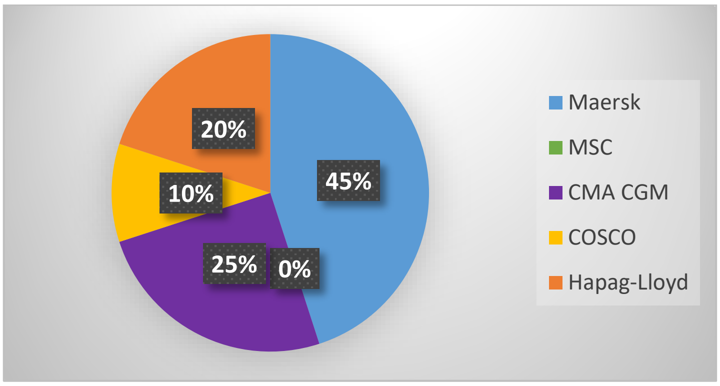


Figure 9.7 Percentage of strings from five shipping companies in a decreasing domain.

- Remain

The last domain is about the performance of each link among the strings remaining steady. The strings in this domain could be further divided into three groups. The first group is all the links within the string arriving on-time without any delay. There were eight strings involved in this group, representing the most reliable performance. None of the links within the string experienced any delay, indicating a high level of performance reliability.

The second group comprises strings with very short delays, which appear in some links irregularly. For example, with the string AE10 Eastbound from Maersk (Table 9.4), among the 8 links, 4 links had a one-day delay. The performance of the entire string was still showing a steady trend. For these strings, although they were less reliable than the strings in the first group because there were still delays in some of the links, they had the ability to catch up the schedule to some extent.

Departure Port	Scheduled Departure	Actual Departure	Arrival Port	Scheduled Arrival	Actual Arrival	Delay (days)
Gdansk	11-Dec-2021	09-Dec-2021	**Bremerhaven**	13-Dec-2021	15-Dec-2021	1
Bremerhaven	15-Dec-2021	15-Dec-2021	**Rotterdam**	15-Dec-2021	17-Dec-2021	1
Rotterdam	19-Dec-2021	19-Dec-2021	**Tanjung Pelepas**	07-Jan-2022	08-Jan-2022	0
Tanjung Pelepas	08-Jan-2022	09-Jan-2022	**Shanghai**	13-Jan-2022	15-Jan-2022	1
Shanghai	15-Jan-2022	16-Jan-2022	**Tianjin**	17-Jan-2022	18-Jan-2022	0
Tianjin	18-Jan-2022	19-Jan-2022	**Qingdao**	20-Jan-2022	20-Jan-2022	0
Qingdao	21-Jan-2022	22-Jan-2022	**Gwangyang**	23-Jan-2022	23-Jan-2022	0
Gwangyang	24-Jan-2022	25-Jan-2022	**Ningbo**	26-Jan-2022	28-Jan-2022	1

Table 9.4 Timetable for the string AE10 Eastbound

The last group in this domain is that delays were generated in one of the links along the string, then the delay days persisted to the destination port. Table 9.5 shows the string Bosphorus Express Westbound operated by CMA CGM. The most significant delay was generated at the port Piraeus for seven days, then the delay days were remained until the destination port. For the strings in this group, they were more reliable compared to the strings in the first domain (increase) since the degree of delay did not increase. However, they were less reliable compared with the strings in second domain (decrease) because they did not have the ability to catch up the schedule and return to usual.

Departure Port	Scheduled Departure	Actual Departure	Arrival Port	Scheduled Arrival	Actual Arrival	Delay (days)
Izmit	16-Dec-2021	15-Dec-2021	Istanbul	16-Dec-2021	16-Dec-2021	0
Istanbul	17-Dec-2021	17-Dec-2021	Constantza	18-Dec-2021	19-Dec-2021	0
Constantza	19-Dec-2021	21-Dec-2021	Odesssa	20-Dec-2021	22-Dec-2021	1
Odesssa	22-Dec-2021	25-Dec-2021	Piraeus	24-Dec-2021	01-Jan-2022	7
Piraeus	25-Dec-2021	01-Jan-2022	Port Said	26-Dec-2021	03-Jan-2022	7
Port Said	27-Dec-2021	04-Jan-2022	Jeddah	30-Dec-2021	07-Jan-2022	7
Jeddah	30-Dec-2021	07-Jan-2022	Port Klang	09-Jan-2022	17-Jan-2022	7

Table 9.5 Timetable for the string Bosphorus Express Westbound

This section introduced the performance of strings based on the developing trend of delay days from three domains: increase, decrease and remain. The strings in the domain “increase” were the most common and unreliable. In contrast, the strings in the domain “decrease” had the ability to catch up the schedule, which could be regarded as the most reliable performance to some extent. These results also confirmed that there were actions and strategies that carriers could use to catch up the schedule so as to improve network reliability. The strings in the domain “remain” were further classified into three groups: all links arriving on time, short delay in certain links, and delay persisting until the destination port. To summarise, the analysis of delay at the string level provided valuable insights into the performance of the entire shipping network, particularly when compared to the average delay at the individual link level. The findings highlighted the significant impact of the propagation effect, which contributed to the worst performance of the entire network.

9.3.4 Performance of nodes

Section 9.3.2 investigated the performance of links based on two metrics: on-time rate and average delay in order to analyse the performance of the entire shipping network. Section 9.3.3 gave new insight for assessing the performance by considering the network configuration. Specifically, the analysis of strings shed light on the propagation effect within the network and its impact on overall network performance. The PCSN established in this chapter, focused on evaluating the reliability of the network’s infrastructure, with particular emphasis on the port infrastructure. Consequently, this section further developed the performance of all the ships in port and provided essential background results to facilitate analyses of infrastructure reliability in ports.

The performance of nodes relied on two metrics: on time rate and average delay of the nodes. The observed database comprised ships from 86 different strings, 568 links and a total of 84 ports of call. The number of ports of call was relatively lower in comparison to the CSN for analysing network configuration reliability and connectivity reliability. This reduction was attributed to certain ships chosen either to reroute or omit the origin port of call during the observation period, resulting in their exclusion from the analysis.

The on-time rate and average delay of nodes were calculated as the average results derived from all the ships that made calls at each respective port. Figure 9.8 shows the distribution of ports according to the on-time rate and average delay. In this figure, the orange node represents the average performance of the shipping network in terms of both average delay and on-time rate. Based on the position of the average node, all the ports of call were categorised into four groups: ports with high on-time rate and low average delay, high on-time rate and high average delay, low on-time rate and low average delay, and low on-time rate and high average delay.

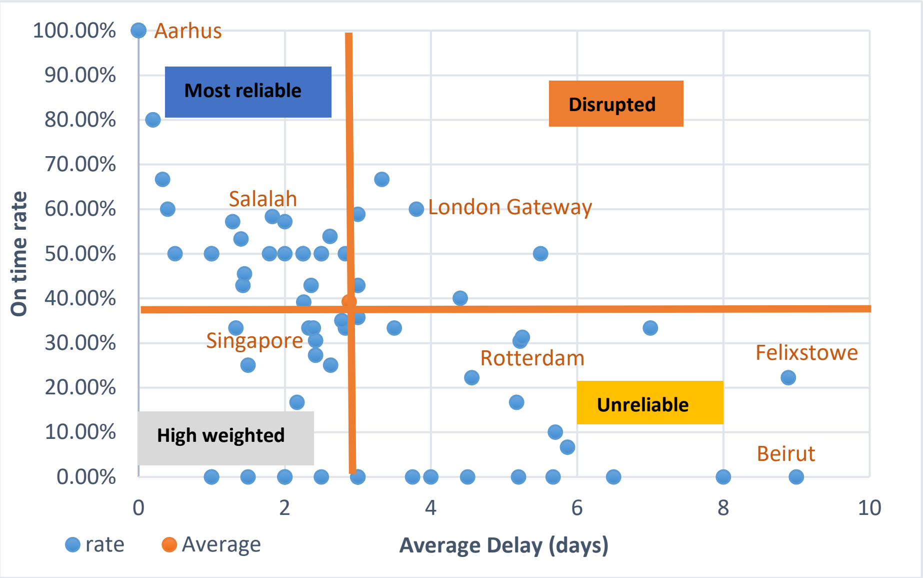


Figure 9.8 Scatter chart based on on-time rate and average delay.

- High on-time rate & low average delay.

The first group comprises ports with high on-time rate and low average delay, which could be regarded as the most reliable nodes among the four groups. There were 39 ports (47%) that were involved in this group, including Jebel Ali, Port Said, Tangier Mediterranee, Nansha, Qingdao, Busan, etc. These ports demonstrate a higher level of reliability in terms of the assessed metrics compared to the other groups. Within this group, the ports can be further classified into two categories according to the number of arrival ships during the observation period: ports with more container ship arrivals (Busan, Jebel Ali, Qingdao, etc.) and ports with less container ship arrivals (Gothenburg, Mersin, Colombo, etc.). Conventionally, traffic volume serves as a fundamental indicator for port congestion. When the number of ships arriving and staying at port increases, the likelihood of congestion and delays also increases, leading to an overall perception of unreliable performance. However, there were still ports with high weight, degree and positioned in the center of the shipping network, providing reliable performance. This suggests that the infrastructure reliability of ports, including factors such as efficiency, utilisation rate and service ability of ports, plays an important role when assessing the performance of ports. These factors have been extensively discussed in the literature review and will be further explored in the following section. There were 47% of ports involved in this domain.

- High on-time rate & high average delay.

Six ports were in this group: London Gateway, Southampton, Hamburg, Tripoli, Koper and Kaohsiung. Despite having a high on-time rate, indicating that a significant proportion of ships could arrive on time, these ports experienced challenges in terms of average delay. The analysis of data revealed that the high average delay was due to few observed ships with very long average delay days, which was either due to the disruptions in previous ports or waiting time at the anchorage influencing the performance results.

The findings from the analysis of ports in this group highlight the importance of considering network vulnerability and the propagation effect. Ports that are more susceptible to disruptions not only affect network connectivity, but also impact the time reliability of the ports themselves. These results provide evidence supporting the significance of understanding the vulnerability of network nodes and their dependency when assessing port performance and overall network reliability.

- Low on-time rate & low average delay.

There were 18 ports (21%) in this group with low on-time rate and low average delay, including: Shanghai, Singapore, Ningbo, Yantian, Jeddah, Wilhelmshaven and so on. Although a significant number of ships experienced delays at these ports, the average delay days were comparatively shorter. It is worth noting that among the ports in this group, the top four ports with very high weighted degree among the network were in this group: Singapore, Shanghai, Ningbo and Yantian ports. When comparing this group with the ports in the first group (high on-time rate and low average delay), many of the ports in this group serve as hub ports with higher weight and degree. The on-time rate of these hub nodes is influenced, to some extent, by traffic volume in the port. Due to their central position within the network and the significant number of ships arriving at these ports, the on-time rate tends to decrease.

- Low on-time rate & high average delay.

This group (21 ports – 25%) involved the ports with most unreliable performance: high average delay and low on-time rate. From a regional perspective, Europe accounts for 60% of the ports in this group, while Asia represents the remaining 40%. Some of the most important nodes in Europe including Felixstowe, Bremerhaven, Rotterdam and Antwerp were in this group. In comparison to other hub nodes around the world, hub ports in Europe demonstrated a lower level of reliability when considering performance. Within Asia, the ports that were in this group were primarily not hub ports including Laem Chabang, Port Klang, Taipei and Xiamen.

9.3.5 Summary

Section 9.3 investigated the performance of the container shipping network. The results revealed that the PCSN, as measured by on-time rate and average delay, was not reliable enough, i.e., the on-time rate was 39.02% and the average delay was 2.88 days. Carriers were facing serious delay. Table 9.6 shows the ranking or time reliability of carriers (1 equals the best).

1	Maersk
2	Hapag-Llyod
3	MSC
4	CMA CGM
5	COSCO

Table 9.6 Carriers ranking for performance.

The assessment and ranking of reliability within the PCSN involved dividing all ports into four groups based on their performance characteristics. Through the observation and analysis of selected ships, the causes of unreliable network performance can be categorised into three domains: the infrastructure reliability of ports, disruptions, and the configuration of the network. The performance of ports, a crucial aspect of infrastructure reliability, is determined by the efficiency of a port's services and the time loss incurred during waiting periods. As highlighted in the literature review, usually turnaround time was used to estimate the infrastructure reliability in port. By enhancing the efficiency and reliability of port infrastructure, time delays can be reduced, thereby improving overall network performance. Section 9.4 will show the turnaround time of each port in order to identify the weak points contributing to the low on-time rate and high average delay observed within the network.

The analysis of the PCSN also showed that container shipping networks operate on a continuous rotation, and container ships make calls to ports in sequence. The design of the string as well as the connectivity of nodes within the network, are important in determining the reliability of links and nodes. For example, the initial links within a string tend to arrive on time with no delay compared with the last few links of the string due to the cumulative delay from the previous links. To overcome this limitation and provide a comprehensive assessment of performance, this research project proposed to estimate the performance of the string from the perspective of the entire shipping network. Additionally, according to the analysis in Chapter 7, the shipping network was highly connected, and the ships could reach their destination ports within a small number of steps. Due to the interconnectivity and network structure, disruptions and delays to important hub ports and shipping services could have rapid and significant impacts across the network. Delay or congestion generated in one node could be due to the performance of other nodes (either directly connected or within the same string). Therefore, the analysis of network reliability should take into account the propagation effect, recognising that the reliability of individual links may be influenced by the reliability of other links or ports within the network.

9.4 Methods for measuring infrastructure reliability

The availability of AIS data offers valuable insights into ship movements within ports, allowing for the analysis of various factors, e.g., the duration of a ship's waiting time for other container ships to vacate a berth. This enables port authorities to identify weaknesses in port operations, enhance infrastructure reliability and deliver improved services to stakeholders.

9.4.1 Infrastructure reliability evaluation indicators

In accordance with the methodology described in Section 6.3.4, the analysis of infrastructure reliability in this research project relied on AIS data. AIS records provide valuable information regarding ship movements within a port, allowing for a dynamic assessment of infrastructure reliability. In the context of this study, a ship within the port is considered a moving object, changing its location over time. To facilitate the analysis, the port was divided into two geographic zones: the anchorage zone and the berth zone. By defining these zones, it became possible to classify ships into five different states based on their location and movement within the ports: move to the anchorage, wait at the anchorage, move from anchorage to berth, moor at berth and move from berth to the next port as shown in Figure 9.9. The ships that did not conform to these states were excluded from this analysis, as some ships waited at the anchorage without moving to berth during the observation.

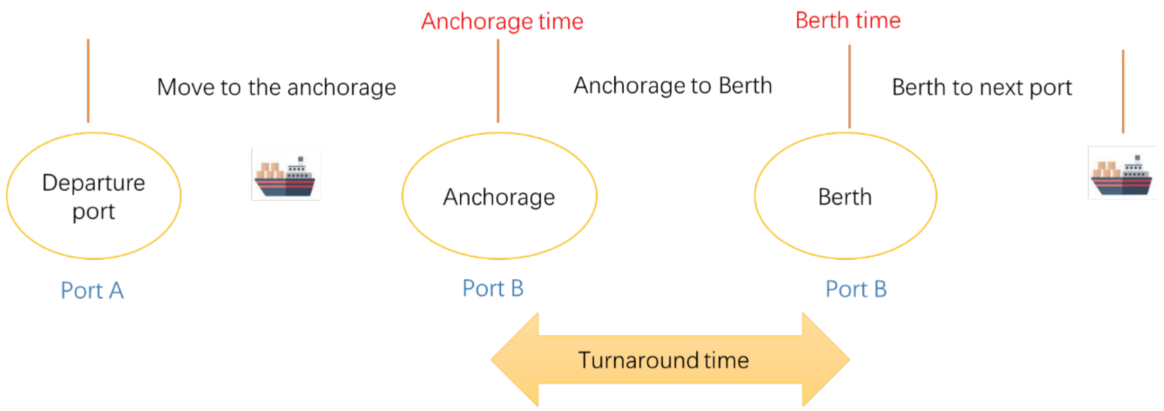


Figure 9.9 States of the observed ships in this research

Within these five states, this research project employed three indicators to analyse the infrastructure reliability: time at anchorage, time at berth and turnaround time. Each of these indicators provides insights into different aspects of port performance and efficiency. Time at anchorage refers to the state when the ship is recorded to enter the port area until the point at which the ship departs from the anchorage zone to sail to the berth area. This indicator captures the waiting time experienced by a ship before it proceeds to the berth. Time at berth refers to the state when the ship is moored at the berth and before it leaves the berth. Time at berth provides insights into the efficiency of port operations. Turnaround time refers to the sum of the two indicators (anchorage time and berth time). That is the total time that a ship takes to complete all activities in a port, which represents the entire efficiency of ports.

The identification of ship states in this research was based on the analysis of ship speed and position. Ships with a speed of below 5 knots were categorised as entering the anchorage area for waiting. A speed of 5 knots was chosen based on the observation that some ships employed slow steaming directly to their berth without a specific time for waiting without engine power (speed 0). This practice was particularly common for ships heading to ports such as Shanghai and Ningbo on the east coast of China. By examining the speed data in relation to the position of the anchorage area, the researcher calculated the time at which ships entered the anchorage zone. Since AIS data can track even very low speed movements, after leaving the anchorage area, the ships with a speed of lower than 1 knot were identified as moving without engine power, indicating that they had already transitioned from the anchorage area to berth. Those ships at berth are supposed to be in activities, e.g., load-discharge.

In this research project, the time that ships spend for mooring at berth and waiting at anchorage is computed based on the trajectory segments. This analysis aims to evaluate the efficiency and potential issues related to port infrastructure. By examining the duration of ships' different states within a port, valuable insights can be gained regarding the efficiency and availability of ports. In order to analyse the time spent in each state, several statistics were taken for assessing the reliability:

- Min/Max: The minimum and maximum time of the ship spent in one state. Range = Max-Min. A smaller time range suggests that a port can handle ships with a smaller time fluctuation. In other words, it indicates that time efficiency is more consistent and reliable.
- Mean: The average time that the ship spent in each state. A smaller mean value implies that the ship spends less time in that state which represents a more efficient service or a smaller volume of containers to be loaded or discharged.
- Standard deviation: This is computed to reflect how far the time is dispersed around the mean. Similar to Min/Max, it can be used to analyse the consistency of port operation. A smaller standard deviation indicates that the variance is relatively small compared to the mean. This statistic can be used to analyse the consistency of port operation with respect to time efficiency.
- Minutes per container move: This refers to the average time that a container needs for handling. This statistic is used for analysing the handling efficiency when ships are at berth. As the mean introduced above, could be affected by the number of containers that the ship brings, the minutes per container move provides a more accurate number for analysing the infrastructure efficiency.

We expect a more reliable port to have a more efficient operation, with less time and higher consistency of total time.

9.4.2 Assessment of turnaround time

The analysis of the time that ships spend in ports is a vital part in assessing infrastructure reliability. It is expected that a more reliable performance corresponds to a shorter time in port and higher consistency of the total time. This section is going to introduce the turnaround time in selected ports and the impact of turnaround time.

Based on the computed turnaround time results, ports were ranked according to their turnaround time from shortest to longest, obtaining a scale from best to worst. All the ports included in this research were divided into five groups based on their ranking – group 1: most efficient (0-24%), group 2: efficient (25%-49%), group 3 inefficient (50%-74%) and group 4 most inefficient (75%-100%). The percentage represents the ranking of ports according to turnaround time. The number in red represents the longest time in the category, while the number in green represents the shortest time in the category. To facilitate visual representation, a colour scheme corresponding to a temperature scale was assigned to each group as indicated in Table 9.7.

Group	Name	Colour
1	Most efficient	🟩
2	Efficient	🟦
3	Inefficient	🟨
4	Most inefficient	🟥

Table 9.7 Temperature scale for ranking turnaround time.

In preparation for the subsequent analysis of individual nodes within the network, a correlation analysis was conducted to examine the relationship between the turnaround time and the performance of each node, which was discovered in Section 9.3.4. The result is illustrated in Figure 9.10, rate in the figure refers to the on-time rate and delay refers to the average delay of nodes analysed in Section 9.3.4. The nodes were divided into two categories. The blue nodes represented the four groups, divided according to the on-time rate and average delay (high on-time rate and low average delay, high on-time rate and high average delay, low on-time rate and low average delay, and low on-time rate and high average delay). The size of the blue nodes depended on the number of ports in each group. The yellow nodes represented the four groups divided according to the turnaround time in port. The links that connected two categories referred to the ports in the first category also involved in the second category. The weight of the link was determined by the number of ports associated with that connection.

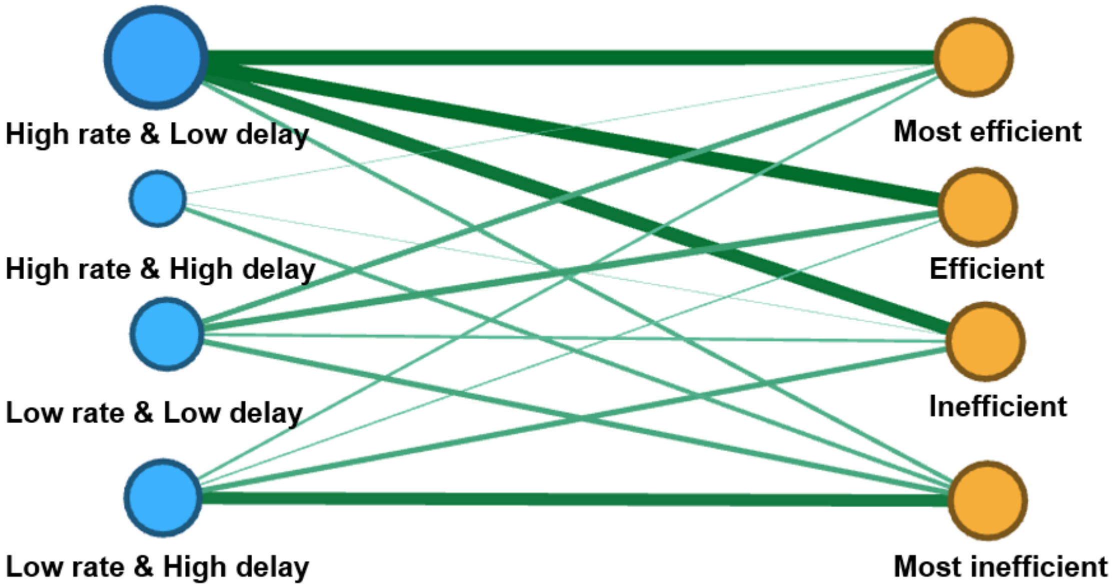


Figure 9.10 Correlation between turnaround time and port performance.
(Source: Author based on the turnaround time analysed in this section, visualised by Gephi)

The ports in the group "high on-time rate & low average delay" represented the most reliable ports within the container shipping network. These ports demonstrate a relatively efficient performance in terms of providing reliable services. The most weighted links were connected with the most efficient performance (31% of the ports in this group), e.g., Salalah and Port Said, and efficient performance (33%), e.g., Jebel Ali and Tangier Mediterranee, followed by inefficient (28%) – only two reliable ports were found in the most inefficient group. The ports with lower efficiency but still maintain a high level of reliability share a common characteristic: they serve as feeder ports with fewer arrivals. Although the service time is long, their accessibility could be guaranteed; thus, contributing to their overall reliability. The reliability was affected by both efficiency and accessibility of port infrastructure.

The group "high on-time rate & high average delay" had the smallest number of ports and these ports were regarded as facing disruptions during the observation, e.g., London Gateway and Southampton. The observed delay in these ports could be attributed to disruptions that occurred in previous ports along the string, as well as disruptions specific to the calling port itself. The majority of ports in this group had a most inefficient performance in which long waiting time was the main reason.

The group “low rate & low delay” primarily consisted of hub ports as analysed in Section 9.3.4. Most of the ports in this group had quite an efficient performance. 28% of the ports in this group had a most efficient performance, e.g., Jeddah. 33% of ports had a relative efficient performance, and most of the hub nodes with high degree and weight were in this group, such as Singapore, Yantian and Shanghai. Around 17% of the ports in this group were regarded as ports with inefficient performance, e.g., Sines and Ningbo. Only two ports in this group – Le Havre and Valencia – exhibited the most inefficient performance. From this group, we can observe the characteristic of most of the hub ports. Despite handling a large number of ship calls, these ports maintained short turnaround time, resulting in reduced delay. However, the high volume of ship calls can adversely impact infrastructure accessibility, contributing to a lower on-time rate. It is worth noting that some hub ports were located at the end of a string, which can further challenge their on-time performance.

The last group consisted of ports with a low rate and a high delay which were regarded as the most unreliable ports. The majority of the ports (53%) in this group were identified as having the most inefficient performance, followed by a subset of ports classified as inefficient ports (24%). The ports classified as unreliable were typically characterised by inefficient infrastructure performance, and vice versa.

The findings presented above proved, to some extent, the relationship between port performance and infrastructure reliability in port. Infrastructure reliability, in the context of this study, is reflected in the time spent by ships in port. The results indicate that the ports with higher infrastructure reliability intended to have better performance. Conversely, for the worse performing ports, most of them were in the most inefficient group, suggesting that improving their efficiency could enhance their reliability to some extent.

Table 9.8 provides a detailed overview of 20 ports, which includes the average ship size, the average turnaround time (both at berth and at anchorage) and their corresponding group according to the temperature scale introduced earlier (1 equals the most efficient).

Port	*Average vessel size (TEU)*	*Average Waiting Time (Days)*	*Average Handling time (Days)*	*Average Turnaround time (Days)*	*Group*
Shanghai	17,275	0.39	1.33	1.72	2
Ningbo	17,878	0.98	1.49	2.47	3
Singapore	16,204	0.28	1.23	1.51	2
Yantian	19,219	0.57	1.02	1.58	2
Rotterdam	17,471	1.08	2.88	3.97	4
Busan	17,086	0.41	1.39	1.80	3
Tanjung Pelepas	18,033	0.35	1.15	1.50	2
Qingdao	18,775	0.56	1.39	1.95	3
Hamburg	16,325	1.27	2.93	4.20	4
Tianjin	18,831	0.28	1.34	1.62	2
Antwerp	17,352	2.50	2.23	4.74	4
Tangier Mediterranee	13,558	0.66	0.91	1.58	2
Port Said	11,326	0.26	0.95	1.21	1
Piraeus	14,861	3.43	1.27	4.70	4
Bremerhaven	15,565	1.43	2.15	3.58	4
Jeddah	9,606	0.18	0.63	0.81	1
Nansha	16,934	0.39	1.18	1.57	2
Felixstowe	17,581	1.88	4.43	6.31	4
Xiamen	15,362	0.72	1.31	2.02	3
Hong Kong	15,563	0.28	0.78	1.06	1

Table 9.8 Top 20 ports (with the highest weight), time in port and average ship size

The results of turnaround time were then loaded into the results of network analysis and visualised by Gephi. Figure 9.11 shows the configuration of the shipping network; the colour of nodes represents the group according to their turnaround time, the size of nodes varies according to the total weight of links to and from the node, and the size of links varies according to carried TEUs. The network analysis results revealed that some of the important nodes within the network (with higher weight) had a very efficient performance, such as Port Said, Jeddah and Hong Kong. Most of the ports with higher weight had an average performance, such as Shanghai, Ningbo and Singapore. However, some ports acting as important hub nodes had bad performance, including Rotterdam, Hamburg and Antwerp, these ports acted as important hub nodes carrying a large number of containers but had an inefficient performance.

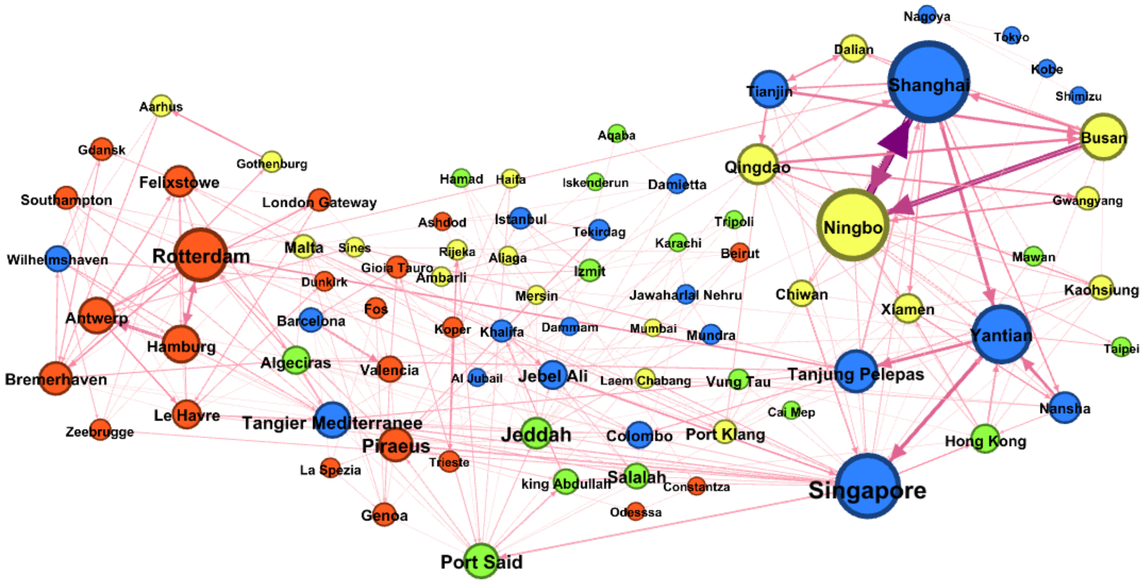


Figure 9.11 Turnaround time with a combination of network configuration.
*The size of nodes varies according to the total weight of links to and from the node and the size of links varies according to carried TEUs. The colour of nodes represents the turnaround time in port.
(Source: Author based on the turnaround time analysed in this section and the network configuration, visualised by Gephi)

In addition, when considering the infrastructure reliability at the network level, the inefficient performance of a port could affect the performance of the ports that tightly are connected with it as well as the entire shipping network due to the connectivity and network configuration. An example of this is observed in the case of Rotterdam, where the long turnaround time directly impacts the efficiency of ships in port. This inefficiency, in turn, extended its influence to closely connected ports, such as Antwerp, Hamburg and Bremerhaven; thus, affecting their respective performance. Conversely, the performance of Rotterdam is also influenced by the performance of these ports. In addition to the European ports, the connectivity analysis reveals that ports in Asia, specifically Singapore and Tanjung Pelepas, have significant weighted links with Rotterdam. This implies that the bad performance of Rotterdam can propagate through the network, impacting Asian ports as well. Similarly, the long turnaround time in Felixstowe is closely connected with ports like

Antwerp and Hamburg. These ports, in turn, have strong connections with Le Havre and Rotterdam. Thus, the unreliable performance in Felixstowe would finally lead to a negative performance in ports such as Le Havre and Rotterdam. The most weighted links in Southern Europe are the links between Barcelona, Valencia and Piraeus. While Barcelona demonstrates better performance compared to Valencia, the links connecting Valencia to Barcelona can be affected by the inefficient performance of Valencia. Additionally, Piraeus experiences a considerably long turnaround time. As an essential transhipment node, the performance of ports such as Singapore, Rotterdam and King Abdullah can be influenced by the inefficient performance of Piraeus.

When representing turnaround time of ports on a map, the most obvious result was the difference between Asia and Europe. Figure 9.12 illustrates the geographical distribution of highly weighted ports with their turnaround time on the map. Compared with nodes in Asia, the hub nodes in European countries usually had deficient performance, highlighting a significant regional imbalance. It could be estimated that the inefficient performance of ports in Europe affected the performance of the entire region, which could further affect the entire shipping network. Infrastructure reliability in Europe could be recognised as a matter of concern within the network.

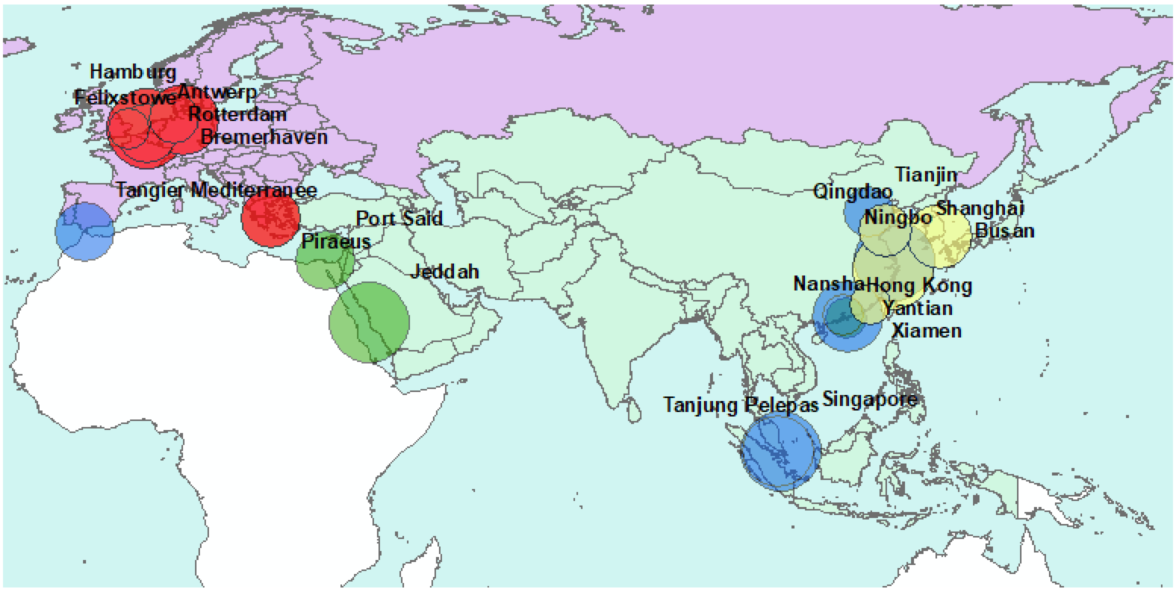


Figure 9.12 Distribution of highly weighted ports with turnaround time.
(Source: Author elaboration based on ArcGIS)

In addition to examining the nodes within the network, this research also investigated the performance of links. Figure 9.13 presents 20 links with the highest weight, accounting for up to 30% of the total weight within the network. In accordance with the calculation method of weight of link, the performance of the link was calculated by the connected ports, representing the average performance of both the origin and the destination port. The average results were then compared to the maximum score and ranked within four groups. The colour of the bar corresponds to the group standard introduced at the beginning of this section – green for most efficient, blue for efficient, yellow for inefficient and red for most inefficient. The figure clearly showed the performance of hub links within the network. Within the hub-spoke network structure, all of the top 20 hub links did not have very efficient performance in terms of their turnaround time. Only seven achieved efficient performance, while ten links were supposed to be inefficient, and three links were considered as most inefficient. As investigated in the network connectivity reliability, a few weighted links accounted for a large share of TEUs in container shipping networks, that is, the network depended on a few links. However, these few links did not have an efficient enough performance to support the entire shipping network. The container shipping network between Asia and Europe relied on a few hub links with unreliable infrastructure performance. Considering the network connectivity and structure, not only would the connected ports be affected, but all the other strings within the network that used these links to operate would also be affected. The impact of performance from the perspective of network connectivity will be introduced at a later stage.

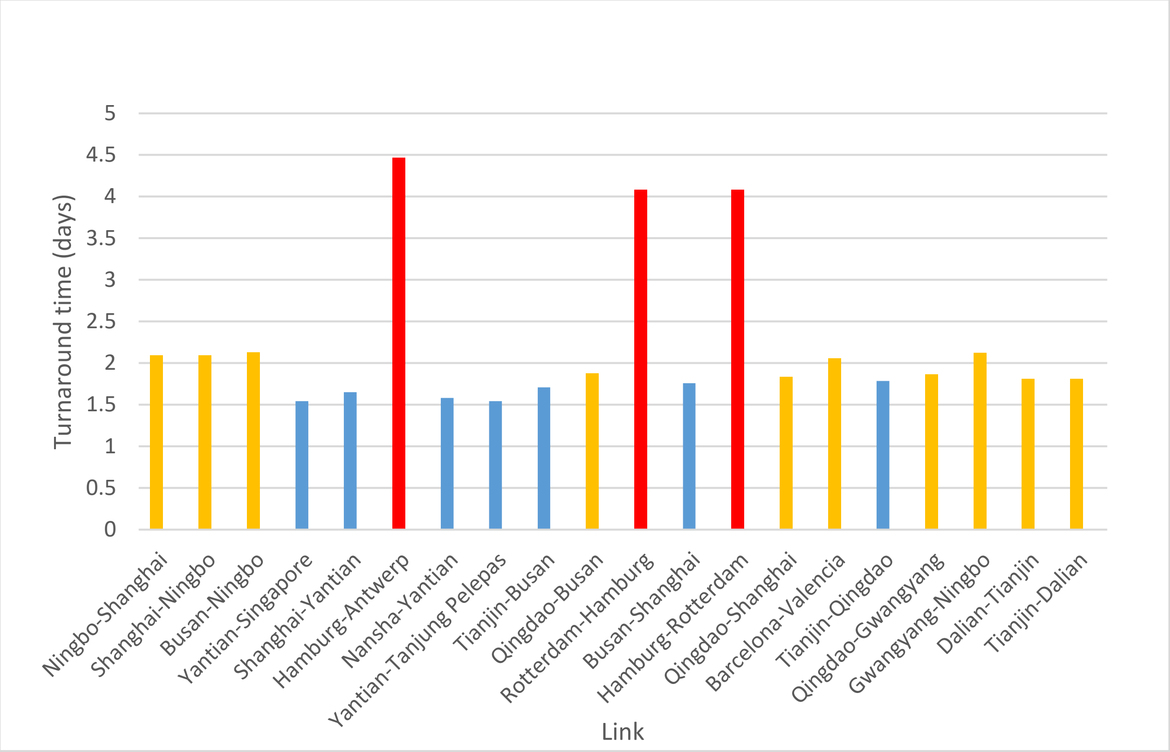


Figure 9.13 Turnaround time of the top 20 weighted links

(Source: Author's calculation based on the performance of both ports on the weighted links)

9.4.3 Assessment of berth time

The estimation of port infrastructure reliability, with a specific focus on infrastructure efficiency, was based on the analysis of berth time. The berth time was defined as the duration between a ship's arrival at berth and its departure from the berth. As discussed in the previous section, the berth time data was collected through the observation of 86 ships within this study. The berth time was computed to assess the port efficiency according to four indicators identified in Section 9.3.1: max/min, mean, coefficient of variation and minutes per container move. The time of each involved port was calculated according to the indicators, Table 9.9 shows the results of the top 20 ports with highest weight (more containers arrived).

Port	*Mean (day)*	*Min (day)*	*Max (day)*	*Range*	*SD*	*Minutes per container move*	*Average container carrying capacity (TEUs)*
Shanghai	1.33	0.33	2.58	2.25	0.43	0.28	17,275
Ningbo	1.49	0.59	2.67	2.08	0.48	0.3	17,878
Singapore	1.23	0.33	2.46	2.13	0.44	0.27	16,204
Yantian	1.02	0.28	2.05	1.77	0.45	0.19	19,219
Rotterdam	2.88	1.50	5.04	3.54	1.10	0.59	17,471
Busan	1.39	0.20	2.67	2.47	0.66	0.29	17,086
Tanjung Pelepas	1.15	0.46	1.75	1.29	0.37	0.21	18,033
Qingdao	1.39	0.18	2.24	2.06	0.57	0.27	18,775
Hamburg	2.93	1.25	5.92	4.67	1.37	0.61	16,325
Tianjin	1.34	0.50	2.34	1.83	0.81	0.26	18,831
Antwerp	2.23	1.17	4.33	3.17	0.83	0.46	17,352
Tangier Mediterranee	0.91	0.37	1.54	1.17	0.38	0.24	13,558
Port Said	0.95	0.16	1.71	1.55	0.42	0.3	11,326
Piraeus	1.27	0.50	2.33	1.83	0.59	0.31	14,861
Bremerhaven	2.15	0.42	3.63	3.21	0.90	0.5	15,565
Jeddah	0.63	0.16	1.42	1.25	0.35	0.24	9,606
Nansha	1.18	0.63	2.42	1.79	0.72	0.25	16,934
Felixstowe	4.43	2.42	7.08	4.66	1.92	0.91	17,581
Xiamen	1.31	0.29	2.05	1.76	0.55	0.31	15,362
Hong Kong	0.78	0.37	1.62	1.25	0.46	0.18	15,563

Table 9.9 Berth time and statistics results of 20 ports.

9.4.3.1 Efficiency analysis

This project employed the mean value as a measure to estimate the average time of ships that moored at berth, serving as an indicator of handling efficiency. A smaller mean value implies less handling time, which suggests a more efficient operation. The average at berth time of the selected ports was 1.54 days. Figure 9.14 shows the distribution of berth time. The figure had a long tail, which illustrated that the berth time was positively skewed. The ranking of time was led by Jeddah, Salalah, Tangier Mediterranee, Port Said and Jebel Ali. Ports in Asia among the top 20 ports were all below the average handling time. Conversely, ports in Europe, such as Hamburg, had the longest at berth time (2.93 days), followed by Rotterdam (2.88 days) and Genoa (2.57 days). The longest time in port was most evident among ports in Europe. All the ports in Europe that are among the top 20 ports were over the average at berth time (Rotterdam, Antwerp, Bremerhaven and Felixstowe). Although larger container volumes may contribute to longer mean and median values, it is worth mentioning that ports with significant container throughput, such as Shanghai and Singapore, still demonstrated more positive performance in terms of at berth time.

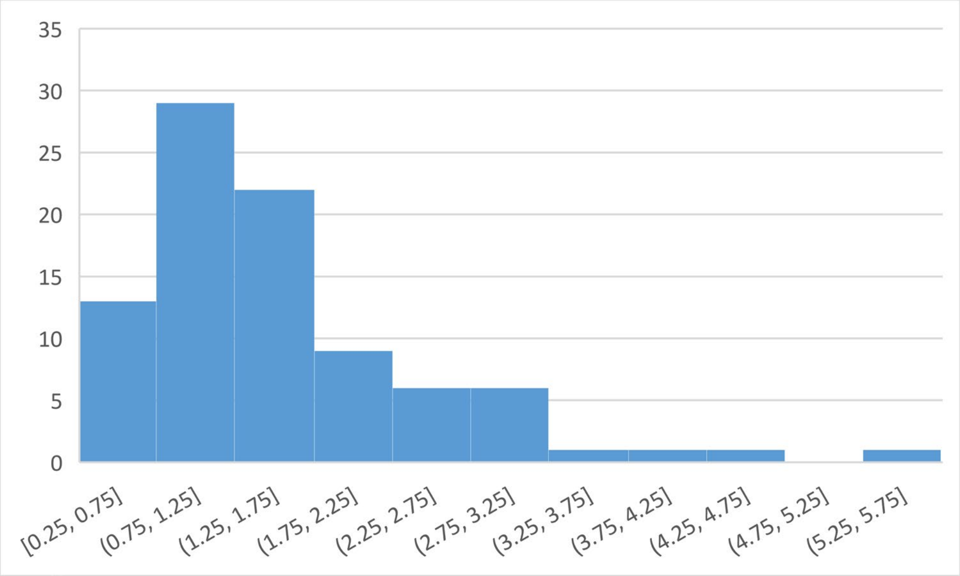


Figure 9.14 Frequency distribution of berth time

In order to provide better visualisation and connect the infrastructure reliability with the container shipping network, the at berth time was firstly grouped into 5 groups: 4+days (including 4); 3-4 days (including 3); 2-3 days (including 2); 1-2 days (including 1); less than 1 day as shown in Table 9.10.

Group	Colour
4+days	🟥
3-4 days	🟧
2-3 days	🟦
1-2 days	🟨
less than 1 day	🟩

Table 9.10 Temperature scale for ranking the berth time.

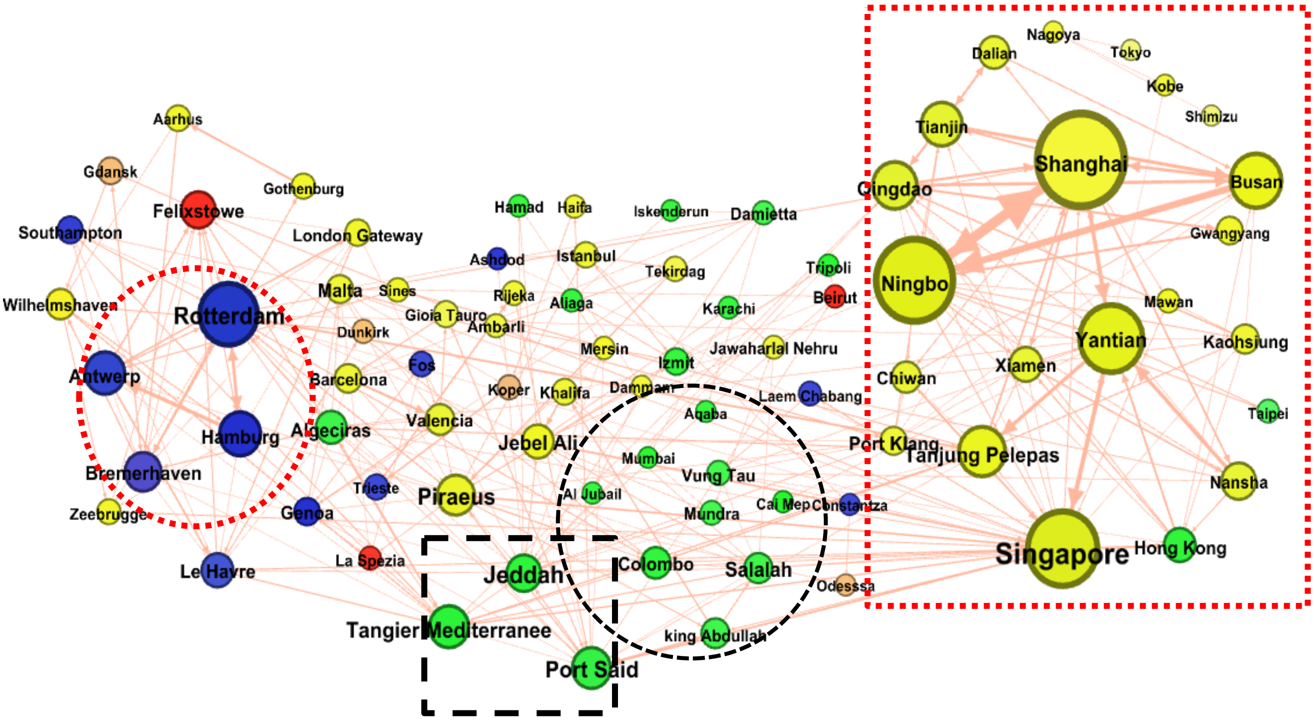


Figure 9.15 Berth time within the network.
(Source: Author based on the at berth time analysed in this section with network configuration, visualised by Gephi)

Figure 9.15 presents the visulisation of berth time within the network; the size of nodes in the figure varies according to the total weight of links to and from the node, the size of links varies according to carried TEUs and the colour of nodes represents the berth time in port. It was obvious from the figure that ports in Asia (on the right side) had a more efficient performance, and most of the nodes were between 1 and 2 days. Important hubs in this area (Shanghai, Singapore, Ningbo, Yantian, and Tanjung Pelepas) had an efficient performance, despite their greater share of larger ships with more containers to handle in these nodes. In contrast, ports in Europe (left side) had a deficient performance, such as the main hub ports in Europe: Rotterdam, Antwerp, Hamburg, Bremerhaven and Le Havre. The visual representation highlights the need to address the performance and infrastructure efficiency between ports in Asia and Europe within the network. Efforts to improve the performance and reliability of ports in Europe, especially the hub nodes are crucial for achieving a more balanced and efficient container shipping network.

The ports with the shortest handling time were mostly of the feeder ports connecting the hub ports in Asia and Europe (nodes involved in the black circle in Figure 9.15), i.e., the nodes in Saudi Arabia and the United Arab Emirates had efficient performance. This observation raises a question regarding the influence of the scale of port on the time spent at berth. There is no doubt that the time ships spend at berth is affected by the carrying capacity of ships – larger ships with more containers to load or unload will need longer time for operations. These ports typically experienced lower ship arrival frequencies and accommodated smaller ship sizes. Ports that receive a greater number of port calls tend to handle larger ships, which in turn, can contribute to operational constraints and longer handling time.

When considering only the ports with higher weight and degree, Jeddah, Port Said, Tangier Mediterrannee and Hong Kong were the hub ports with very efficient at berth time (ports in the black square in Figure 9.15). However, as shown in Table 9.9, in comparison to other ports with highest weight, Jeddah, Port Said and Tangier Mediterrannee had relatively smaller average container carrying capacity, that is, there were usually small ships operated in these ports. Again, smaller ships with fewer containers to be loaded or unloaded would normally require shorter time for handling compared with other hub ports with larger ships. Hong Kong did not have such a small average container carrying capacity, but it was the port with the least weighted degree among all the hub ports.

Among the hub nodes within the network, the majority of ports had an at berth time of longer than two days. However, when comparing the ports with similar port call size and average ship size, the results of time were still different. Certain ports demonstrated remarkably fast handling time despite accommodating a high number of port calls and larger container ships. For instance, Shanghai had a handling time of 1.33 days, Singapore 1.23 days and Ningbo 1.49 days. Yantian port in China, stood out as the most efficient port, with very short handling time (1.02 days) and the largest average ship size (19,219 TEUs). These efficient ports benefit from economy of scale and investment on infrastructure, so that their efficiency increases and in turn attracts more vessels (UNCTAD, 2021). Although the number of calling ships and the average ship size in these ports would typically need longer handing time, the minutes per container move provides insights into the handling efficiency independent of average ship size. Table 9.9 above also provides the minutes per container move of the top 20 ports (according to weight), which is calculated based on the total number of containers carried by each ship. Due to the limitation of information, this research was not able to get the actual data regarding the loading factors of each ship or how many containers would be loaded or unloaded in each port which is a topic that perhaps could be addressed in future research. A comparison of the minutes per container move across ports of different sizes reveals the infrastructure reliability of hub nodes, particularly those benefiting from economies of scale. The following groups can be identified based on the minutes per container move. The first group consisted of hub ports with a large ship size and a large number of calling ships. The second group consisted of feeder ports with high efficiency, which was indicated in previous sections, along with smaller ship size and less weight compared with the hub nodes. The last group consisted of hub ports in Europe, which were recognised as ports with longer berth time. The minutes per container moves are shown below:

- Group 1: Shanghai (0.28), Ningbo (0.3), Singapore (0.27) and Yantian (0.19).
- Group 2: Salalah (0.28), Mundra (0.31), Hamad (0.39).
- Group 3: Rotterdam (0.59), Hamburg (0.61), Antwerp (0.46).

From the result, it was obvious that the hub nodes in group 1 required shorter time to load and unload one container compared with the ports with shorter average at berth time in group 2. This finding demonstrates a non-linear relationship between the number of port calls and the average at berth time in port, which also reminded us of the importance of assessing the average time when comparing infrastructure reliability. Ports with a higher number of port calls can accommodate larger ships, which, in turn, require more time for handling due to the greater number of containers involved. Nevertheless, well-equipped hub ports with higher infrastructure reliability are capable of maintaining efficient operations despite handling larger ships. However, there were still hub ports with a large number of ships but less reliable infrastructure as observed in the last group. The minutes per container move in this group was almost twice than that of the ports with similar size in group 1. The berth time of these ports was no doubt much longer than other ports within the network due to the weighted degree and infrastructure reliability. If the infrastructure reliability in these ports increased, the entire performance of the European part of the network could improve significantly.

The longer handing time makes the other ships wait for a longer time in port, thereby exacerbating congestion as a consequence. Meanwhile, when considering the network configuration, inefficiency in one port could have a negative impact on the ports connected with it, and the impact of congestion may spread. Given the high connectivity of the container shipping network, the reliability of infrastructure in each port was essential to the entire network. This is the reason why congestion not only takes place in busy environments. In order to ensure the reliability of the network, the port with longer handling time and less efficiency performance should not be put in the centre of the network. More efficient ports could attract more ships and become the centre of the shipping network.

9.4.3.2 Consistency

The statistics range (Max-Min) and standard deviation were used to estimate the consistency of berth time, which showed the reliability of ports from the perspective of whether they could provide reliable service in a consistent period. The range was calculated based on the minimum and maximum at berth time of the ship. A smaller time range suggests that a port could handle ships with a smaller time fluctuation. The results of time range showed:

- Hamburg, Felixstowe, London Gateway and Trieste had the largest time range which was longer than four days.
- Followed by Genoa, Rotterdam, Valencia, Beirut, Bremerhaven, Antwerp and Fos, with the results between three and four days.
- Some of the efficient hub nodes were within the range of two to three days: Kaohsiung, Southampton, Koper, Busan, Le Havre, Ambarli, Rijeka, Shanghai, Singapore, Ningbo, Qingdao, Wilhelmshaven.
- Most of the nodes (75%) had a range of less than two days, around 50% of the nodes had a range less than one day.

The standard deviation is computed as how far a set of time spans is dispersed around the mean. Similar to the results of time range, a smaller standard deviation value indicated that the variance is relatively small compared to the mean, indicating a more consistent service. Felixstowe, Trieste, London Gateway and Hamburg still had the highest value, suggesting that these ports were not reliable enough to provide consistent services. The results of both time range and standard deviation showed that most of the nodes in the network could provide a consistent service. The performance was not affected much within a long time period. When analysing the ports that had a large range and standard deviation, there were basically two factors that decreased the reliability of infrastructure: one was the ability of handling large ships, as ports encountering difficulties in efficiently managing larger ships experienced increased variability in their service time. The second was the disruptions in port.

Figure 9.16 provides a comparison of the ship at berth time between two ports: Hamburg and Shanghai. The two ports were the highest weighted ports in Asia and Europe, respectively; however, the efficiency and consistency performance of the two ports were different. When considering the consistency, the distribution of at berth time in Hamburg varied greatly compared with Shanghai. The figure clearly illustrates that the at berth time in Shanghai is consistently lower than that of Hamburg across all ship sizes. This observation aligns with the findings discussed in the previous section regarding efficiency. Further analysis by distinguishing ships according to their size reveals interesting patterns. For ships below 10,000 TEUs, the handling time in two ports was relatively similar. When the ship size increased to around 15,000 TEUs, the time in Hamburg started to rise, and the time in Shanghai remained relatively consistent. As ship size reached 20,000 TEUs, the gap widened. The highest handling time in two ports was found to be associated with similar ship sizes, 20,150 TEUs in Hamburg and 20,988 TEUs in Shanghai, yet the berth time was around 5 days and 3 days, respectively. The increase in time was relatively small in different ship sizes in Shanghai port compared with Hamburg. These results indicate that the reliability of port infrastructure, particularly in terms of its ability to handle large size ships, plays a crucial role in determining the range (as indicated by Min and Max time) and standard deviation of a consistently efficient port performance.

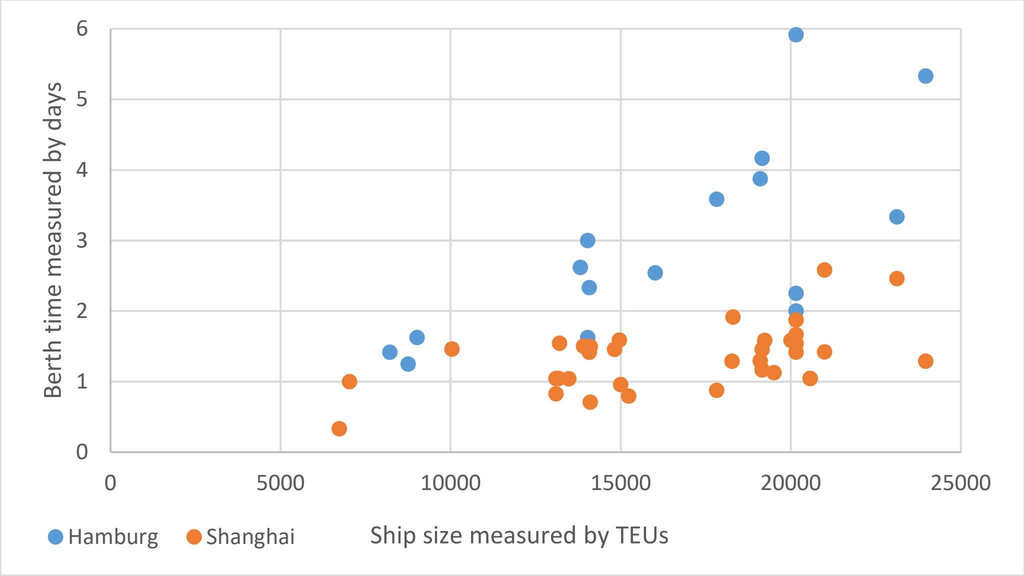


Figure 9.16 Comparison of ship at berth time in Hamburg and Shanghai

The other factor that affected the consistency of port performance was the disruptions in ports and the ability to recover, which could be defined as the resilience of a port. For some ports, the higher range and standard deviation could be attributed to several ships with very long berth time in a similar period. Take the port Felixstowe as an example, two observed ships: namely MSC Amsterdam and MSC Melatilde, had a longer time at berth (7.08 days and 6.83 days); thus, contributing to the high standard deviation result of Felixstowe. These extended berth times occurred in February 2022 as a result of the storm Eunice, which caused port closures, bottlenecks and widespread disruptions within the entire shipping industry, the impact lasted for some time. The berth time in Felixstowe increased three times longer than the usual time, and operations of other ports in the UK were also affected to varying degrees. The risks in ports, such as weather, congestion, strikes, pandemic and so on will directly affect the berth time in port, particularly in ports that heavily rely on human resources. The effect of disruptions will not only affect the ship that make calls to the port at that time but also the ships that will make port calls later. The consistency of the port performance is also connected with the resilience of the port performance, that is how long it takes the port to return to normal.

9.4.4 Assessment of anchorage time

During the observation, ships usually adopted three ways for waiting before moving to the berth:

- Wait at the anchorage. A ship usually needed to wait at the anchorage until the berth was available. The number of ships at the anchorage provided an indication of the congestion status in port. This was the most usual way for ships waiting for berth or facing disruptions in port. This state was also the waiting time that we measured in this research project. In some cases, ships waited at berth for handling, although it was still a waiting time, but it was calculated as berth time as the ships had already moved to berth in this research.
- Slow steaming. In some cases, ships did not wait at the anchorage for the berth to be available – they chose slow steaming until reaching their berth. This waiting approach was frequently observed in East Asia. Ships preferred this kind of operation measure when heading to the Shanghai and Ningbo ports. For these cases, the waiting time was calculated from the moment the ships entered the port entrance area until they moved to the berth. The specific area was observed according to the position of anchorage. Moreover, slow steaming was also employed during weather-related disruptions, such as typhoons and storms, as ships chose this method to go against strong winds.
  For some ports, e.g., Guangzhou, the trajectories of ships in their anchorage area show a pattern of moving in a circle on a small number of occasions, which indicated that ships were waiting. As a result, their waiting times were also calculated as the time period between moving to the port area and moving to their berth.
- Wait at the origin anchorage. This was only observed on a small number of ships. For example, MSC Leni from Maersk, tended to move from Singapore to Yantian. However, there was a COVID restriction at Yantian at that time, so the ship waited at the anchorage of Singapore after leaving its berth. In this kind of situation, it was difficult to calculate the waiting time at another anchorage and these occurrences were relatively rare. Therefore, the waiting time at the origin anchorage was not included in this research project.

In many existing studies, there is no clear distinction between at berth time and at anchorage time. In this research project, anchorage time refers to the time that ships enter the port area and before they move to the berth, including the entrance channel and queuing time to their berth. According to AbuAlhaol *et al.* (2018), port congestion was measured in two dimensions: traffic volume and turnaround time. The reason for having separate waiting times in this research is that it denotes the time lost in the port area. This is a critical factor in measuring port congestion, and it directly influences the additional time and cost for container shipping. Furthermore, the anchorage time of ships serves as an indicator of traffic volume and, theoretically, the capacity and potential risks of congestion that a port may face in the long term.

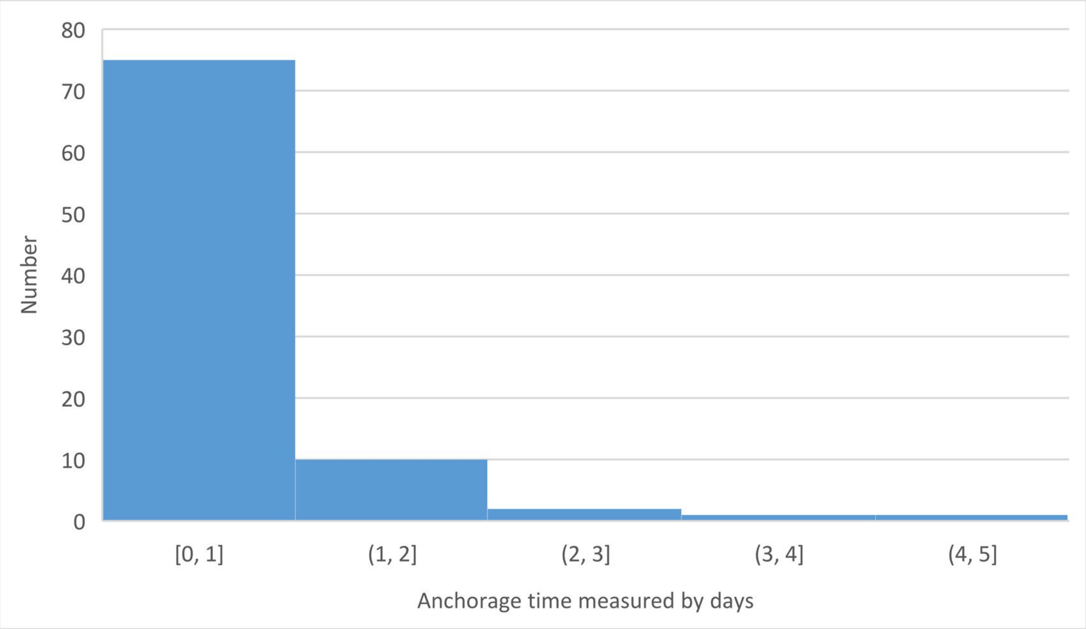


Figure 9.17 Frequency distribution of anchorage time.

Figure 9.17 shows the frequency distribution of the results. The average waiting time across the selected ports was 0.6 days. The frequency distribution figure showed a long tail skewed, with most of the ships tending to wait less than one day. The shortest waiting time was in Salalah, resulting in only 0.17 days and the longest waiting time in the top 20 weighted ports was in Piraeus, resulting in 3.43 days. The longest waiting time among all the ports was in Gdansk, which resulted in 4.46 days. More specifically, there were 14 ports that had an anchorage time of longer than one day among all the selected ports (Gdansk; Piraeus; Zeebrugge; Antwerp; La Spezia; Felixstowe; Aliaga; Bremerhaven; Le Havre; Southampton; Hamburg; Genoa; Mumbai), including 4 ports with an anchorage time of longer than 2 days

(Gdansk: 4.46 days; Piraeus: 3.43 days; Zeebrugge; 2.75 days; Antwerp: 2.5 days). The longest waiting time was in Piraeus port: 16.83 days (CSCL Venus).

As stated above, the anchorage time is a significant indication of port congestion when ships experience further time waiting for the berth to become available; meanwhile, it indicates the infrastructure reliability of ports, with a focus on port capacity, infrastructure utilisation, port planning etc. Figure 9.18 shows the results for all the ports considering both waiting time and number of port calls. The bubble size varies according to the average ship size. As shown in the frequency distribution figure above, the waiting time at anchorage for most ports was relatively short and similar, implying that ships did not experience significant delays before moving to the berth. As shown by the analysis in the last section, ports with more port calls tended to receive larger ships – larger ships with more containers would normally need longer time at berth, and thus, hub ports which tend to attract more ships were more likely to get congested. Despite these challenges, as shown in Figure 9.18, hub nodes such as Shanghai, Ningbo and Singapore, had a large number of port calls with a large average ship size, but demonstrated shorter waiting time, especially in Singapore. When examining the range of waiting time, from one perspective, ports with fewer port calls and lower container volumes experienced shorter waiting time. At the other end of the scale, ports with a large number of port calls and the ability to handle larger ships had shorter waiting time as well.

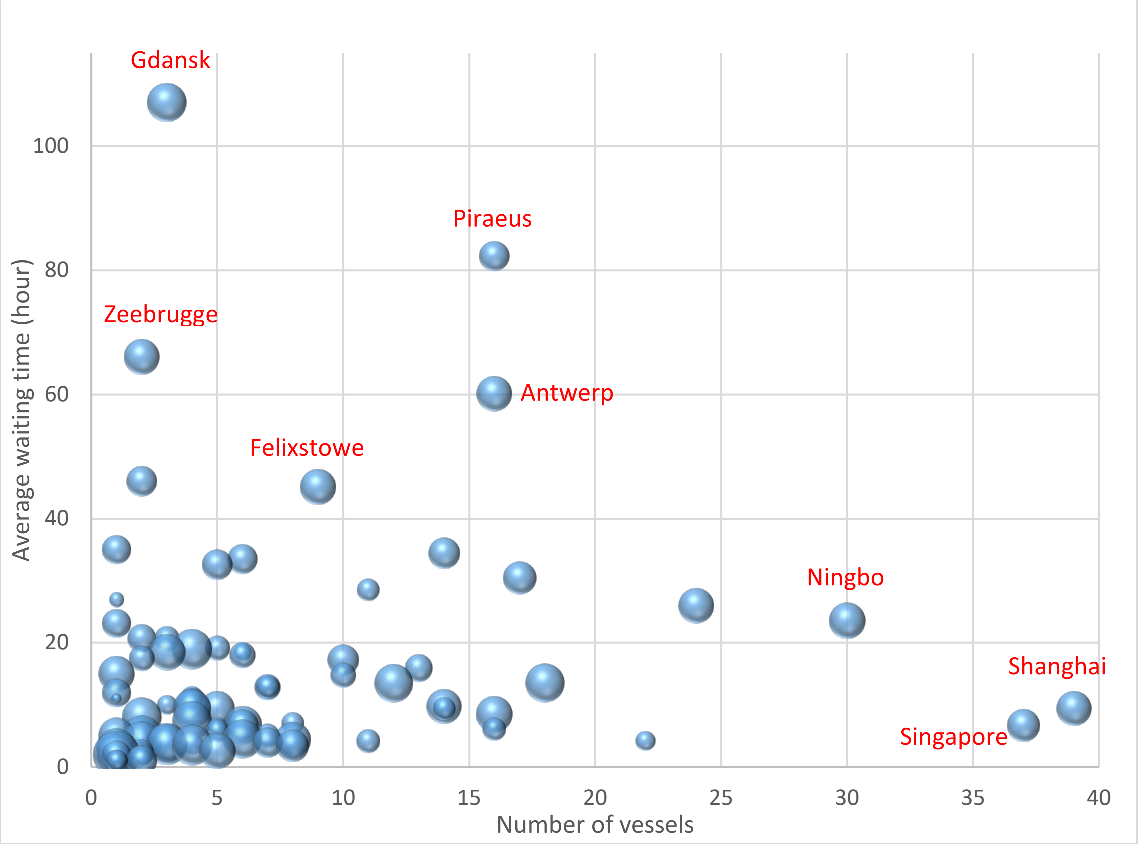


Figure 9.18 Waiting time in port with number and average size of ships.

Bremerhaven, Piraeus, Tangier Mediterranee, Qingdao, Busan, Tanjung Pelepas and Port Said were ports with a similar number of ship arrivals among the selected ports, but the waiting time varied widely. Piraeus had the longest waiting time, 3.43 days, followed by Bremerhaven with 1.43 days, Tangier Mediterranee with 0.66 days, Qingdao with 0.56 days, Busan with 0.41 days, Tanjung Pelepas with 0.35 days and Port Said with 0.26 days. On the whole, ports in Asia still had better performance compared with ports in Europe. The waiting time issues in European ports had reached critical levels, leading to common occurrences of congestion. The waiting times of the major ports in Europe were long, e.g., Bremerhaven, consequently impacting other highly connected ports, e.g., Antwerp, Rotterdam and Hamburg. Even the feeder ports felt the impact of congestion in hub ports, resulting in increased waiting time for ports like Gdansk, Zeebrugge and Le Spezia.

Waiting time also occasionally needed to be combined with the on-time rate to assess the reliability. Occasionally, ships would arrive ahead of the schedule and subsequently need to wait at the anchorage for the planned time. For example, Maersk Kimi waited in Rotterdam for more than six days for berth before its scheduled arrival time, which was a result of cancellations of previous ports of call. Typically, the waiting time ranged from one to three days. Examples include Maersk Izmir in Port Said (1.92 days), Colombo Express in Mersin (2.29 days), Baltic Bridge in Mumbai (1.12 days) and Marit Maersk in Ningbo (2.67 days). Despite the long waiting time in port, the ships still operated on time.

9.4.5 Summary of findings

Section 9.3 analysed the PCSN with the analysis of links, strings and nodes. The results showed that the performance of the container shipping network was not reliable enough, carriers were facing serious delay. Section 9.4 further explored the factors contributing to this unreliability based on ship trajectory within ports. The determinates were broadly divided into two perspectives: one was the infrastructure efficiency in port which was assessed by the at berth time, the other was the infrastructure availability and capacity which was assessed by the waiting time at the anchorage area. These two indicators were employed to investigate the performance of ports according to different parameters.

A 3-D plot graph was used to show the combined results of infrastructure reliability. Figure 9.19 shows the 3-D plot of the top 20 ports with highest weight based on three indicators: (1) Weight – number of TEUs that makes calls to the port; (2) Berth time measured in hours – which refers to the handling efficiency of the port; and (3) Anchorage time measured in hours – which indicates how long a ship needs to wait before moving to berth.

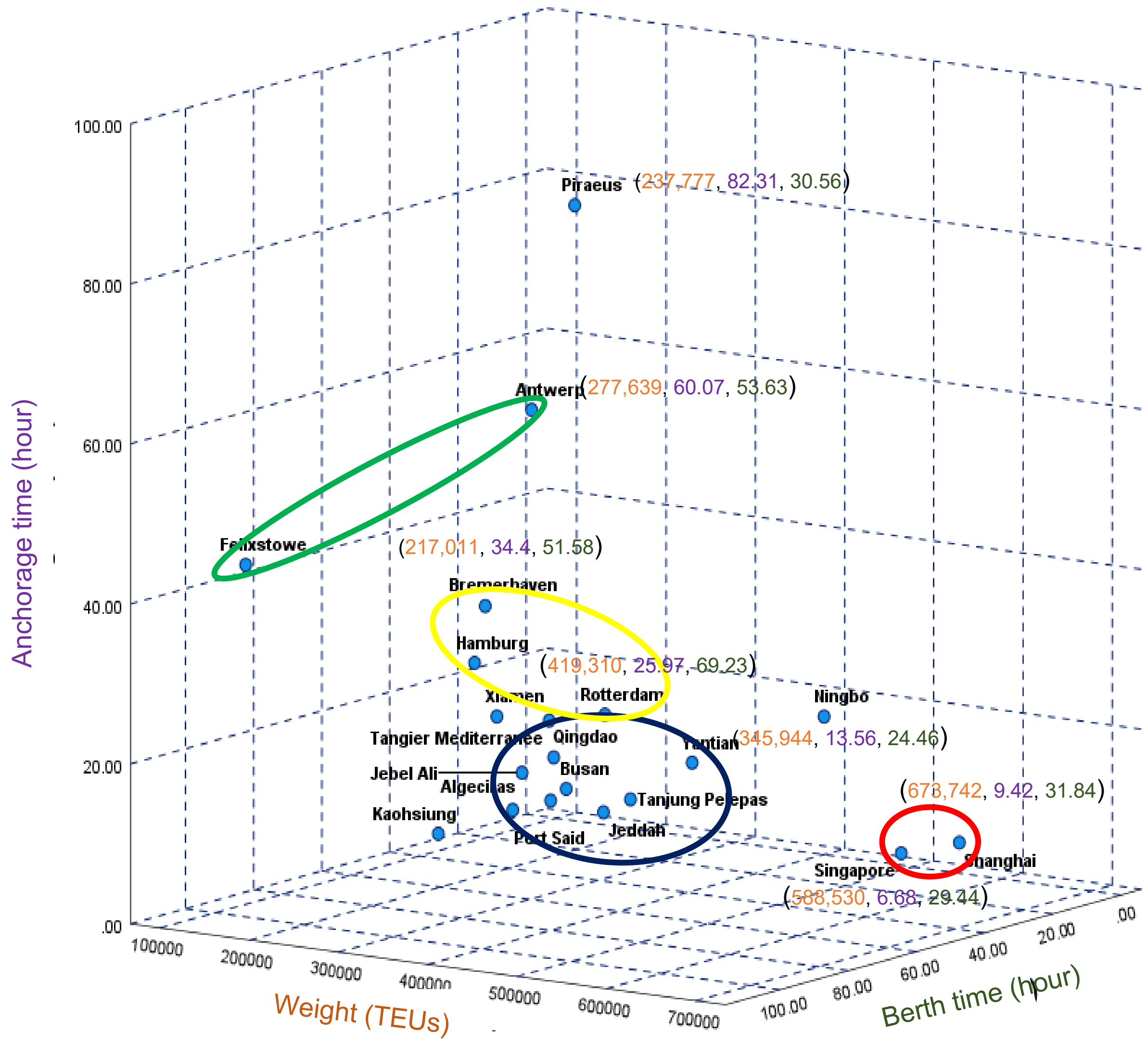


Figure 9.19 Ships' performance in the top 20 highest weighted ports.

The results from the combination of different indicators related to infrastructure reliability, as considered in this chapter, helped to answer the question of how the nodes among the network performed when considering the impact of infrastructure reliability. And the results could be divided into four groups as shown in different colours in Figure 9.19:

- Red: Ports in red had relatively short handling time and also waiting time on average but highest weight, it could be assumed that these ports had the most efficient performance among the hub ports. This group was the case of Shanghai port and Singapore port. These two ports were the most weighted ports in the selected network yet managed to provide efficient services. When comparing the two ports, Singapore showed a better performance in terms of berth time and anchorage time.

- Green: Ports in green exhibited medium to worst performance compared with the ports in red. These ports had long anchorage time and berth time, and with a quite high weight compared with other hub nodes in the network. Antwerp and Felixstowe were examples in this group. Felixstowe had the longest berth time compared with all other hub nodes; meanwhile, Felixstowe and Antwerp had a similarly high waiting time (except Piraeus).
- Yellow: Ports in yellow demonstrated relatively poor handling performance within the network. Bremerhaven, Hamburg and Rotterdam were included in this group. Ports in this group usually were supposed to be less efficient in terms of infrastructure reliability. Among the selected ports in yellow, Hamburg displayed both the longest waiting time and handling time.
- Blue: Ports in the blue group were considered the most reliable ports in terms of both short berth time and anchorage time which represented that they had reliable infrastructure performance on efficiency and availability. Ports in this group were hub nodes with a medium number of calls compared with Singapore and Shanghai, and they usually acted as transshipment points. They included Yantian, Tanjung Pelepas, Busan, Qingdao, Jeddah, Port Said Algeciras and Jebel Ali. Jeddah had the shortest handling time and waiting time, which was regarded to be the most reliable port considering infrastructure reliability within the container shipping network.

Although we analysed connectivity reliability in Chapter 7, which represented the availability of the container shipping network, the infrastructure reliability could directly affect the functional implementation of the shipping network. A reliable infrastructure, encompassing port efficiency and capacity, enables ports to effectively handle the increasing freight demand within the container shipping network. It ensures the quality of liner performance, even in the face of significant increases in container volume or disruptions. Furthermore, reliable infrastructure helps alleviate the impact of congestion; thus, enhancing the overall efficiency and resilience of the container shipping networks.

Section 8.4 pointed out that the impact of attacks on ports can vary depending on their roles within the shipping network. This result also applied when analysing the impact of infrastructure reliability. At the micro level, Figure 9.19 showed the results when considering the entire performance of the ports – ports with longer berth time and anchorage time were identified to be the weak points within the network. At the network level, the performance of ports in terms of connectivity could be influenced by the low performance of the connected ports or the ports within the same string. The improvement of infrastructure reliability in these recognised important nodes could guarantee the reliability of the entire container shipping network to some extent. Accurate estimation and prediction of infrastructure reliability enables port operators to effectively allocate available resources in the short term and assess the necessity of infrastructure upgrades in the long term, particularly when faced with needing to deal with persistent congestion.

9.5 Propagation effect

Chapter 7 of this research delved into an analysis of the CSN, focusing on the connectivity reliability of the network between Asia and Europe. The analysis revealed that this particular network exhibited a highly connected and clustered structure, characterised by a hub-spoke network configuration. Furthermore, a few weighted links and nodes accounted for a large share of TEUs in the network. Another fundamental aspect explored in this research pertained to the interdependency of ports within the network configuration reliability. Notably, disruptions happening in one port had the potential to propagate the impact to other ports in the network. The extent of the impact varied based on the role of nodes within the network connectivity, e.g., hub nodes had greater impact than feeder nodes. Moreover, this chapter delved into the reliability of the infrastructure reliability. It was established that the performance of individual ports could be affected by the inefficiency performance of other ports, primarily due to the configuration of the network. Additionally, delays or congestions experienced at a particular node could be attributed to the performance of interconnected nodes within the network. In light of these findings, a critical inquiry arose concerning the propagation effect within the container shipping network: how the impact of disruptions or congestions propagated to other ports and whether all the ports possessed similar tendency to propagate the impacts.

9.5.1 Propagation impact based on the role of port

It is important to acknowledge that the reliability of a port cannot be solely attributed to the performance of other ports within the network. The role of ports within the network, as well as the distances between node pairs play significant roles in determining their reliability. Not all the ports are influential enough to propagate congestion to the other ports. When analysing the connectivity of the network, the researcher introduced several metrics to show the role of ports within the network, such as betweenness centrality and closeness centrality. Betweenness centrality measured the number of shortest paths passing through a given node, indicating its importance as a transshipment node within the network. Ports with higher betweenness centrality frequently lie on the shortest paths between node pairs. The results obtained through betweenness centrality demonstrated that the network relies on a few ports as hub nodes for transshipment, while the majority of ports within the network function as feeder ports. Closeness centrality, on the other hand, measures the average inverse distance from a given starting node to all other nodes in the network. Ports with higher closeness centrality exhibit shorter distance to other ports in the network, and thus, could be considered to be transhipment nodes.

Additionally, degree and weight serve as metrics directly assessing the number of connections and the carrying capacity, respectively. Figure 7.13 in Chapter 7, distinguished the ports' position with a combination of degree and weight, which divided the nodes into four groups: regional hub port, local hub port, transhipment port and feeder port. Based on the aforementioned metrics and groups, it can be inferred that regional hub ports, such as Singapore and Shanghai exert a substantial influence on global shipping networks. These ports exhibit numerous connections within the respective regions and handle a large number of containers, thereby impacting a significant number of containers, particularly those ports in close geographical proximity. Transhipment ports, acting as vital bridges between different regions, are also significantly affected. However, due to their higher resilience and the availability of alternative ports, they possess greater adaptability compared to hub nodes. Feeder ports, in contrast, exert a relatively lower influence on the network. This can be attributed to their limited connections (with many ports having a betweenness score of 0) and the ease with which alternative backup nodes can be identified.

In summary, the impact of nodes within the network varies depending on the role played by the ports. Regional hub nodes are more susceptible to the influence of other regional hub nodes, while transhipment ports are primarily affected by regional hub nodes and other transhipment nodes directly linked to them. Feeder nodes are easily influenced by the hub nodes either to which they are directly connected or those within the same geographic zone. The metrics employed in this analysis demonstrate that a small number of nodes hold pivotal positions within the network, thereby exerting a considerable influence on directly connected nodes. The differentiated impacts arise from the diverse roles played by ports in the network.

9.5.2 Propagation impact based on network dependency

Beyond the role of ports, the investigation into infrastructure reliability also sheds light on the propagation effect, emphasising the influence of network configuration. To provide a comprehensive depiction of the dependency results, a metric was introduced in this research project; namely the **dependency metric**, which served to assess the propagation effect within the shipping network. The dependency metric, denoted as D_{ij} quantified the level of dependency between port i and port j by counting the number of ships that docked at both port i and port j within a single string. Section 9.3.3 elucidated that delays or congestion occurring at a particular node could stem from the performance of other nodes within the same string. Notably, the impact was not limited to nodes directly connected to the target node – it extended to preceding nodes along the string. In line with this finding, the dependency metric considered all the nodes within a given string, thereby accounting for the potential impact of all previous links that a ship traversed.

By examining the frequency of occurrence wherein two nodes were present within the same string (operated by the same ship), the dependency metric provided insights into the interdependencies among nodes. Figure 9.20 presents a heatmap showcasing the top 20 ports exhibiting the highest degree based on the dependency metric, with rows representing the origin ports and columns representing the destination ports. It is important to note that the container shipping network was treated as a directed network, where the routes within the network possessed a specific direction. Consequently, the performance of destination ports was influenced by the origin ports within the network. This visualisation offered a comprehensive overview of the interplay between nodes and their level of dependency within the network.

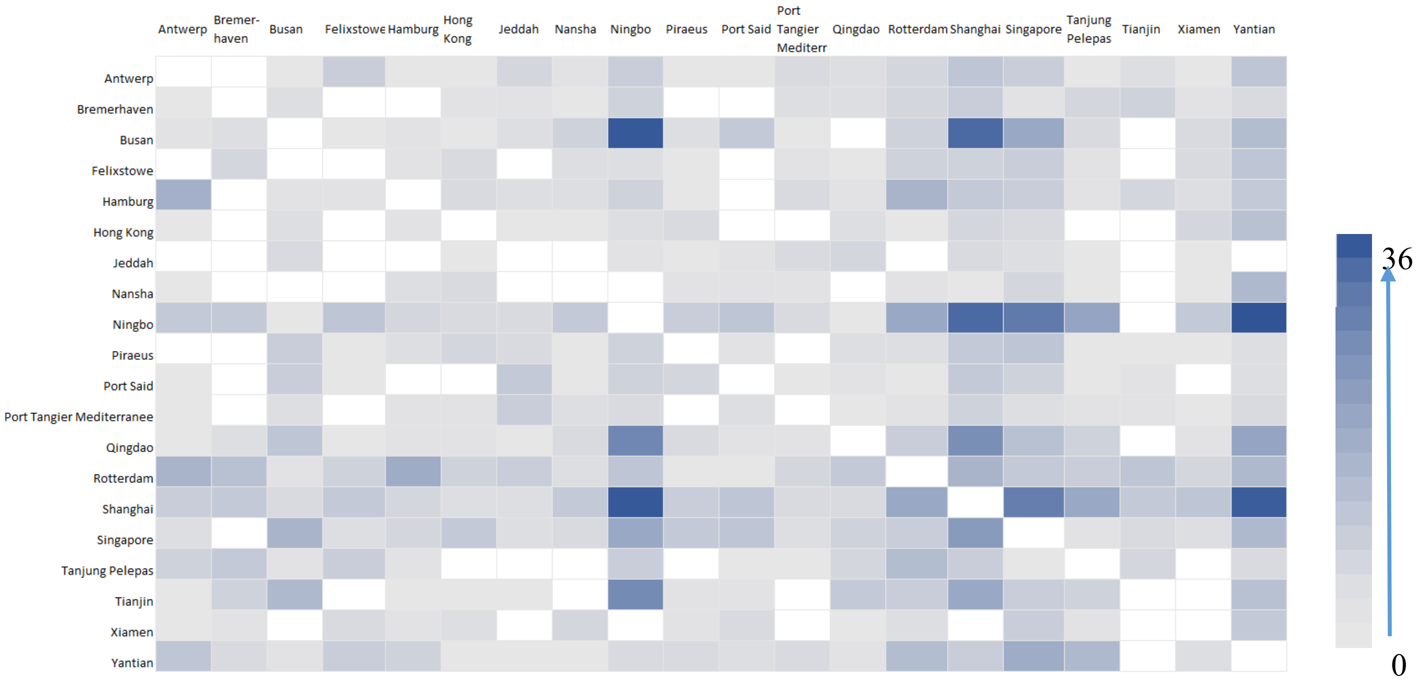


Figure 9.20 Dependency metric for the top 20 weighted ports.

The performance of one node could be affected by other nodes; meanwhile, not all ports are influential enough to propagate congestion to the other ports. The dependency metric presented in Figure 9.20 proves valuable in identifying the influential ports within the PCSN. By examining the heatmap, it becomes apparent that certain ports exhibit a higher dependency score, indicating a greater impact within the same strings. Among all the shipping routes, Ningbo and Yantian had the highest dependency metric. These two ports most often appeared in the same string, followed by Shanghai and Ningbo, Busan and Ningbo, Shanghai and Yantian, Ningbo and Shanghai, and Busan and Shanghai. These results demonstrate that ports in close geographic proximity tend to exhibit higher dependency values. Moreover, links with higher degree, e.g., Shanghai and Ningbo, correspondingly demonstrate higher dependency values.

The influence of specific ports varied within the PCSN, with different ports being most influential for different destinations. Taking Felixstowe as an example, it was primarily affected by Ningbo, followed by Shanghai, Antwerp, Rotterdam and Tanjung Pelepas in terms of network configuration. On the other hand, ports such as Nansha, Hong Kong and Jeddah did not significantly impact the performance of Felixstowe, despite their important roles within the network. Conversely, the occurrence of low performance or congestion in

Felixstowe has a considerable impact on several other ports within the PCSN: Bremerhaven, Rotterdam, Singapore and Yantian. These ports were particularly susceptible to disruptions originating from Felixstowe, indicating a notable dependency on the performance of Felixstowe within the network. In the case of the Shanghai port, the most influential ports in terms of the congestion propagation effect were Busan and Ningbo, followed by Qingdao and Singapore. Only the Xiamen port did not directly affect the performance of Shanghai, highlighting the specific nature of dependency with Shanghai. As an origin port, the performance in Shanghai mostly affected Ningbo and Yantian, followed by Singapore, Tanjung Pelepas and Rotterdam. The Singapore port, boasting the highest degree within the network, held a pivotal position. All the top weighted ports within the network either had direct or indirect connections with Singapore, implying that the performance of Singapore had the potential to influence the majority of ports within the network, and vice versa. In essence, the examination of the dependency metric went beyond the sole consideration of a port's role, focusing instead on the network configuration and its implications for impact propagation. By introducing this novel metric and its associated visualisation, the research project facilitated a deeper understanding of the dependency and influence propagation within the container shipping network.

The dependency metric provides a valuable measure of the propagation effect within the container shipping network. However, there are additional factors that should be considered when assessing the strength of the propagation effect. One factor is the distance between nodes within the network. It could be assumed that the longer the distance is between two nodes, the time required for congestion to spread to other nodes also increases. This extended timeframe allows for more buffer time, enabling ships to take appropriate actions and regain their schedule. Consequently, the propagation effect of congestion is likely to be lower. As a result, ports that are geographically close to each other are expected to exhibit a stronger correlation in terms of propagation effect. For example, Busan and Ningbo, Ningbo and Shanghai, Xiamen and Yantian, Singapore and Tanjung Pelepas, and Hamburg and Bremerhaven may demonstrate a higher degree of dependency due to their close proximity. In accordance with this factor, it is important to note that while ports with a high dependency value in the analysis above may suggest a strong propagation effect, this may not always be the case. The distance between the ports plays a significant role in determining the likelihood of being affected by congestion. For instance, despite the results indicating that Felixstowe was most influenced by Ningbo according to the dependency metric, the actual distance between Ningbo and Felixstowe may decrease the probability of experiencing a highly significant impact.

In addition to considering the distance between ports, another crucial factor that warrants attention is the infrastructure reliability within the ports, particularly in relation to waiting time. As discussed in Section 9.4.4, waiting time serves as a significant indicator of congestion, as it reflects the time lost within the ports. The impact of congestion, when measured in terms of time, theoretically encompasses the time lost within the port and the subsequent voyage time to the next port. The waiting time directly reflected the infrastructure reliability of ports and their ability to recover from disruptions, as addressed in this chapter. When ships experience shorter waiting time, the propagation effect to the next port is expected to decrease. Shorter waiting time signifies efficient port operations and a reduced likelihood of delays cascading to subsequent nodes within the network.

The analysis of anchorage time and berth time within ports holds significant value for port authorities and carriers, as it enables the identification of weak points within port operations. By examining these time metrics, port stakeholders gain insights into areas where improvements can be made, ultimately enhancing the overall efficiency and reliability of port services. Furthermore, the analysis of propagation effects, whether from the perspective of port roles or the application of the dependency metric, plays a vital role in assessing the reliability and performance of the entire shipping network, particularly in the long term. Understanding the dependency and propagation effect within the network offers valuable insights into how disruptions and low performance can propagate through various nodes, potentially affecting the overall network efficiency and service quality. By quantifying the propagation effects, researchers and stakeholders can gauge the robustness and reliability of the network, enabling informed decisions to be made regarding infrastructure investments, operational adjustments and contingency planning.

9.6 Systematic analysis of container shipping network reliability

This research proposes a conceptual framework aimed at understanding the reliability of the container shipping network. The framework encompasses three themes: infrastructure reliability, network configuration reliability and connectivity reliability. To comprehensively investigate these themes, Chapters 7, 8 and 9 undertook network analysis and simulation methods to shed light on these three themes. Within this section, the researcher intends to provide a systematic insight of network reliability by selecting two pivotal ports and examining them through the lens of the three aforementioned identified themes. This approach facilitates a systematic exploration and provides valuable insights into container shipping network reliability. Moreover, it introduces a comparative methodology to supplement the analysis. Given the specific container shipping network under investigation, namely the shipping network between Asia and Europe (CSN), the researcher has chosen one port from each region: Shanghai from Asia and Rotterdam from Europe. These two ports have been identified as being the most critical hub nodes due to their position and pivotal roles within the network.

In accordance with the prevailing research trend, the connectivity reliability of the two ports was firstly identified. Table 9.11 provides an overview of the connectivity reliability with metrics developed in Chapter 7. Overall, the two ports had good performance on connectivity reliability in terms of their degree, weight and clustering coefficient. Furthermore, they were topologically close to other ports within their respective regions. It is worth noting that Shanghai demonstrated the highest weight among ports, indicating a high frequency of container transportations and a relatively accommodating capacity of large container ships. On the other hand, Rotterdam played greater connectivity with other ports within the network. When considering the centrality-related metrics, e.g., betweenness centrality and closeness centrality, Rotterdam showed significant advantages over Shanghai. In the context of port roles within the network, Rotterdam emerged as an influential transhipment and hub node, while Shanghai assumed the role of a hub node with a high weight. In summary, in terms of connectivity reliability, both ports can be considered reliable and they are recognised as hub nodes within the hub-spoke network structure. This implies that the container shipping demand to these two ports can be easily met, and ships face fewer limitations when reaching them. However, in a comparative analysis between the two ports, it is evident that Rotterdam plays a more pivotal role within the network, serving as both a hub node with high weight and an important transhipment node which estimated higher connectivity reliability.

	Degree (Rank)	**In-degree**	**Out-degree**	**Weight (TEUs)**	**Ranking of weight**	**Clustering coefficient**	**Closeness centrality (Ranking)**	**Betweenness centrality (Ranking)**
Shanghai	7	10	10	28,404,845	1	0.24	41	15
Rotterdam	3	13	13	16,222,970	6	0.25	7	6

Table 9.11 Shanghai and Rotterdam connectivity metrics

In terms of infrastructure reliability, Table 9.12 presents the results of metrics, including turnaround time, berth time, minutes per container move and anchorage time. These metrics provide insights into the efficiency and availability of ports under consideration. It is evident from the findings that the performance of Rotterdam was much lower compared with Shanghai. Specifically, ships spent twice as much time in Rotterdam, both at anchorage and at berth. The worst performance of time signifies a lower level of reliability in terms of infrastructure reliability of Rotterdam. Due to the high connectivity, substantial container volume, the role of Rotterdam within the network and the prolonged time spent by ships in the port, Rotterdam is more prone to being congested. The combination of these factors increased the likelihood of congestion issues arising within Rotterdam.

	Turnaround time (day)	**Berth time (day)**	**Minutes per container move**	**Anchorage time**
Shanghai	1.72	0.39	0.28	1.33
Rotterdam	3.97	1.08	0.59	2.88

Table 9.12 Shanghai and Rotterdam infrastructure metrics

The ability of propagating congestion to other ports will be analysed together with its vulnerability and resilience. Section 8.4 simulated attacks to the two ports and the results were illustrated. The attack on Rotterdam resulted in a greater decrease of links (8%) compared to the attack on Shanghai, which involved cutting off a single node from the network. Rotterdam had an increase of network diameter, indicating a less densely connected network. This increase meant that the shortest path length between the most distant pairs of nodes in the network had grown. Conversely, the impact on Shanghai demonstrated a distinct characteristic: fewer nodes were affected, and there was a high frequency of links, indicating a large number of containers being affected.

Through the combination of vulnerability simulation and the utilisation of dependency metrics developed in the last section, the five most important container trading ports were identified, and they are presented in Table 9.13. Disruptions happening in Shanghai and Rotterdam would have the most impacts on these ports due to the higher frequency of shipping and the carrying TEUs by the corresponding node pairs. From the perspective of infrastructure reliability, the performance of Shanghai and Rotterdam was heavily influenced by the performance of these identified key ports.

Shanghai	**Rotterdam**
Ningbo	Hamburg
Yantian	Bremerhaven
Qingdao	Antwerp
Nansha	Felixstowe
Xiamen	Yantian

Table 9.13 Main trading ports with Shanghai and Rotterdam

The last aspect examined in this section is the resilience of the two ports, which was assessed using a resilience metric based on the number of nodes from the first and second domains within the same region, identified in Section 8.5. Figure 9.21 shows the distribution of ports in the first domain and the second domain. For the ports in the first domain, Shanghai exhibited three ports that operated within the same region whereas Rotterdam had two such ports. Furthermore, Shanghai benefited from the presence of six ports in the second domain that provided support and connectivity. Rotterdam had four ports in the second domain. However, it is important to note that ports surrounding Rotterdam were in close proximity, while ports connected to Shanghai were more widely dispersed across East Asia. This distribution has implications for the resilience of the ports. Rotterdam, being surrounded by ports in short distance, has a greater convenience in terms of finding a backup port within a short distance. In contrast, Shanghai faces the challenge of finding a suitable backup ports, it may require longer distance and more complex arrangements for land transportation.

Figure 9.21 Distribution of ports in the first domain and the second domain near Shanghai and Rotterdam

(Source: Author elaboration based on the network vulnerability results analysed in Section 8.3.1.4)

This research project suggested a framework encompassing connectivity reliability, network configuration reliability and infrastructure reliability with the network analysis method, which provided a comprehensive understanding of reliability in the context of container shipping networks. In agreement with the framework and methods reviewed in Chapter 5, this section analysed two ports from the three themes systematically. The results showed that the reliability depended on: (i) the role of a port within the network, with the identification of weight and degree; (ii) the impact to the network when facing disruptions; (iii) the number of ports that can be selected as a backup port, especially when considering the distance between two ports, as well as the ability to recover quickly from disruptions; (iv) infrastructure efficiency, including the ability to handle large container ships; (v) infrastructure capacity and availability; (vi) performance of ports that are either directly connected with it or are on the same string; and (vii) dependency from other ports within the network.

9.7 Conclusion

By recognising the significance of network analysis as being the most suitable method for assessing the reliability of container shipping networks, the researcher constructed the performance network (PCSN) to facilitate the analysis. This network was designed to examine the impact of infrastructure on network reliability by distinguishing between berth time and anchorage time. This distinction provided valuable insights into how infrastructure efficiency and availability influence the reliability of both individual ports and the entire network from the network level. This entailed exploring how the reliability of a specific port could be affected by the performance of directly connected ports, as well as examining the propagation effects of disruptions e.g., congestion to other ports within the context of the network.

Chapter 10. Conclusion

10.1 Introduction

This chapter restates the research questions and highlights the research design procedures employed throughout the research. A concise summary of the results and outcomes is provided, along with an examination of the contributions made by this research project. Furthermore, recommendations for future research directions are outlined.

10.2 Research questions and research design

Reliability has long been a question of great interest in a wide range of fields, and it is explained in different aspects of maritime transportation with a variety of meanings (Stathopoulos and Tsekeris, 2003; Prabhu Gaonkar *et al.*, 2013; Tierney *et al.*, 2019). However, few studies have investigated reliability in any systematic way especially in the context of container shipping networks. This research project, therefore, set out to address this gap by providing a comprehensive understanding of reliability in the context of container shipping networks and systematic approaches to assessing it.

The research objectives of this research project were twofold:

(1) To investigate the relationship between reliability and container shipping networks.
(2) To determine the best approach for comprehensively assessing the reliability of container shipping networks.

To address the research objectives, four research questions were detailed:

RQ1: How is reliability best understood in the context of container shipping networks?
RQ2: What factors influence the network reliability?
RQ3: How can the impact of these factors on container shipping networks be measured?
RQ4: Would there be a more comprehensive approach to assess the reliability?

The purpose of this research project is to understand what reliability in the context of container shipping (i.e., liner) networks means, what are the influencing factors and how can such reliability be measured. According to the literature review, the understanding of reliability appeared in this research project drawing from different fields and disciplines. Meanwhile, the research project also requires analysing from an industry perspective in order to find out a more comprehensive approach to assess the reliability. To address the research questions in a holistic and comprehensive manner, pragmatism was adopted, bridging the gap between positivism and phenomenology. Pragmatism is valuable as it allows for the exploration of practical solutions that can be implemented in the industry. In addition, pragmatism encourages an interdisciplinary approach to research, and makes it possible to work with different approaches and multi methods instead of one particular knowledge or method. By adopting pragmatism, this research project aimed to integrate insights from various fields. Meanwhile, the methodology in this research project combined quantitative and qualitative methods in order to explore the research questions holistically and comprehensively.

10.3 Results discussion

10.3.1 The understanding of reliability and container shipping networks

With regard to the first research objective, which aims to investigate the relationship between reliability and container shipping networks, two research questions were generated: (RQ1) How is reliability best understood in the context of container shipping networks? (RQ2) What factors influence the network reliability. To address these questions, a combination of qualitative and quantitative approaches was employed, including systematic literature review and interviews with key industry stakeholders.

Concerning the first research question, the proposed definition of reliability in the context of container shipping networks in this research is regarded as the quality of liner performance under uncertainty from consignor to consignee. The definition of reliability in the context of the container shipping networks should be explored comprehensively and systematically within different fields rather than as an absolute concept. The key output of the analysis in terms of the first research question was the integrative framework: (1) Infrastructure reliability – reliability was defined as the availability, capacity and efficiency of infrastructure among the network; (2) Network configuration reliability – reliability was defined as whether the network was easily affected by disruptions and the ability of the system to perform well even when parts of the system have failed; (3) Connectivity reliability – reliability was defined as the probability of the components in the network being connected as well as the integration of different stakeholders among the supply chain and the availability of the container services. The framework suggested that there was no unified or absolute definition of reliability in the context of container shipping networks, but that different approaches to understand it were taken depending upon the focus and frame of reference adopted.

Concerning the second research question, the researcher identified the influencing factors through a systematic literature review, and also through interviews with stakeholders. A total of twelve determinants were identified and distributed across the three themes within the integrative framework. The factors in each theme were not mutually separate or independent. The researcher suggested adopting a systematic approach to gather the different determinates together.

10.3.2 Approach for comprehensively assessing the reliability

The second objective of this research was to determine the best approach for comprehensively assessing the reliability of container shipping networks with two research questions: (RQ3) How can the impact of these factors on container shipping networks be measured? (RQ4) Would there be a more comprehensive approach to assess the reliability?

To address the first research question, the researcher conducted a comprehensive review of available indices and existing approaches that were used to measure the factors that impact network reliability. These metrics were classified according to the integrative framework proposed in this research project (infrastructure reliability, network configuration reliability and connectivity reliability). Each metric or approach addressed different aspects of reliability, and thus, provided only partial insight for the analysis of container shipping network reliability. The review showed that the available metrics had not provided a specific approach to assess the reliability in the context of container shipping networks, considering the definition and determinants of the network comprehensively. As a consequence, there is a need for an approach that can specifically and comprehensively assess container shipping network's reliability.

To answer the RQ4, the researcher applied network analysis and simulation for the development of a new and comprehensive approach to assess the reliability in the context of container shipping networks. The network analysis was selected based on the understanding of reliability, and it was best examined within the context of a network, as established by the findings of the literature review (Calatayud *et al.*, 2017; Wu *et al.*, 2019). Network analysis and graph theory allowed the researcher to translate ports and shipping lines into nodes and links within the network, so as to analyse the network structure as well as compare the reliability between nodes. Unlike the available metrics which usually focused only on one perspective, in agreement with the literature review, the research project integrated the three identified themes to analyse the reliability of the existing container shipping network, along with important features influencing reliability. This approach allowed for the analysis in terms of these distinct dimensions, providing insights into the reliability of the entire shipping network and the characteristics of nodes; for instance, which nodes were more reliable within the network and which nodes were more critical to the network's reliability.

To investigate the connectivity reliability of the network, a container shipping network specific to the trade between Asia and Europe was developed (CSN). The network consisted of 115 strings, 89 nodes and 353 weighted links. The purpose of this analysis was to examine the network's structure and the degree of connectivity of ports within the CSN. In order to analyse the connectivity reliability of the network, it was critical to understand whether the containers could reach their destination ports – this is referred to as the accessibility of the network. The results showed that the CSN was highly connected and clustered, indicating that ships could reach their destination port within a small number of steps. Additionally, the results identified the characteristics of the network, such as a small number of ports accounted for a large share of TEUs within the container shipping network. This finding highlighted the presence of a hub-spoke network structure, where a limited number of ports served as hub nodes. By building upon the network connectivity, the research further investigated the role of ports with regard to the network structure. Four groups were identified: regional hub ports (e.g., Singapore), transhipment ports (e.g., Jeddah), local hub ports (e.g., Busan) and feeder ports (e.g., Nansha), according to their degree, weight and centrality-related metrics. By employing network analysis, the research facilitated an understanding of reliability by considering the impact of ports' positions within the container shipping network.

The analysis of connectivity reliability revealed the interdependency of connected ports in the CSN, indicating that the network was highly sensitive to disruptions. Any disruption happening in one node could affect other nodes within the network. To further assess the impact of disruptions and the configuration reliability of the shipping network, the researcher conducted simulations involving random and intentional attacks on the network. The simulation results demonstrated that the extent of network failure depended on the number of nodes facing disruptions. Specifically, when the proportion of failed nodes reached 11%, the performance of the network became limited. When the proportion increased to 17%, the network started to experience partial failure, and if it reached 40%, the network completely failed. These findings provided insights into the network configuration reliability by quantifying the impact of disruptions on the overall network. Moreover, considering the different roles of ports within the network identified in previous analysis, the impact of attacks varied. For example, if disruptions happen in the nodes with higher weight, there will be more containers stuck in the port, e.g., Shanghai. If disruptions happen in the nodes with higher degree, the transhipments to other ports would be more affected especially for the nodes with higher degree, e.g., Singapore. The protection of recognised important nodes could guarantee the reliability of the entire container shipping network to some extent.

Furthermore, the network had the ability to perform well even when parts of the network failed. This suggested that in order to analyse the network configuration reliability more accurately, then the resilience of the network should be considered. This research developed the resilience metrics to discover the ability as to whether the network could recover to the pre-disrupted state or close to it when facing disruptions. The resilience of a given region depends on the number of backup ports within that region, the shipping network can divert containers from disrupted ports to alternative ports.

Following the analysis of the characteristics of the container shipping network, the research shifted its focus to assessing the performance of the network, so as to understand the impact of infrastructure on network reliability. The first step was to examine the performance of the container shipping network between Asia and Europe (PCSN) by considering the on-time rate and average delay. The results revealed that the PCSN was not reliable enough; carriers were facing serious delay. Given the observed unreliability in network performance, the researcher further investigated whether this could be attributed to the infrastructure reliability of ports. This examination was conducted by analysing the time that ships spent in ports, specifically the at berth time and the at anchorage time. These two metrics provided insight into the efficiency and availability of port infrastructure, as well as identifying the weak points within the port. For example, the lack of ability to handle large size ships in some hub ports, e.g., Hamburg, plays a crucial role in determining their inefficient performance.

Indeed, it is critical to consider the infrastructure reliability when assessing network reliability, as a more reliable infrastructure enables ports to effectively handle the existing freight demands and accommodate increasing demand when the networks are facing disruptions. Concerning the network structure – a few weighted links accounted for a large share of TEUs within the network – also shed light on the infrastructure reliability, as the performance of the network depended on these critical but inefficient links. The ports with longer handling time and less performance efficiency should not be put in the centre of the network. It provided further insight into the network configuration reliability.

Beyond the individual performance of nodes, network analysis also provided a broader understanding of reliability-related dynamics from the perspective of network. It has been evidenced from the analysis of network performance that a delay or congestion generated in one port could be attributed to the delay generated in previous ports of call within the string. For example, the bad performance of Rotterdam can propagate through the network, impacting Asian ports as well. This finding had also been proved by the analysis of network configuration reliability, which revealed that disruptions happening in one port had the potential to propagate their impact to other ports within the network. However, not all ports had an equal influence on the network. This research developed a dependency metric to analyse the ability of ports to propagate impact to other ports within the network. The results demonstrated that not all the ports were influential to the network; it varied based on the role of ports as well as the connectivity with the affected port. Given the existing network configuration and characteristics of ports within the network from previous analysis, the reliability of the port was not only determined by its own performance, but also by its connections with other nodes, either directly or within the same string. Additionally, the importance of connectors within the network and the geographical region to which a port belonged also played a significant role in determining port reliability.

Based on all the findings in this research project, the researcher suggests that a more comprehensive approach to assessing reliability in the context of container shipping networks should take into account the following factors:

- The connectivity of the network – is it easy to reach the destination port;
- The role of the port within the network, considering weight, degree and centrality of the port;
- The impact of disruptions on the port and the network;
- The ability of the ports to recover from disruptions;
- The performance of infrastructure (efficiency and availability) in port;
- The performance of the network with a focus on the directly connected links with the port and the indirectly connected ports within the same string;

- Network configuration – how it is connected with other ports and the ports within the same string;
- Dependency on other ports within the network.

10.4 Contribution

Through the results summarised above, this research contributed in a number of ways to advance the literature on reliability and provide a more comprehensive approach to assessing the reliability at the network level. The contributions are:

- Contribution to the definition of reliability in the context of container shipping networks, and development of a systematic framework for comprehensively understanding reliability based on three themes;
- A comprehensive review and classification of existing metrics and methods that are used to assess reliability;
- Proposing a more comprehensive network analysis model by considering network vulnerability, resilience, port performance and propagation effects;
- Identification of important nodes and links, risks and vulnerable elements within the network so that decision-makers and industry stakeholders can improve the reliability of the shipping networks.

This research project has made contributions to advancing the understanding of reliability in container shipping networks as well as addressing the existing knowledge gap in this field. By adopting a comprehensive approach based on three themes and considering the perspective of the shipping industry, this research has provided valuable insights into the concept of reliability and its assessment within container shipping networks. By providing a review and classification of existing metrics and approaches, this research has contributed to the development of a clearer understanding of how reliability is measured and evaluated in the container shipping context. Moreover, the findings of this research project have identified important and weak nodes in container shipping networks, shedding light on the determinants of network reliability. The output of the research contributes to helping stakeholders identify – for any container shipping network – the key nodes and links, sources of risks and vulnerable elements, and then decide what actions are necessary to avoid and mitigate disruptions, and to ensure networks become more resilient.

10.5 Limitations and future research directions

This research specifically focused on container shipping networks between Asia and Europe within a sample time period of three months. Section 6.3.3 acknowledged the exclusion of round-the-world services and feeder services within the network. The inclusion of these two services would lead to a more complete shipping network. By incorporating these two services, we can capture all the connections and strings that contribute to the overall efficiency of the CSN. The metrics such as degree, average path length and clustering coefficient may be skewed if two services are not considered. As the scale of the network was extended, including these two services may provide a more comprehensive view of the network dynamics when analysing network configuration. Furthermore, feeder ports are also vital to regional trade and transportation, and feeder services contribute to the efficiency of the entire supply chain. There is potential for future research to consider expanding the scope of the study by collecting data including those services and also extending for a broader time period, as well as adopting a global perspective to encompass other container shipping networks around the world / in other regions. Such an expanded scope would allow for exploration of the different network structures and the examination of ports with varying roles within the network, thereby providing valuable insights into the impact of network reliability. This longitudinal approach would enhance the understanding of network dynamics and enable stakeholders to make more informed decisions based on reliable forecasts.

In light of the indices discussed in Chapter 5, the analysis of reliability in container shipping networks has the potential of contributing to the development of a new index for ranking ports within the network. Similar to the existing indices, such as the Port Performance Scorecard, which focuses on port performance, and the Liner Shipping Connectivity Index (LSCI) and bilateral CPCI by Bartholdi *et al.* (2016), which assess connectivity in maritime transportation, a reliability index could serve as a benchmark with standardised data and aspire to become an industry standard for ports and carriers to enhance their reliability. Further research may need to assess the weight of the including factors, the synergies among determinants and the methodology for developing a new index.

As discussed in Chapter 2, network analysis is recognised as a valuable tool for acquiring insights into the configuration and behaviour of container shipping networks. However, it is crucial to note that topological models, inherent to network analysis, predominantly analyse network structure and may overlook other perspectives of networks. While this research tends to fill this gap by integrating the analysis of port performance with network configuration, it acknowledges the insufficiency of relying solely on time as the operability variable for assessing such a complex system within the network. Moreover, the network analysis model employed in this research is constrained in its ability to capture the logical relationships among the various agents and processes operating within the network. Network analysis in isolation might not capture the full complexity of the entire shipping network. Enhancing the network analysis results could be achieved through the incorporation of modelling optimisation processes within the network. This strategic addition aims to refine the analytical outcomes and contribute to a more comprehensive understanding of the network dynamics.

As introduced in this research, the container shipping network is expanding its service from its core container maritime transportation to “door-to-door.” The global container shipping network has become the backbone of not only maritime transportation but also logistics networks. The existing literature reviewed in this research project further supports this understanding, highlighting the importance of considering reliability in the context of container shipping networks as a comprehensive integration of supply chain operations, connectivity with hinterlands, and coordination within the entire transport system. However, due to the data available and the research scale, this research only focused on the maritime transportation component. For instance, the examination of port infrastructure reliability only focused on the performance in port, without taking into account crucial factors such as hinterland infrastructure availability, information sharing and trade facilitation procedures. Therefore, further research is warranted to encompass these additional determinants which are essential for a more comprehensive assessment of reliability in container shipping networks.

Furthermore, it is important to acknowledge that sustainability-related issues are becoming increasingly significant in the field of container shipping and supply chain management. Although this research did not directly incorporate sustainability factors into the framework of reliability, it is imperative that future research addresses this aspect. By considering sustainability factors, such as carbon emissions, the environmental impact of container shipping networks can be assessed more comprehensively. The researcher has already presented a related topic at the 2022 RGS Annual International Conference, specifically examining the additional carbon footprint resulting from disruptions in container shipping networks. While this topic falls outside the direct scope of reliability, it highlights the importance of considering sustainability implications in relation to network performance. Future research could delve deeper into the analysis of additional emissions generated by unreliable network performance.

It is worth noting that this research primarily focused on the container shipping component. Further research could expand the analysis to incorporate other modes of transport and examine the interplay between different modes. Additionally, investigating the impact of reliability on the actual products carried within containers (e.g., opportunity costs implications) would be valuable for assessing the multi-layered effects of network reliability.

10.6 Conclusion

This concluding chapter has presented a synthesis of the findings obtained from the analysis and interpretation of the collected data, aligning them with the predetermined research objectives. Furthermore, it highlighted the contributions made by this research and offered suggestions for future studies based on the insights gained from the analysis.

Appendix 1

The modified Critical Appraisal Skills Program checklist for evaluating studies (ten questions) (Wang and Notteboom, 2014)

A: Screening questions: Does this study address a clear question?

1. #Does the study address a clearly focused issue? • A clear statement of the aims of the research? • Have an appropriate study design?	Yes ☐	Can't tell ☐	No ☐
2. #Is the study relevant to the synthesis topic? Address the formulated review questions?	Yes ☐	Can't tell ☐	No ☐

B: Are the results of this study valid?

3. Does the study clearly explain the research method which fits for authors' stated aims?	Yes ☐	Can't tell ☐	No ☐
4. *Does the study describe explicitly about the data collection? How and why the data collected?	Yes ☐	Can't tell ☐	No ☐
5. Does the study explain clearly how the data analysis is done?	Yes ☐	Can't tell ☐	No ☐
6. *Is the data analysis sufficiently rigorous to address the aims? Links between data and interpretations?	Yes ☐	Can't tell ☐	No ☐

C: How are the results?

7. Are the finding of the study explicit and easy to understand?	Yes ☐	Can't tell ☐	No ☐
8. *Are data collection and analysis sufficiently presented to support the descriptive findings?	Yes ☐	Can't tell ☐	No ☐

9. Does the study add to knowledge or theory in the field?	Yes ☐	Can’t tell ☐	No ☐
10. Are these findings important to practice?	Yes ☐	Can’t tell ☐	No ☐

Overall assessment of study This study will be included in the synthesis or not? Two requirements are considered of the inclusion of studies: Two screening questions with # must be YES. Not all answers to the three key questions with * are NO.	Yes ☐	No ☐

Appendix 2

Ms. Zhongyun Yue, PhD candidate (z.yue3@ncl.ac.uk)
Marine, Offshore and Subsea Technology (MOST) Group
School of Engineering

Research Title: The role of reliability in container shipping networks.
Research Supervisory Committee: Professor John Mangan and Dr Paul Stott.

Interview Agenda

Date and Time: ____________________________

Interviewee: ____________________________

The following are some points I would like to explore during our discussion:

1. Tell me a little about your company and your role within the company.
2. Please describe the container shipping network(s) that you use / operate.
3. In container shipping what in your view are the key performance related and other criteria that are important?
4. 'Reliability' is often regarded as a key performance criterion in container shipping – what is your interpretation / understanding of reliability?
5. In your experience what reliability related issues usually arise in your network?
6. In your opinion, what factors influence reliability in your network and which of these are of most importance?
7. How is reliability measured in your network?
8. What actions do you take when there are issues or concerns around reliability?

Appendix 3

The list of ports in the third domain considering network vulnerability

Rank	Port	Regional position	Rank	Port	Regional position
37	Izmit	Middle East	**64**	Aliaga	Middle East
38	Fos	Western Europe	**65**	Karachi	Middle East
39	Damietta	Southern Europe	**66**	Dammam	Middle East
40	king Abdullah	Middle East	**67**	Gwangyang	East Asia
41	Istanbul	Middle East	**68**	Gothenburg	Western Europe
42	Mundra	South Asia	**69**	Trieste	Southern Europe
43	Ambarli	Middle East	**70**	Rijeka	Southern Europe
44	Jawaharlal Nehru	South Asia	**71**	Dunkirk	Western Europe
45	Dalian	East Asia	**72**	Sines	Western Europe
46	Khalifa	Middle East	**73**	Taipei	East Asia
47	Zeebrugge	Western Europe	**74**	Haifa	Middle East
48	La Spezia	Southern Europe	**75**	Al Jubail	Middle East
49	Mersin	Middle East	**76**	Cai Mep	Southeast Asia
50	Beirut	Middle East	**77**	Constantza	Western Europe
51	Gdansk	Western Europe	**78**	Odesssa	Western Europe
52	Gioia Tauro	Southern Europe	**79**	Aqaba	Middle East
53	Mawan	East Asia	**80**	Hazira	South Asia
54	Shekou	East Asia	**81**	Iskenderun	Middle East
55	Hamad	Middle East	**82**	Mumbai	South Asia
56	Tripoli	Middle East	**83**	Alexandria	Southern Europe
57	Ashdod	Middle East	**84**	Doha	Middle East
58	Nagoya	East Asia	**85**	Novorossiysk	Western Europe
59	Kobe	East Asia	**86**	Yarimca	East Asia
60	Aarhus	Western Europe	**87**	Tokyo	East Asia
61	Tekirdag	Middle East	**88**	Shimizu	East Asia
62	Koper	Southern Europe	**89**	Tangier Med2 [4]	Southern Europe
63	Laem Chabang	Southeast Asia			
63	Aliaga	Middle East			

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[4] Tangier Med2 is a Moroccan port, located at the Strait of Gibraltar and is regarded as the largest port in Africa. To facilitate the regional analysis of the CSN configuration, Tangier Med2 is involved in the Southern Europe region for further examination.

References

AbuAlhaol, I., Falcon, R., Abielmona, R. and Petriu, E. (2018) 'Mining Port Congestion Indicators from Big AIS Data', *2018 International Joint Conference on Neural Networks (IJCNN)*. pp. 1-8.

Achurra-Gonzalez, P.E., Angeloudis, P., Goldbeck, N., Graham, D.J., Zavitsas, K. and Stettler, M.E.J. (2019) 'Evaluation of port disruption impacts in the global liner shipping network', *Journal of Shipping and Trade*, 4(1), p. 3.

Achurra-Gonzalez, P.E., Novati, M., Foulser-Piggott, R., Graham, D.J., Bowman, G., Bell, M.G.H. and Angeloudis, P. (2019) 'Modelling the impact of liner shipping network perturbations on container cargo routing: Southeast Asia to Europe application', *Accident Analysis & Prevention*, 123, pp. 399-410.

Adland, R., Bjerknes, F. and Herje, C. (2017) 'Spatial efficiency in the bulk freight market', *Maritime Policy & Management*, 44(4), pp. 413-425.

Almoghathawi, Y., Barker, K. and Albert, L.A. (2019) 'Resilience-driven restoration model for interdependent infrastructure networks', *Reliability Engineering & System Safety*, 185, pp. 12-23.

An, Y., Zeng, B. and Zhang, Y. (2011) 'Hub-spoke Design with Temporary Hubs for Congestion Mitigation', *IIE Annual Conference. Proceedings*, p. 1.

An, Y., Zhang, Y. and Zeng, B. (2015) 'The reliable hub-and-spoke design problem: Models and algorithms', *Transportation Research Part B: Methodological*, 77, pp. 103-122.

Asadabadi, A. and Miller-Hooks, E. (2018) 'Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach', *Transportation Research Part B: Methodological*, 108, pp. 281-298.

Asadabadi, A. and Miller-Hooks, E. (2020) 'Maritime port network resiliency and reliability through co-opetition', *Transportation Research Part E: Logistics and Transportation Review*, 137.

Aversa, R., Botter, R.C., Haralambides, H.E. and Yoshizaki, H.T.Y. (2005) 'A Mixed Integer Programming Model on the Location of a Hub Port in the East Coast of South America', *Maritime Economics & Logistics*, 7(1), pp. 1-18.

Azizi, N. (2019) 'Managing facility disruption in hub-and-spoke networks: formulations and efficient solution methods', *Annals of Operations Research*, 272(1), pp. 159-185.

Azizi, N., Chauhan, S., Salhi, S. and Vidyarthi, N. (2016) 'The impact of hub failure in hub-and-spoke networks: Mathematical formulations and solution techniques', *Computers & Operations Research*, 65, pp. 174-188.

Azungah, T. (2018) 'Qualitative research: deductive and inductive approaches to data analysis', *Qualitative Research Journal*, 18(4), pp. 383-400.

Balliauw, M., Kort, P.M., Meersman, H., Smet, C., Van De Voorde, E. and Vanelslander, T. (2019) 'Port capacity investment size and timing under uncertainty and congestion', *Maritime Policy and Management*.

Barabási, A.-L., Albert, R. and Jeong, H. (2000) 'Scale-free characteristics of random networks: the topology of the world-wide web', *Physica A: Statistical Mechanics and its Applications*, 281(1), pp. 69-77.

Barabási, A.-L.s. (2014) *Linked : how everything is connected to everything else and what it means for business, science, and everyday life*. New York : Basic Books.

Barabási, A.L., Jeong, H., Néda, Z., Ravasz, E., Schubert, A. and Vicsek, T. (2002) 'Evolution of the social network of scientific collaborations', *Physica A: Statistical Mechanics and its Applications*, 311(3), pp. 590-614.

Barahimi, P. and Vergara, H.A. (2020) 'Reliable p-Hub Network Design under Multiple Disruptions', *Networks and Spatial Economics*, 20(1), pp. 301-327.

Barros, C.P. and Athanassiou, M. (2015) 'Efficiency in European Seaports with DEA: Evidence from Greece and Portugal', in Haralambides, H.E. (ed.) *Port Management*. London: Palgrave Macmillan UK, pp. 293-313.

Bärthel, F. and Woxenius, J. (2004) 'Developing intermodal transport for small flows over short distances', *Transportation Planning and Technology*, 27(5), pp. 403-424.

Bartholdi, J.J., Jarumaneeroj, P. and Ramudhin, A. (2016) 'A new connectivity index for container ports', *Maritime Economics & Logistics*, 18(3), pp. 231-249.

Barton, J., Emery, M., Flood, R.L., Selsky, J.W. and Wolstenholme, E. (2004) 'A Maturing of Systems Thinking? Evidence from Three Perspectives', *Systemic Practice and Action Research*, 17(1), pp. 3-36.

Bastian, M., Heymann, S. and Jacomy, M. (2009) 'Gephi: An Open Source Software for Exploring and Manipulating Networks', *Proceedings of the International AAAI Conference on Web and Social Media*, 3(1), pp. 361-362.

Bayraktar, M. and Yuksel, O. (2023) 'A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations', *Ocean Engineering*, 278, p. 114295.

Beenstock, M. (1985) 'A theory of ship prices', *Maritime Policy & Management*, 12(3), pp. 215-225.

Bell, M.G.H. (2000) 'A game theory approach to measuring the performance reliability of transport networks', *Transportation Research Part B: Methodological*, 34(6), pp. 533-545.

Berdica, K. (2002) 'An introduction to road vulnerability: what has been done, is done and should be done', *Transport Policy*, 9(2), pp. 117-127.

Berelson, B. (1952) *Content analysis in communication research*. New York, NY, US: Free Press.

Berle, Ø., Rice Jr, J.B. and Asbjørnslett, B.E. (2011) 'Failure modes in the maritime transportation system: a functional approach to throughput vulnerability', *Maritime Policy & Management*, 38(6), pp. 605-632.

Berman-Brown, R. and Saunders, M. (2008) *Dealing with Statistics: what you need to know*. Maidenhead: Open University.

Beysenbaev, R. and Dus, Y. (2020) 'Proposals for improving the Logistics Performance Index', *The Asian Journal of Shipping and Logistics*, 36(1), pp. 34-42.

Bouman, E.A., Lindstad, E., Rialland, A.I. and Strømman, A.H. (2017) 'State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review', *Transportation Research Part D: Transport and Environment*, 52, pp. 408-421.

Burrell, G. and Morgan, G. (1979) 'Sociological Paradigms and Organisational Analysis', *Ashgate Publishing, Aldershot*.

Cabral, A.M.R. and Ramos, F.d.S. (2014) 'Cluster analysis of the competitiveness of container ports in Brazil', *Transportation Research Part A: Policy and Practice*, 69, pp. 423-431.

Calatayud, A., Mangan, J. and Christopher, M. (2019) 'The self-thinking supply chain', *Supply Chain Management: An International Journal*, 24(1), pp. 22-38.

Calatayud, A., Mangan, J. and Palacin, R. (2017) 'Vulnerability of international freight flows to shipping network disruptions: A multiplex network perspective', *Transportation Research Part E: Logistics and Transportation Review*, 108, pp. 195-208.

Calatayud, A., Palacin, R., Mangan, J., Jackson, E. and Ruiz-Rua, A. (2016) 'Understanding connectivity to international markets: a systematic review', *Transport Reviews*, 36(6), pp. 713-736.

Campbell, J.F. (1996) 'Hub Location and the p-Hub Median Problem', *Operations Research*, 44(6), pp. 923-935.

Caniato, F., Golini, R. and Kalchschmidt, M. (2013) 'The effect of global supply chain configuration on the relationship between supply chain improvement programs and performance', *International Journal of Production Economics*, 143(2), pp. 285-293.

Cantillo, J., Cantillo, V. and Arellana, J. (2018) 'Modelling with joint choice of ports and countries of origin and destination: application to Colombian ports', *Maritime Policy and Management*, 45(6), pp. 720-738.

Carvalho, H., Barroso, A.P., Machado, V.H., Azevedo, S. and Cruz-Machado, V. (2012) 'Supply chain redesign for resilience using simulation', *Computers & Industrial Engineering*, 62(1), pp. 329-341.

Caschili, S. and Medda, F.R. (2012) 'A review of the maritime container shipping industry as a complex adaptive system', *Scientific Journal INDECS*.

Çemberci, M., Civelek, M.E. and Canbolat, N. (2015) 'The Moderator Effect of Global Competitiveness Index on Dimensions of Logistics Performance Index', *Procedia - Social and Behavioral Sciences*, 195, pp. 1514-1524.

Chang, J.S. (2010) 'Assessing travel time reliability in transport appraisal', *Journal of Transport Geography*, 18(3), pp. 419-425.

Chang, Y.-T., Lee, S.-Y. and Tongzon, J.L. (2008) 'Port selection factors by shipping lines: Different perspectives between trunk liners and feeder service providers', *Marine Policy*, 32(6), pp. 877-885.

Chen, A., Zhou, Z., Chootinan, P., Ryu, S., Yang, C. and Wong, S.C. (2011) 'Transport Network Design Problem under Uncertainty: A Review and New Developments', *Transport Reviews*, 31(6), pp. 743-768.

Chen, H., Cullinane, K. and Liu, N. (2017) 'Developing a model for measuring the resilience of a port-hinterland container transportation network', *Transportation Research Part E: Logistics and Transportation Review*, 97, pp. 282-301.

Chen., Huang, T., Xie, X., Lee, P.T.W. and Hua, C. (2019) 'Constructing governance framework of a green and smart port', *Journal of Marine Science and Engineering*, 7(4).

Chen., Tsai, Y.H. and Schonfeld, P. 2548 (2016) 'Schedule coordination, delay propagation, and disruption resilience in intermodal logistics networks' *Transportation Research Record*. pp. 16-23.

Cheung, W., Leung, L.C. and Wong, Y.M. (2001) 'Strategic service network design for DHL hong kong', *Interfaces*, 31(4), pp. 1-14.

Cho, J., Lim, G.J., Kim, S.J. and Biobaku, T. (2018) 'Liquefied natural gas inventory routing problem under uncertain weather conditions', *International Journal of Production Economics*, 204, pp. 18-29.

Chou, C.C. (2010) 'AHP model for the container port choice in the multiple-ports region', *Journal of Marine Science and Technology*, 18(2), pp. 221-232.

Cohen, J.P. and Morrison Paul, C.J. (2003) 'Airport infrastructure spillovers in a network system', *Journal of Urban Economics*, 54(3), pp. 459-473.

Collis, J. (2014) *Business research a practical guide for undergraduate & postgraduate students*. Fourth edition.. edn. Basingstoke, Hampshire : Palgrave Macmillan.

Collison, F.M. (1984) 'North to Alaska: Marketing in the Pacific Northwest–Central Alaska linear trade', *Maritime Policy & Management*, 11(2), pp. 99-112.

Comtois, C., Wiegmans, B., Witte, P. and Slack, B. (2018) 'Ships time in port', *International Journal of Shipping and Transport Logistics*, 10(1).

Coronado Mondragon, A.E., Lalwani, C.S., Coronado Mondragon, E.S. and Coronado Mondragon, C.E. (2009) 'Facilitating multimodal logistics and enabling information systems connectivity through wireless vehicular networks', *International Journal of Production Economics*, 122(1), pp. 229-240.

Crucitti, P., Latora, V., Marchiori, M. and Rapisarda, A. (2003) 'Efficiency of scale-free networks: error and attack tolerance', *Physica A: Statistical Mechanics and its Applications*, 320, pp. 622-642.

Cui, T., Ouyang, Y. and Shen, Z.-J.M. (2010) 'Reliable Facility Location Design Under the Risk of Disruptions', *Operations Research*, 58(4-part-1), pp. 998-1011.

Davarzani, H., Fahimnia, B., Bell, M. and Sarkis, J. (2016) 'Greening ports and maritime logistics: A review', *Transportation Research Part D: Transport and Environment*, 48, pp. 473-487.

De Benedictis, L. and Tajoli, L. (2011) 'The World Trade Network', *The World Economy*, 34(8), pp. 1417-1454.

De Borger, B., Proost, S. , Van Dender, K. ,2008. (2008) 'Private port pricing and public investment in port and hinterland capacity.', *Journal of Transport Economics and Policy 42 (3), 527–561 .*

De Langen, P.W. and Sharypova, K. (2013) 'Intermodal connectivity as a port performance indicator', *Research in Transportation Business and Management*, 8, pp. 97-102.

Dekker, S., Verhaeghe, R. and Wiegmans, B. (2011) 'Economically-efficient port expansion strategies: An optimal control approach', *Transportation Research Part E: Logistics and Transportation Review*, 47(2), pp. 204-215.

Deng, P., Lu, S. and Xiao, H. (2013) 'Evaluating the Capabilities of Port Logistics Based on Structural Equation Modeling', in *ICTIS 2013*. pp. 2148-2155.

Denyer, D. and Tranfield, D. (2009) 'Producing a systematic review', in *The Sage handbook of organizational research methods.* Thousand Oaks, CA: Sage Publications Ltd, pp. 671-689.

Di Francesco, M., Lai, M. and Zuddas, P. (2013) 'Maritime repositioning of empty containers under uncertain port disruptions', *Computers & Industrial Engineering*, 64(3), pp. 827-837.

Dill, J., Candiloro, B., Downer, J., Wiesman, R., Fallin, L. and Smith, R. (1998) 'Material handling robot system for flow through storage applications', *Proceedings of SPIE - The International Society for Optical Engineering*, 3525, pp. 42-49.

Djankov, S., Freund, C. and Pham, C.S. (2010) 'Trading on Time', *The Review of Economics and Statistics*, 92(1), pp. 166-173.

Doll, C., Papanikolaou, A. and Maurer, H. (2014) 'The vulnerability of transport logistics to extreme weather events', *International Journal of Shipping and Transport Logistics*, 6(3), pp. 293-313.

Douaioui, K., Fri, M., Mabrouki, C. and Semma, E.A. (2018) 'Smart port: Design and perspectives', *Proceedings - GOL 2018: 4th IEEE International Conference on Logistics Operations Management*. pp. 1-6.

Ducruet, C. (2013) 'Network diversity and maritime flows', *Journal of Transport Geography*, 30, pp. 77-88.

Ducruet, C. (2017) 'Multilayer dynamics of complex spatial networks: The case of global maritime flows (1977–2008)', *Journal of Transport Geography*, 60, pp. 47-58.

Ducruet, C. (2020) 'The geography of maritime networks: A critical review', *Journal of Transport Geography*, 88.

Ducruet, C. (2022) 'Port specialization and connectivity in the global maritime network', *Maritime Policy & Management*, 49(1), pp. 1-17.

Ducruet, C. and Notteboom , T.E. (2012) 'The worldwide maritime network of container shipping: spatial structure and regional dynamics', *Global Networks*, 12(3), pp. 395-423.

Ducruet, C. and Notteboom, T.E. (2021) 'Global maritime networks in container shipping', in *Maritime Logistics. A Guide to Contemporary Shipping and Port Management*.

Ducruet, C., Rozenblat, C. and Zaidi, F. (2010) 'Ports in multi-level maritime networks: evidence from the Atlantic (1996–2006)', *Journal of Transport Geography*, 18(4), pp. 508-518.

Ducruet, C. and Zaidi, F. (2012) 'Maritime constellations: a complex network approach to shipping and ports', *Maritime Policy and Management*, 39(2), pp. 151-168.

Earnest, D.C., Yetiv, S. and Carmel, S.M. (2012) 'Contagion in the Transpacific Shipping Network: International Networks and Vulnerability Interdependence', *International Interactions*, 38(5), pp. 571-596.

Easterby-Smith, M., Thorpe, R. and Lowe, A. (1991) *Management Research: an Introduction*. Sage Publications, London.

Ebery, J. (2001) 'Solving large single allocation p-hub problems with two or three hubs', *European Journal of Operational Research*, 128(2), pp. 447-458.

Ehmke, J.F., Campbell, A.M. and Urban, T.L. (2015) 'Ensuring service levels in routing problems with time windows and stochastic travel times', *European Journal of Operational Research*, 240(2), pp. 539-550.

Eide, M.S., Longva, T., Hoffmann, P., Endresen, Ø. and Dalsøren, S.B. (2011) 'Future cost scenarios for reduction of ship CO2 emissions', *Maritime Policy & Management*, 38(1), pp. 11-37.

Eisner, H., Marciniak, J. and McMillan, R. (1991) *Conference Proceedings 1991 IEEE International Conference on Systems, Man, and Cybernetics*. 13-16 Oct. 1991.

Erol, S. (2017) 'Calculation of the freight revenues in Turkey-focused maritime transportation', *Maritime Policy & Management*, 44(7), pp. 815-824.

Facchini, F., Digiesi, S. and Mossa, G. (2020) 'Optimal dry port configuration for container terminals: A non-linear model for sustainable decision making', *International Journal of Production Economics*, 219, pp. 164-178.

Falatoonitoosi, E., Leman, Z. and Sorooshian, S. (2013) 'Modeling for Green Supply Chain Evaluation', *Mathematical Problems in Engineering*, 2013, p. 201208.

Fan, H.S.L. (2002) 'A decision support system for port planning', *Journal of Decision Systems*, 11(3-4), pp. 317-332.

Fawcett Stanley, E., Osterhaus, P., Magnan Gregory, M., Brau James, C. and McCarter Matthew, W. (2007) 'Information sharing and supply chain performance: the role of connectivity and willingness', *Supply Chain Management: An International Journal*, 12(5), pp. 358-368.

Feng, M., Mangan, J. and Lalwani, C. (2012) 'Comparing port performance: Western European versus Eastern Asian ports', *International Journal of Physical Distribution & Logistics Management*, 42(5), pp. 490-512.

Feng, M., Shaw, S.L., Peng, G. and Fang, Z. (2020) 'Time efficiency assessment of ship movements in maritime ports: A case study of two ports based on AIS data', *Journal of Transport Geography*, 86.

Ferrari, C., Parola, F. and Tei, A. (2015) 'Determinants of slow steaming and implications on service patterns', *Maritime Policy & Management*, 42(7), pp. 636-652.

Forozandeh, M., Teimoury, E. and Makui, A. (2019) 'A mathematical formulation of time-cost and reliability optimization for supply chain management in research-development projects', *RAIRO - Operations Research*, 53(4), pp. 1385-1406.

Forrester, J.W. (1970) 'Urban Dynamics', *Industrial management review : IMR /*, 11(3), p. 67.

Frohlich, M.T. and Westbrook, R. (2001) 'Arcs of integration: an international study of supply chain strategies', *Journal of Operations Management*, 19(2), pp. 185-200.

Fusillo, M. (2004) 'Is Liner Shipping Supply Fixed?', *Maritime Economics & Logistics*, 6(3), pp. 220-235.

Gelareh, S. and Nickel, S. (2011) 'Hub location problems in transportation networks', *Transportation Research Part E: Logistics and Transportation Review*, 47(6), pp. 1092-1111.

Gelareh, S., Nickel, S. and Pisinger, D. (2010) 'Liner shipping hub network design in a competitive environment', *Transportation Research Part E: Logistics and Transportation Review*, 46(6), pp. 991-1004.

Gereffi, G. and Lee, J. (2014) 'Economic and social upgrading in global value chains and industrial clusters: Why governance matters', *Journal of Business Ethics*, 133(1), pp. 1-14.

Gidado, U. (2015) 'Consequences of port congestion on logistics and supply chain in African ports', *Developing Country Studies, Vol.5, No.6, pp.160-167.*

Gilman, S. (1980) 'A critique of the super-port idea', *Maritime Policy & Management*, 7(2), pp. 77-78.

Godschalk, D.R. (2003) 'Urban Hazard Mitigation: Creating Resilient Cities', *Natural Hazards Review*, 4(3), pp. 136-143.

Goldbeck, N., Angeloudis, P. and Ochieng, W. (2020) 'Optimal supply chain resilience with consideration of failure propagation and repair logistics', *Transportation Research Part E: Logistics and Transportation Review*, 133, p. 101830.

Gorod, A., Sauser, B. and Boardman, J. (2008) 'System-of-Systems Engineering Management: A Review of Modern History and a Path Forward', *IEEE Systems Journal*, 2(4), pp. 484-499.

Gouvernal, E. and Slack, B. (2012) 'Container freight rates and economic distance: a new perspective on the world map', *Maritime Policy and Management*, 39(2), pp. 133-149.

Guericke, S. and Tierney, K. (2015) 'Liner shipping cargo allocation with service levels and speed optimization', *Transportation Research Part E: Logistics and Transportation Review*, 84, pp. 40-60.

Guerrero, D. and Rodrigue, J.-P. (2014) 'The waves of containerization: shifts in global maritime transportation', *Journal of Transport Geography*, 34, pp. 151-164.

Gülmez, S., Denktaş Şakar, G. and Baştuğ, S. (2023) 'An overview of maritime logistics: trends and research agenda', *Maritime Policy & Management*, 50(1), pp. 97-116.

Gurning, S., Cahoon, S., Dragovic, B. and Nguyen, H.O. (2013) 'Modelling of multi-mitigation strategies for maritime disruptions in the wheat supply chain', *Strojniski Vestnik/Journal of Mechanical Engineering*, 59(9), pp. 499-510.

Guy, E. and Urli, B. (2006) 'Port Selection and Multicriteria Analysis: An Application to the Montreal-New York Alternative', *Maritime Economics & Logistics*, 8(2), pp. 169-186.

Ha, M.-S. (2003) 'A comparison of service quality at major container ports: implications for Korean ports', *Journal of Transport Geography*, 11(2), pp. 131-137.

Habibi, M. and Rehmatulla, N. (2009) 'Carbon Emission Policies in the Context of the Shipping Industry', *City University, London, CASS Business School*.

Haralambides, H. (2017) 'Globalization, public sector reform, and the role of ports in international supply chains', *Maritime Economics & Logistics*, 19(1), pp. 1-51.

Haralambides, H.E. (2002) 'Competition, Excess Capacity, and the Pricing of Port Infrastructure', *International journal of maritime economics*, 4(4), pp. 323-347.

Haralambides, H.E. (2019) 'Gigantism in container shipping, ports and global logistics: a time-lapse into the future', *Maritime Economics & Logistics*, 21(1), pp. 1-60.

He, Y., Yang, Y., Wang, M. and Zhang, X. (2022) 'Resilience Analysis of Container Port Shipping Network Structure: The Case of China', *Sustainability (Switzerland)*, 14(15).

Heydecker, B.G., Lam, W.H.K. and Zhang, N. (2007) 'Use of travel demand satisfaction to assess road network reliability', *Transportmetrica*, 3(2), pp. 139-171.

Heymann, S. and Grand, B.L. (2013) *2013 17th International Conference on Information Visualisation*. 16-18 July 2013.

Holling, C.S. (1973) 'Resilience and Stability of Ecological Systems', *Annual Review of Ecology and Systematics*, 4(1), pp. 1-23.

Hu, Y. and Zhu, D. (2009) 'Empirical analysis of the worldwide maritime transportation network', *Physica A: Statistical Mechanics and its Applications*, 388(10), pp. 2061-2071.

Hummels, D.L. and Schaur, G. (2013) 'Time as a Trade Barrier', *American Economic Review*, 103(7), pp. 2935-59.

Hussey, J. and Hussey, R. (1997) *Business Research: A Practical Guide for Undergraduate and Postgraduate Students*. Macmillan Press, London.

IMO (2015) 'Third IMO Greenhouse Gas Study 2014', *Suffolk, UK: International Maritime Organization*.

IMO (2022) *Rules on ship carbon intensity and rating system enter into force*. International Maritime Organization.

Ivanov, D. and Sokolov, B. (2013) 'Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under uncertainty', *European Journal of Operational Research*, 224(2), pp. 313-323.

Ivanova, G. (2021) *2021 13th Electrical Engineering Faculty Conference (BulEF)*. 8-11 Sept. 2021.

Jackson, M.C. (2009) 'Fifty years of systems thinking for management', *Journal of the Operational Research Society*, 60(1), pp. S24-S32.

Jiang, L., Jia, Y., Zhang, C., Wang, W. and Feng, X. (2019) 'Analysis of topology and routing strategy of container shipping network on "Maritime Silk Road"', *Sustainable Computing: Informatics and Systems*, 21, pp. 72-79.

Jiang, X., Fan, H., Luo, M. and Xu, Z. (2020) 'Strategic port competition in multimodal network development considering shippers' choice', *Transport Policy*, 90, pp. 68-89.

Kadaifci, C., Asan, U., Serdarasan, S. and Arican, U. (2019) 'A new rule-based integrated decision making approach to container transshipment terminal selection', *Maritime Policy & Management*, 46(2), pp. 237-256.

Kaluza, P., Kolzsch, A., Gastner, M.T. and Blasius, B. (2010) 'The complex network of global cargo ship movements', *J R Soc Interface*, 7(48), pp. 1093-103.

Karamperidis, S., Jackson, E. and Mangan, J. (2013) 'The use of indices in the maritime transport sector', *Maritime Policy and Management*, 40(4), pp. 339-350.

Karsten, C.V., Pisinger, D., Ropke, S. and Brouer, B.D. (2015) 'The time constrained multi-commodity network flow problem and its application to liner shipping network design', *Transportation Research Part E: Logistics and Transportation Review*, 76, pp. 122-138.

Kashiha, M., Thill, J.-C. and Depken, C.A. (2016) 'Shipping route choice across geographies: Coastal vs. landlocked countries', *Transportation Research Part E: Logistics and Transportation Review*, 91, pp. 1-14.

Kavussanos, M.G. and Visvikis, I.D. (2004) 'Market interactions in returns and volatilities between spot and forward shipping freight markets', *Journal of Banking & Finance*, 28(8), pp. 2015-2049.

Kepaptsoglou, K., Fountas, G. and Karlaftis, M.G. (2015) 'Weather impact on containership routing in closed seas: A chance-constraint optimization approach', *Transportation Research Part C: Emerging Technologies*, 55, pp. 139-155.

Ketokivi, M. and Mantere, S. (2010) 'Two Strategies for Inductive Reasoning in Organizational Research', *The Academy of Management Review*, 35(2), pp. 315-333.

Khaslavskaya, A. and Roso, V. (2020) 'Dry ports: research outcomes, trends, and future implications', *Maritime Economics and Logistics*, 22(2), pp. 265-292.

Kim, H. and O'Kelly, M.E. (2009) 'Reliable p-Hub Location Problems in Telecommunication Networks', *Geographical Analysis*, 41(3), pp. 283-306.

Kim, K., Jeong, B. and Jung, H. (2014) 'Supply chain surplus: Comparing conventional and sustainable supply chains', *Flexible Services and Manufacturing Journal*, 26(1-2), pp. 5-23.

Kireyev, A. and Leonidov, A. (2018) 'Network Effects of International Shocks and Spillovers', *Networks and Spatial Economics*, 18(4), pp. 805-836.

Koberg, E. and Longoni, A. (2019) 'A systematic review of sustainable supply chain management in global supply chains', *Journal of Cleaner Production*, 207, pp. 1084-1098.

Kou, Y., Luo, M. and Zhao, Y. (2018) 'Examining the theoretical–empirical inconsistency on stationarity of shipping freight rate', *Maritime Policy and Management*, 45(2), pp. 145-158.

Lai, K.-H., Lun, V.Y.H., Wong, C.W.Y. and Cheng, T.C.E. (2011) 'Green shipping practices in the shipping industry: Conceptualization, adoption, and implications', *Resources, Conservation and Recycling*, 55(6), pp. 631-638.

Lam, J.S.L. and Bai, X. (2016) 'A quality function deployment approach to improve maritime supply chain resilience', *Transportation Research Part E: Logistics and Transportation Review*, 92, pp. 16-27.

Lam, J.S.L. and Dai, J. (2012) 'A decision support system for port selection', *Transportation Planning and Technology*, 35(4), pp. 509-524.

Lam, J.S.L. and Gu, Y. (2013) 'Port hinterland intermodal container flow optimisation with green concerns: a literature review and research agenda', *Shipping and Transport Logistics, Vol. 5, No. 3, 2013*.

Lam, J.S.L. and Notteboom, T. (2014) 'The Greening of Ports: A Comparison of Port Management Tools Used by Leading Ports in Asia and Europe', *Transport Reviews*, 34(2), pp. 169-189.

Langen, P.W.d. (2007) 'Port competition and selection in contestable hinterlands; the case of Austria', *European Journal of Transport and Infrastructure Research*, 7(1).

Lättilä, L., Henttu, V. and Hilmola, O.-P. (2013) 'Hinterland operations of sea ports do matter: Dry port usage effects on transportation costs and CO2 emissions', *Transportation Research Part E: Logistics and Transportation Review*, 55, pp. 23-42.

Lee, C.-Y., Lee, H.L. and Zhang, J. (2015) 'The impact of slow ocean steaming on delivery reliability and fuel consumption', *Transportation Research Part E: Logistics and Transportation Review*, 76, pp. 176-190.

Lee, S. and Park, S.J. (2020) 'Who should lead carbon emissions reductions? Upstream vs. downstream firms', *International Journal of Production Economics*, 230.

Lhomme, S. (2016) 'Vulnerability and resilience of ports and maritime networks to cascading failures and targeted attacks', in *Maritime Networks: Spatial Structures and Time Dynamics*. pp. 229-241.

Li, H., He, F., Lin, X., Wang, Y. and Li, M. (2019) 'Travel time reliability measure based on predictability using the Lempel–Ziv algorithm', *Transportation Research Part C: Emerging Technologies*, 101, pp. 161-180.

Li, W. and Cai, X. (2007) 'Empirical analysis of a scale-free railway network in China', *Physica A: Statistical Mechanics and its Applications*, 382(2), pp. 693-703.

Lin, Y. and Wang, X. (2019) 'Port selection based on customer questionnaire: a case study of German port selection', *European Transport Research Review*, 11(1).

Lindstad, H., Asbjørnslett, B.E. and Strømman, A.H. (2011) 'Reductions in greenhouse gas emissions and cost by shipping at lower speeds', *Energy Policy*, 39(6), pp. 3456-3464.

Lindstad, H., Asbjørnslett, B.E. and Strømman, A.H. (2012) 'The importance of economies of scale for reductions in greenhouse gas emissions from shipping', *Energy Policy*, 46, pp. 386-398.

Lirn, T.C., Thanopoulou, H.A., Beynon, M.J. and Beresford, A.K.C. (2004) 'An application of AHP on transhipment port selection: A global perspective', *Maritime Economics and Logistics*, 6(1), pp. 70-91.

Liu, C.-L., Shang, K.-C., Lirn, T.-C., Lai, K.-H. and Lun, Y.H.V. (2018) 'Supply chain resilience, firm performance, and management policies in the liner shipping industry', *Transportation Research Part A: Policy and Practice*, 110, pp. 202-219.

Liu, C., Wang, J. and Zhang, H. (2018) 'Spatial heterogeneity of ports in the global maritime network detected by weighted ego network analysis', *Maritime Policy & Management*, 45(1), pp. 89-104.

Liu, H., Tian, Z., Huang, A. and Yang, Z. (2018) 'Analysis of vulnerabilities in maritime supply chains', *Reliability Engineering & System Safety*, 169, pp. 475-484.

Lordan, O., Sallan, J.M., Simo, P. and Gonzalez-Prieto, D. (2014) 'Robustness of the air transport network', *Transportation Research Part E: Logistics and Transportation Review*, 68, pp. 155-163.

Lordan, O., Sallan, J.M., Simo, P. and Gonzalez-Prieto, D. (2015) 'Robustness of airline alliance route networks', *Communications in Nonlinear Science and Numerical Simulation*, 22(1), pp. 587-595.

Lun, Y.H.V. (2011) 'Green management practices and firm performance: A case of container terminal operations', *Resources, Conservation and Recycling*, 55(6), pp. 559-566.

Malchow, M.B. and Kanafani, A. (2004) 'A disaggregate analysis of port selection', *Transportation Research Part E: Logistics and Transportation Review*, 40(4), pp. 317-337.

Mangan, J. and Lalwani, C. (2016) *Global Logistics and Supply Chain Management (3rd edition)*. John Wiley & Sons.

Mangan, J., Lalwani, C. and Gardner, B. (2002) 'Modelling port/ferry choice in RoRo freight transportation', *International Journal of Transport Management*, 1(1), pp. 15-28.

Mangan, J., Lalwani, C. and Gardner, B. (2004) 'Combining quantitative and qualitative methodologies in logistics research', *International Journal of Physical Distribution & Logistics Management*, 34(7), pp. 565-578.

Mangan, J. and McKinnon, A. (2019) 'Review of trends in manufacturing and global supply chains, and their impact on UK freight', *Future of Mobility*.

Mansouri, M., Nilchiani, R. and Mostashari, A. (2010) 'A policy making framework for resilient port infrastructure systems', *Marine Policy*, 34(6), pp. 1125-1134.

Manzano, M., Sahneh, F., Scoglio, C., Calle, E. and Marzo, J.L. (2014) 'Robustness surfaces of complex networks', *Scientific Reports*, 4(1), p. 6133.

Marín, A., Cánovas, L. and Landete, M. (2006) 'New formulations for the uncapacitated multiple allocation hub location problem', *European Journal of Operational Research*, 172(1), pp. 274-292.

Martí, L., Puertas, R. and García, L. (2014) 'The importance of the Logistics Performance Index in international trade', *Applied Economics*, 46(24), pp. 2982-2992.

Martínez-Pardo, A., Garcia-Alonso, L. and Orro, A. (2018) 'The role of the degree of use of the facilities in the port choice process: The Spanish dockside cranes case', *International Journal of Shipping and Transport Logistics*, 10(5-6), pp. 514-532.

Martínez-Zarzoso, I. and Nowak-Lehmann, F.D. (2007) 'Is distance a good proxy for transport costs? The case of competing transport modes', *The Journal of International Trade & Economic Development*, 16(3), pp. 411-434.

McCalla, R.J. (1994) 'Canadian container ports: how have they fared? How will they do?', *Maritime Policy & Management*, 21(3), pp. 207-217.

McGee, J.B., Rossetti, M.D. and Mason, S.J. (2004) 'Simulating transportation practices in Multi-Indenture Multi-Echelon (MIME) systems', *Proceedings - Winter Simulation Conference*. pp. 974-981.

Miller-Hooks, E., Zhang, X. and Faturechi, R. (2012) 'Measuring and maximizing resilience of freight transportation networks', *Computers & Operations Research*, 39(7), pp. 1633-1643.

Mingers, J. and Brocklesby, J. (1997) 'Multimethodology: Towards a framework for mixing methodologies', *Omega*, 25(5), pp. 489-509.

Mingers, J. and White, L. (2010) 'A review of the recent contribution of systems thinking to operational research and management science', *European Journal of Operational Research*, 207(3), pp. 1147-1161.

Mohammadi, M., Jula, P. and Tavakkoli-Moghaddam, R. (2019) 'Reliable single-allocation hub location problem with disruptions', *Transportation Research Part E: Logistics and Transportation Review*, 123, pp. 90-120.

Mohammadi, M. and Tavakkoli-Moghaddam, R. (2016) 'Design of a fuzzy bi-objective reliable p-hub center problem', *Journal of Intelligent and Fuzzy Systems*, 30(5), pp. 2563-2580.

Mokashi, A.J., Wang, J. and Vermar, A.K. (2002) 'A study of reliability-centred maintenance in maritime operations', *Marine Policy*, 26(5), pp. 325-335.

Molavi, A., Lim, G.J. and Race, B. (2020) 'A framework for building a smart port and smart port index', *International Journal of Sustainable Transportation*, 14(9), pp. 686-700.

Monios, J. (2011) 'The role of inland terminal development in the hinterland access strategies of Spanish ports', *Research in Transportation Economics*, 33(1), pp. 59-66.

Moon, D.S.-H. and Woo, J.K. (2014) 'The impact of port operations on efficient ship operation from both economic and environmental perspectives', *Maritime Policy & Management*, 41(5), pp. 444-461.

Moore, E.F. and Shannon, C.E. (1956) 'Reliable circuits using less reliable relays', *Journal of the Franklin Institute*, 262(3), pp. 191-208.

Morgan, G. and Smircich, L. (1980) 'The Case for Qualitative Research', *Academy of Management Review*, 5(4), pp. 491-500.

Mukherjee, P.K. and & Brownrigg, M. (2013) *Farthing on international shipping*. 4 edn. Springer, Berlin, Heidelberg.

Munim, Z.H. and Schramm, H.J. (2017) 'Forecasting container shipping freight rates for the Far East-Northern Europe trade lane', *Maritime Economics and Logistics*, 19(1), pp. 106-125.

Murray-tuite, P.M. (2006) *Proceedings of the 2006 Winter Simulation Conference*. 3-6 Dec. 2006.

Mutombo, K. and Ölçer, A. (2017) 'Towards port infrastructure adaptation: a global port climate risk analysis', *WMU Journal of Maritime Affairs*, 16(2), pp. 161-173.

Nam, H.-S. and Song, D.-W. (2011) 'Defining maritime logistics hub and its implication for container port', *Maritime Policy & Management*, 38(3), pp. 269-292.

Näslund, D. (2002) 'Logistics needs qualitative research – especially action research', *International Journal of Physical Distribution & Logistics Management*, 32(5), pp. 321-338.

Nath, M., Venkatramanan, S., Kaperick, B., Eubank, S., Marathe, M.V., Marathe, A. and Adiga, A. 812 (2019) 'Using Network Reliability to Understand International Food Trade Dynamics' *Studies in Computational Intelligence* [Conference Paper]. pp. 524-535.

Nguyen, S. and Wang, H. (2018) 'Prioritizing operational risks in container shipping systems by using cognitive assessment technique', *Maritime Business Review*, 3(2), pp. 185-206.

Nie, T., Guo, Z., Zhao, K. and Lu, Z.-M. (2015) 'New attack strategies for complex networks', *Physica A: Statistical Mechanics and its Applications*, 424, pp. 248-253.

Nielsen, P., Jiang, L., Rytter, N.G.M. and Chen, G. (2014) 'An investigation of forecast horizon and observation fit's influence on an econometric rate forecast model in the liner shipping industry', *Maritime Policy & Management*, 41(7), pp. 667-682.

Nir, A.S., Lin, K. and Liang, G.S. (2003) 'Port choice behaviour - From the perspective of the shipper', *Maritime Policy and Management*, 30(2), pp. 165-173.

Notteboom, T., Pallis, T. and Rodrigue, J.-P. (2021) 'Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis', *Maritime Economics & Logistics*, 23(2), pp. 179-210.

Notteboom, T. and Rodrigue, J.P. (2007) 'Re-assessing port-hinterland relationships in the context of global commodity chains', in *Ports, Cities, and Global Supply Chains*. pp. 51-68.

Notteboom, T.E. (2006) 'The Time Factor in Liner Shipping Services', *Maritime Economics & Logistics*, 8(1), pp. 19-39.

Notteboom, T.E., Parola, F., Satta, G. and Pallis, A.A. (2017) 'The relationship between port choice and terminal involvement of alliance members in container shipping', *Journal of Transport Geography*, 64, pp. 158-173.

Novaes, A.G.N., Scholz-Reiter, B., Silva, V.M.D. and Rosa, H. (2012) 'Long-term planning of a container terminal under demand uncertainty and economies of scale', *Pesquisa Operacional*, 32, pp. 55-86.

O'Kelly, M.E. (1986) 'The Location of Interacting Hub Facilities', *Transportation Science*, 20(2), pp. 92-106.

Omer, M., Mostashari, A., Nilchiani, R. and Mansouri, M. (2012) 'A framework for assessing resiliency of maritime transportation systems', *Maritime Policy & Management*, 39(7), pp. 685-703.

Pagell, M. and Shevchenko, A. (2014) 'Why Research in Sustainable Supply Chain Management Should Have no Future', *Journal of Supply Chain Management*, 50(1), pp. 44-55.

Pais Montes, C., Freire Seoane, M.J. and González Laxe, F. (2012) 'General cargo and containership emergent routes: A complex networks description', *Transport Policy*, 24, pp. 126-140.

Paridaens, H. and Notteboom, T. (2022) 'Logistics integration strategies in container shipping: A multiple case-study on Maersk Line, MSC and CMA CGM', *Research in Transportation Business & Management*, 45, p. 100868.

Parola, F., Risitano, M., Ferretti, M. and Panetti, E. (2016) 'The drivers of port competitiveness: a critical review', *Transport Reviews*, 37(1), pp. 116-138.

Parvaresh, F., Husseini, S.M.M., Golpayegany, S.A.H. and Karimi, B. (2014) 'Hub network design problem in the presence of disruptions', *Journal of Intelligent Manufacturing*, 25(4), pp. 755-774.

Peng, W., Bai, X., Yang, D., Yuen, K.F. and Wu, J. (2022) 'A deep learning approach for port congestion estimation and prediction', *Maritime Policy & Management*, 0(0), pp. 1-26.

Peris-Mora, E., Orejas, J.M.D., Subirats, A., Ibáñez, S. and Alvarez, P. (2005) 'Development of a system of indicators for sustainable port management', *Marine Pollution Bulletin*, 50(12), pp. 1649-1660.

Peters, H.J. (1990) 'SeaTrade, Logistics and Transport'.

Poirier, C. (1999) *Advanced supply chain management: How to build a sustained competitive advantage.* . San Francisco: Berrett-Koehler.

Potter, S. (2010) 'Transport integration — an impossible dream?', *Paper presented at the Universities Transport Study Group Annual Conferences, University of Plymouth.*

Prabhu Gaonkar, R.S. and Mariappan, V. (2020) 'Transportation time reliability appraisal in maritime context', *International Journal of Systems Assurance Engineering and Management*, 11(3), pp. 736-746.

Prabhu Gaonkar, R.S., Xie, M. and Fu, X. (2013) 'Reliability estimation of maritime transportation: A study of two fuzzy reliability models', *Ocean Engineering*, 72, pp. 1-10.

Prabhu Gaonkar, R.S., Xie, M. and Huang, H.Z. (2013) 'Optimizing maritime travel time reliability', *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 227(2), pp. 167-176.

Prabhu Gaonkar, R.S., Xie, M., Ng, K.M. and Habibullah, M.S. (2011) 'Subjective operational reliability assessment of maritime transportation system', *Expert Systems with Applications*, 38(11), pp. 13835-13846.

Preston, J. (2012) 'Integration for seamless transportation (Discussion Paper 2012–01).', *Paris: International Transport Forum.*

Psaraftis, H.N. and Kontovas, C.A. (2010) 'Balancing the economic and environmental performance of maritime transportation', *Transportation Research Part D: Transport and Environment*, 15(8), pp. 458-462.

Puerto, J., Ramos, A.B., Rodríguez-Chía, A.M. and Sánchez-Gil, M.C. (2016) 'Ordered median hub location problems with capacity constraints', *Transportation Research Part C: Emerging Technologies*, 70, pp. 142-156.

Qi, X. and Song, D.-P. (2012) 'Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times', *Transportation Research Part E: Logistics and Transportation Review*, 48(4), pp. 863-880.

Rajabi, A., Khodadad Saryazdi, A., Belfkih, A. and Duvallet, C. (2019) 'Towards Smart Port: An Application of AIS Data', *20th International Conference on High Performance Computing and Communications*. pp. 1414-1421.

Reggiani, A. (2013) 'Network resilience for transport security: Some methodological considerations', *Transport Policy*, 28, pp. 63-68.

Robinson, R. (2002) 'Ports as elements in value-driven chain systems: the new paradigm', *Maritime Policy & Management*, 29(3), pp. 241-255.

Romero-Faz, D. and Camarero-Orive, A. (2017) 'Risk assessment of critical infrastructures – New parameters for commercial ports', *International Journal of Critical Infrastructure Protection*, 18, pp. 50-57.

Salleh, N.H.M., Md Hanafiah, R., Ngah, A.H., Jeevan, J. and Abdullah, L. (2019) 'A framework proposal for evaluating the organizational reliability and capability of a liner shipping operator in a fuzzy context', *International Journal of Engineering and Advanced Technology*, 8(6 Special Issue 3), pp. 327-341.

Sánchez-Silva, M., Daniels, M., Lleras, G. and Patiño, D. (2005) 'A transport network reliability model for the efficient assignment of resources', *Transportation Research Part B: Methodological*, 39(1), pp. 47-63.

Saunders, M., Lewis, P. and Thornhill, A. (2009) *Research Methods for Business Students Ebook*. Harlow, UNITED KINGDOM: Pearson Education, Limited.

Saunders, M.N.K. (2015) *Research methods for business students*. Pearson Education.

Serra, P., Fadda, P. and Fancello, G. (2020) 'Investigating the potential mitigating role of network design measures for reducing the environmental impact of maritime Chains: The Mediterranean case', *Case Studies on Transport Policy*.

Serra, P. and Fancello, G. (2020) 'Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping', *Sustainability 12 (8), 3220*.

Serrano, M.Á. and Boguñá, M. (2003) 'Topology of the world trade web', *Physical Review E*, 68(1), p. 015101.

Seuring, S. (2011) 'Supply chain management for sustainable products – insights from research applying mixed methodologies', *Business Strategy and the Environment*, 20(7), pp. 471-484.

Shaw, S., Grant, D.B. and Mangan, J. (2021) 'A supply chain practice-based view of enablers, inhibitors and benefits for environmental supply chain performance measurement', *Production Planning & Control*, 32(5), pp. 382-396.

Shelmerdine, R.L. (2015) 'Teasing out the detail: How our understanding of marine AIS data can better inform industries, developments, and planning', *Marine Policy*, 54, pp. 17-25.

Shi, W., Li, K.X., Yang, Z. and Wang, G. (2017) 'Time-varying copula models in the shipping derivatives market', *Empirical Economics*, 53(3), pp. 1039-1058.

Sienkiewicz, J. and Hołyst, J.A. (2005) 'Statistical analysis of 22 public transport networks in Poland', *Physical Review E*, 72(4), p. 046127.

Skorin-Kapov, D., Skorin-Kapov, J. and O'Kelly, M. (1996) 'Tight linear programming relaxations of uncapacitated p-hub median problems', *European Journal of Operational Research*, 94(3), pp. 582-593.

Slack, B. (1985) 'Containerization, inter-port competition, and port selection', *Maritime Policy & Management*, 12(4), pp. 293-303.

Slack, B. (1999) 'Across the pond: container shipping on the North Atlantic in the era of globalisation', *GeoJournal*, 48(1), pp. 9-14.

Slack, B. and Gouvernal, E. (2016) 'Container Transshipment and Logistics in the Context of Urban Economic Development', *Growth and Change*, 47(3), pp. 406-415.

Snyder, L.V. and Daskin, M.S. (2005) 'Reliability Models for Facility Location: The Expected Failure Cost Case', *Transportation Science*, 39(3), pp. 400-416.

Song, D.-W. and Panayides, P.M. (2008) 'Global supply chain and port/terminal: integration and competitiveness', *Maritime Policy & Management*, 35(1), pp. 73-87.

Song, D.W. and Yeo, K.T. (2004) 'A competitive analysis of Chinese container ports using the analytic hierarchy process', *Maritime Economics and Logistics*, 6(1), pp. 34-52.

Soza-Parra, J., Raveau, S., Muñoz, J.C. and Cats, O. (2019) 'The underlying effect of public transport reliability on users' satisfaction', *Transportation Research Part A: Policy and Practice*, 126, pp. 83-93.

Spangler, W.S., Kreulen, J.T., Chen, Y., Proctor, L., Alba, A., Lelescu, A. and Behal, A. (2010) 'A smarter process for sensing the information space', *IBM Journal of Research and Development*, 54(4), pp. 1-13.

Spector, J.M., Christensen, D.L., Sioutine, A.V. and McCormack, D. (2001) 'Models and simulations for learning in complex domains: using causal loop diagrams for assessment and evaluation', *Computers in Human Behavior*, 17(5), pp. 517-545.

Sriver, R.L., Lempert, R.J., Wikman-Svahn, P. and Keller, K. (2018) 'Characterizing uncertain sea-level rise projections to support investment decisions', *PLOS ONE*, 13(2), p. e0190641.

Stathopoulos, A. and Tsekeris, T. (2003) 'Framework for analysing reliability and information degradation of demand matrices in extended transport networks', *Transport Reviews*, 23(1), pp. 89-103.

Stopford, M. (2009) 'Maritime Economics.', *3rd ed. London: Routledge.*

Styhre, L., Winnes, H., Black, J., Lee, J. and Le-Griffin, H. (2017) 'Greenhouse gas emissions from ships in ports – Case studies in four continents', *Transportation Research Part D: Transport and Environment*, 54, pp. 212-224.

Sun, X.T., Chung, S.H., Chan, F.T.S. and Wang, Z. (2018) 'The impact of liner shipping unreliability on the production–distribution scheduling of a decentralized manufacturing system', *Transportation Research Part E: Logistics and Transportation Review*, 114, pp. 242-269.

Suryawanshi, P. and Dutta, P. (2022) 'Optimization models for supply chains under risk, uncertainty, and resilience: A state-of-the-art review and future research directions', *Transportation Research Part E: Logistics and Transportation Review*, 157, p. 102553.

Tang, O. and Nurmaya Musa, S. (2011) 'Identifying risk issues and research advancements in supply chain risk management', *International Journal of Production Economics*, 133(1), pp. 25-34.

Thacker, S., Pant, R. and Hall, J.W. (2017) 'System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures', *Reliability Engineering & System Safety*, 167, pp. 30-41.

Thadakamalla, H.P., Raghavan, U.N., Kumara, S. and Albert, R. (2004) 'Survivability of multiagent-based supply networks: A topological perspective', *IEEE Intelligent Systems*, 19(5), pp. 24-31.

Tierney, K., Ehmke, J.F., Campbell, A.M. and Müller, D. (2019) 'Liner shipping single service design problem with arrival time service levels', *Flexible Services and Manufacturing Journal*, 31(3), pp. 620-652.

Tiwari, P., Itoh, H. and Doi, M. (2003) 'Shippers' Port and Carrier Selection Behaviour in China: A Discrete Choice Analysis', *Maritime Economics & Logistics*, 5(1), pp. 23-39.

Tongzon, J. (2001) 'Efficiency measurement of selected Australian and other international ports using data envelopment analysis', *Transportation Research Part A: Policy and Practice*, 35(2), pp. 107-122.

Tongzon, J.L. (2009) 'Port choice and freight forwarders', *Transportation Research Part E: Logistics and Transportation Review*, 45(1), pp. 186-195.

Tongzon, J.L. and Sawant, L. (2007) 'Port choice in a competitive environment: From the shipping lines' perspective', *Applied Economics*, 39(4), pp. 477-492.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review', *British Journal of Management*, 14(3), pp. 207-222.

Tsiotas, D. and Polyzos, S. (2015) 'Analyzing the Maritime Transportation System in Greece: a Complex Network Approach', *Networks and Spatial Economics*, 15(4), pp. 981-1010.

Tsolakis, S.D., Cridland, C. and Haralambides, H.E. (2003) 'Econometric Modelling of Second-hand Ship Prices', *Maritime Economics & Logistics*, 5(4), pp. 347-377.

Tvedt, J. (2003) 'A new perspective on price dynamics of the dry bulk market', *Maritime Policy & Management*, 30(3), pp. 221-230.

Ugboma, C., Ugboma, O. and Ogwude, I.C. (2006) 'An Analytic Hierarchy Process (AHP) Approach to Port Selection Decisions – Empirical Evidence from Nigerian Ports', *Maritime Economics and Logistics*, 8(3), pp. 251-266.

UNCTAD (2019) 'United Nations Conference on Trade and Development', *Review of Maritime Transport, Geneva: UNCTAD.*

UNCTAD (2021) 'United Nations Conference on Trade and Development', *Review of Maritime Transport, Geneva: UNCTAD.*

Veenstra, A.W. and Franses, P.H. (1997) 'A co-integration approach to forecasting freight rates in the dry bulk shipping sector', *Transportation Research Part A: Policy and Practice*, 31(6), pp. 447-458.

Vega, L., Cantillo, V. and Arellana, J. (2019) 'Assessing the impact of major infrastructure projects on port choice decision: The Colombian case', *Transportation Research Part A: Policy and Practice*, 120, pp. 132-148.

Veldman, S., Garcia-Alonso, L. and Liu, M. (2016) 'Testing port choice models using physical and monetary data: a comparative case study for the Spanish container trades', *Maritime Policy and Management*, 43(4), pp. 495-508.

Veldman, S., Garcia-Alonso, L. and Vallejo-Pinto, J.A. (2013) 'A port choice model with logit models: A case study for the Spanish container trade', *International Journal of Shipping and Transport Logistics*, 5(4-5), pp. 373-389.

Verschuur, J., Pant, R., Koks, E. and Hall, J. (2022) 'A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards', *Maritime Economics & Logistics*, 24(3), pp. 489-506.

Viljoen, N.M. and Joubert, J.W. (2016) 'The vulnerability of the global container shipping network to targeted link disruption', *Physica A: Statistical Mechanics and its Applications*, 462, pp. 396-409.

Wan, C., Yang, Z., Yan, X., Zhang, D., Blanco-Davis, E. and Ren, J. (2020) 'Risk-based resilience analysis of maritime container transport networks', *Proceedings of the 29th European Safety and Reliability Conference, ESREL 2019*. pp. 3667-3674.

Wan, C., Yang, Z., Zhang, D., Yan, X. and Fan, S. (2018) 'Resilience in transportation systems: a systematic review and future directions', *Transport Reviews*, 38(4), pp. 479-498.

Wang, C. and Wang, J. (2011) 'Spatial pattern of the global shipping network and its hub-and-spoke system', *Research in Transportation Economics*, 32(1), pp. 54-63.

Wang, G.W.Y., Zeng, Q., Li, K. and Yang, J. (2016) 'Port connectivity in a logistic network: The case of Bohai Bay, China', *Transportation Research Part E: Logistics and Transportation Review*, 95, pp. 341-354.

Wang, J.C., Wang, Z., Wang, Y.Y. and Lai, F. (2017) 'Impacts of information reliability in a supply chain with market disruption risks', *International Transactions in Operational Research*, 24(4), pp. 737-761.

Wang, J.J. and Cheng, M.C. (2010) 'From a hub port city to a global supply chain management center: a case study of Hong Kong', *Journal of Transport Geography*, 18(1), pp. 104-115.

Wang, S. and Notteboom, T. (2014) 'The Adoption of Liquefied Natural Gas as a Ship Fuel: A Systematic Review of Perspectives and Challenges', *Transport Reviews*, 34(6), pp. 749-774.

Wang, W.F. and Yun, W.Y. (2013) 'Scheduling for inland container truck and train transportation', *International Journal of Production Economics*, 143(2), pp. 349-356.

Wang, X., Meng, Q. and Miao, L. (2016) 'Delimiting port hinterlands based on intermodal network flows: Model and algorithm', *Transportation Research Part E: Logistics and Transportation Review*, 88, pp. 32-51.

Wanke, P.F., Barbastefano, R.G. and Hijjar, M.F. (2011) 'Determinants of Efficiency at Major Brazilian Port Terminals', *Transport Reviews*, 31(5), pp. 653-677.

Wanzala, W.G. and Zhihong, J. (2016) 'Integration of the extended gateway concept in Supply Chain disruptions Management in East Africa-Conceptual paper', *International Journal of Engineering Research in Africa*, 20, pp. 235-247.

WCED (1987) 'World Commission on Environment and Development', *Our common future. Oxford University Press, Oxford*.

Wei, H. and Sheng, Z. (2017) 'Dry ports-seaports sustainable logistics network optimization: Considering the environment constraints and the concession cooperation relationships', *Polish Maritime Research*, 24(S3), pp. 143-151.

Wiegmans, B.W., Hoest, A.V.D. and Notteboom, T.E. (2008) 'Port and terminal selection by deep-sea container operators', *Maritime Policy and Management*, 35(6), pp. 517-534.

Willingale, M.C. (1981) 'The port-routeing behaviour of short-sea ship operators; theory and practice', *Maritime Policy & Management*, 8(2), pp. 109-120.

Wilmsmeier, G. and Hoffmann, J. (2008) 'Liner Shipping Connectivity and Port Infrastructure as Determinants of Freight Rates in the Caribbean', *Maritime Economics & Logistics*, 10(1), pp. 130-151.

Wilmsmeier, G., Monios, J. and Lambert, B. (2011) 'The directional development of intermodal freight corridors in relation to inland terminals', *Journal of Transport Geography*, 19(6), pp. 1379-1386.

Winnes, H., Styhre, L. and Fridell, E. (2015) 'Reducing GHG emissions from ships in port areas', *Research in Transportation Business & Management*, 17, pp. 73-82.

Wittgenstein, L. (1961) *Tractatus Logico-Philosophicus*. RKP, London.

Wohlin, C., Runeson, P., da Mota Silveira Neto, P.A., Engström, E., do Carmo Machado, I. and de Almeida, E.S. (2013) 'On the reliability of mapping studies in software engineering', *Journal of Systems and Software*, 86(10), pp. 2594-2610.

Wolf, J. (2014) 'The Relationship Between Sustainable Supply Chain Management, Stakeholder Pressure and Corporate Sustainability Performance', *Journal of Business Ethics*, 119(3), pp. 317-328.

Woo, J.-K. and Moon, D.S.-H. (2014) 'The effects of slow steaming on the environmental performance in liner shipping', *Maritime Policy & Management*, 41(2), pp. 176-191.

Woo, S.H., Pettit Stephen, J. and Beresford Anthony, K.C. (2013) 'An assessment of the integration of seaports into supply chains using a structural equation model', *Supply Chain Management: An International Journal*, 18(3), pp. 235-252.

Wu, D., Wang, N., Yu, A. and Wu, N. (2019) 'Vulnerability analysis of global container shipping liner network based on main channel disruption', *Maritime Policy and Management*, 46(4), pp. 394-409.

Wu, J., Zhang, D. and Wan, C. (2019) 'Resilience assessment of maritime container shipping networks-A case of the Maritime Silk Road', *ICTIS 2019 - 5th International Conference on Transportation Information and Safety*. pp. 252-259.

Wu, P., Deng, G. and Tian, W. (2009) 'Research on time reliability of container liner shipping network', *2009 International Conference on Measuring Technology and Mechatronics Automation, ICMTMA 2009*. pp. 847-850.

Xiao, T. and Qi, X. (2016) 'A two-stage supply chain with demand sensitive to price, delivery time, and reliability of delivery', *Annals of Operations Research*, 241(1-2), pp. 475-496.

Xing, J. and Zhong, M. (2017) 'A reactive container rerouting model for container flow recovery in a hub-and-spoke liner shipping network', *Maritime Policy and Management*, 44(6), pp. 744-760.

Xing, M., Shi, X. and Zhang, W. (2018) 'Connectivity reliabilitsy of container shipping network of the 21st century maritime silk road', *5th International Conference on Industrial Economics System and Industrial Security Engineering, IEIS 2018 - Proceeding.*

Xu, J. (2017) 'Reasons of container terminal congestion of Shanghai Port and suggested solutions', *CHINA SHIP SURVEY.*

Xu, J.J., Yip, T.L. and Marlow, P.B. (2011) 'The dynamics between freight volatility and fleet size growth in dry bulk shipping markets', *Transportation Research Part E: Logistics and Transportation Review*, 47(6), pp. 983-991.

Xu, L., Shi, J., Chen, J. and Li, L. (2021) 'Estimating the effect of COVID-19 epidemic on shipping trade: An empirical analysis using panel data', *Marine Policy*, 133, p. 104768.

Yang, C.C., Marlow, P.B. and Lu, C.S. (2008) 'Evaluating key logistics service capabilities for Taiwanese liner shipping firms', *Proceedings of International Forum on Shipping, Ports and Airports, IFSPA 2008 - Trade-Based Global Supply Chain and Transport Logistics Hubs: Trends and Future Development*. pp. 122-136.

Yang, M., Liu, Y. and You, Z. (2010) 'The Reliability of Travel Time Forecasting', *IEEE Transactions on Intelligent Transportation Systems*, 11(1), pp. 162-171.

Yang, Z. and Chen, D. (2017) 'Robust optimisation of liner shipping network on Yangtze River with considering weather influences', *International Journal of Shipping and Transport Logistics*, 9(5), pp. 626-639.

Yau, K.L.A., Peng, S., Qadir, J., Low, Y.C. and Ling, M.H. (2020) 'Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology', *IEEE Access*, 8, pp. 83387-83404.

Yedla, S. and Shrestha, R.M. (2003) 'Multi-criteria approach for the selection of alternative options for environmentally sustainable transport system in Delhi', *Transportation Research Part A: Policy and Practice*, 37(8), pp. 717-729.

Yeo, G.-T., Roe, M. and Dinwoodie, J. (2008) 'Evaluating the competitiveness of container ports in Korea and China', *Transportation Research Part A: Policy and Practice*, 42(6), pp. 910-921.

Yeo, G.T., Bourlakis, M., Roe, M. and Dinwoodie, J. (2011) 'Measuring the competitiveness of container ports: logisticians' perspectives', *European Journal of Marketing*, 45(3), pp. 455-470.

Yin, J., Fan, L., Yang, Z. and Li, K.X. (2014) 'Slow steaming of liner trade: its economic and environmental impacts', *Maritime Policy & Management*, 41(2), pp. 149-158.

Yin, J. and Shi, J. (2018) 'Seasonality patterns in the container shipping freight rate market', *Maritime Policy and Management*, 45(2), pp. 159-173.

Yu, H., Fang, Z., Peng, G. and Feng, M. (2017) 'Revealing the linkage network dynamic structures of Chinese maritime ports through automatic information system data', *Sustainability (Switzerland)*, 9(10).

Yuan, C.Y., Hsieh, C.H. and Su, D.T. (2019) 'Effects of new shipping routes on the operational resilience of container lines: potential impacts of the Arctic Sea Route and the Kra Canal on the Europe-Far East seaborne trades', *Maritime Economics and Logistics*.

Yuen, C.-l.A., Zhang, A. and Cheung, W. (2012) 'Port competitiveness from the users' perspective: An analysis of major container ports in China and its neighboring countries', *Research in Transportation Economics*, 35(1), pp. 34-40.

Zacharia, Z.G., Sanders, N.R. and Nix, N.W. (2011) 'The Emerging Role of the Third-Party Logistics Provider (3PL) as an Orchestrator', *Journal of Business Logistics*, 32(1), pp. 40-54.

Zhang, L., Zeng, G., Guo, S., Li, D. and Gao, Z. (2017) 'Comparison of traffic reliability index with real traffic data', *EPJ Data Science*, 6(1), p. 19.

Zheng, J., Meng, Q. and Sun, Z. (2014) 'Impact analysis of maritime cabotage legislations on liner hub-and-spoke shipping network design', *European Journal of Operational Research*, 234(3), pp. 874-884.

Zhou, X., Jing, D., Dai, L., Wang, Y., Guo, S. and Hu, H. (2022) 'Evaluating the economic impacts of COVID-19 pandemic on shipping and port industry: A case study of the port of Shanghai', *Ocean & Coastal Management*, 230, p. 106339.

Zhou, Z., Cheng, S. and Hua, B. (2000) 'Supply chain optimization of continuous process industries with sustainability considerations', *Computers & Chemical Engineering*, 24(2), pp. 1151-1158.

Zsidisin, G.A. and Smith, M.E. (2005) 'Managing Supply Risk with Early Supplier Involvement: A Case Study and Research Propositions', *Journal of Supply Chain Management*, 41(4), pp. 44-57.