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Modelling the Factors Affecting Port Time Variability

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Modelling the Factors Affecting Port Time Variability

ABSTRACT

This paper investigates the impact of port-specific factors on port time variability by identifying, analysing, and modelling their effects. Key factors are innovatively extracted from Automatic Identification System (AIS) data and country-level port data, capturing port dynamics and complex vessel flow network metrics. Structural equation modelling (SEM) is employed to assess their influence on port time variability, defined as the deviation from the average port time - the interval between a vessel's arrival and departure.

The findings reveal that high-quality port infrastructure and geographically favourable locations enhance port logistics efficiency, leading to reduced port time variability. Additionally, port infrastructure quality, location conditions, and network connectivity positively influence port dynamic flow. Port network connectivity and dynamic flow partially mediate the relationship between location conditions and port time variability. These insights contribute to developing strategic port management approaches aimed at improving operational efficiency, reducing congestion and delays, and guiding long-term infrastructure investments to strengthen inter-port connectivity.

Key Words: Port time variability; Port delay; Port-specific factors; Port performance; and Port planning

1. Introduction

Port congestion and ship delay remained a major challenge for most port authorities and liner shipping companies. The global average time vessels spend at ports, used as a proxy for port congestion, has increased from 31.7 per cent in 2019 to 34.2 per cent in 2020, 34.9 per cent in 2021, and 35.7 per cent between January and September 2022 (Clarksons Research 2022). Likewise, approximately 32 per cent of global containership fleets have reported delays at ports between 2016 and 2019, and this is expected to increase to 37 per cent in 2022 (UNCTAD 2022). In addition, port turnaround time is projected to increase by 14 percent between 2021 and 2022. Out of twenty-five countries with the most vessel arrivals, twenty-three recorded an increase in port turnaround time, and fifteen are likely to experience a double-digit increase in 2021 (UNCTAD 2022). An improved theorisation of the factors affecting port delays is essential to manage supply chain disruptions, port performance, and the loss of trade (Fan et al. 2012; Gekara and Chhetri 2013; UNCTAD 2022).

Given the growing complexity and fragmented global supply chains in the post-covid era and recent trade war, port congestion is not only a major operational problem but also a strategic and policy challenge (Chen and Liu 2016; Leachman and Jula 2011; Meersman et al. 2012; Peng et al. 2022). Ports are also critical infrastructure vital for building national security and supply chain resilience to trade shocks. Port delay and congestion remain a main issue in global shipping, further compounded by increase in trade volumes, larger vessel sizes, and the complexity that comes with supply chain. Existing literature has discussed various time-based measures of port performances such as port turnaround time and port dwell time. Although these measures are valuable yet limited in providing actual information about port operations. Hence, it requires a more innovative and holistic approach to effectively capture port delays. In the following section, critical analysis of prevalent concepts and recognition of important shortcomings are proposed together with the new metric of ‘port time variability’ to address these shortcomings. The access to near-time Automatic Identification System (AIS) data may overcome some of the limitations associated with port turnaround time and port dwell time to enable better inter-port comparison and benchmarking of port performance. However, to effectively use AIS data, new measures of port delays need to be computed. In this study, a new concept called ‘port time variability’

is proposed as a surrogate measure of port delay. It is measured as the deviation from the average port time – the time interval between the arrival and departure of all vessels at a port in a particular period of time. The assumption is that the greater the deviation from the average port time, the greater the port delay. The average port time, similar to port turnaround time or port dwell time, is used as a standard or expected timeframe to help benchmark port delays.

There is lack of a general theory to conceptualise the complex interrelationships and interactions between port-related factors and port time variability. By understanding the factors that contribute to port time variability, the key drivers of success or failure can be identified to help formulate operational strategies to enhance port performance globally. More targeted strategies then can be deployed to enhance logistics efficiency, stimulate economic growth, and support sustainable port development. The use of a generic concept of port time variability may specifically assist port authorities to monitor and manage port congestion/delay against standard benchmarks, as well as devise instruments for long-term strategic investment in port infrastructure to enhance inter-port connectivity across port supply networks.

The broader aim of this paper is to identify, analyse, and model the effect of port-specific factors on port time variability. To achieve this aim, the study addresses the following three key research questions:

- How can port time variability be defined and measured to provide a standard metric for evaluating port delays port time variability at a global level?
- What are key port-specific factors that affect port time variability, and how do they interact within the context of the vicious circle theory?
- How the relationships between the port specific factors and port time variability be empirically modelled and tested?

The remainder of this paper is structured as follows. Section 2 reviews the literature related to port delays and congestion. Section 3 develops the conceptual framework using the theory of the vicious circle of port time variability and sets out the hypotheses for the structural model. Section 4 presents the source of datasets, meta data and variable construction. Section 5 undertakes construct validity and

presents model results. Section 6 includes a discussion and the managerial implications. Finally, section 7 summarises the conclusions of this study and discusses future research directions.

2. Literature review

2.1. Port time variability Concept

In the extant literature, port delay or congestion are well-defined and sufficiently measured constructs. However, there is no single universally acceptable concept agreed thus far to accurately reflect on the frequency and scale of port delay, despite the prevalence of myriad concepts. For example, port turnaround time, port dwell time, and port congestion are widely applied to measure port delay though with different connotations. For instance, port turnaround time is a metric used to measure the efficiency of a port's operations, specifically the time it takes for a vessel to complete its operations and depart from the port. It includes the time spent at the berth for loading or unloading cargo, as well as time spent waiting for berthing or for other services, such as pilotage or tug assistance (Ducruet et al. 2014). Whilst port dwell time is the time a vessel spends at port securing the vessel, discharging or loading cargo, and other activities (Raballand et al. 2012). Despite of many studies (Beuran et al. 2012; Moini et al. 2012; Moon and Woo 2014; Slack et al. 2018), the use of dwell time and turnaround time as the sole metric for assessing port congestion and delay remained debatable. For instance, port turnaround time only measures the time a ship spends in a port; thus, it may not include the waiting time to gain access to a berth, or the time it may take for customs and quarantine clearance. Port turnaround time is an absolute rather than a relative measure of port efficiency, which may be heavily affected by inadequate infrastructure, technological advancement, and location conditions. It will thus be unreasonable to compare the port efficiency of the Port of Mombasa with Port of Singapore as the factors driving port delays are substantially different. This lack of consensus on a common terminology to reflect port delay at an aggregate level consequently may lead to benchmarking and performance measurement issues. Korinek and Sourdin (2011) identified that port congestion causes a time delay in the movement of containerised cargo. Peng et al. (2022) stated that port congestion is often driven by longer queuing and increased waiting time of ships at ports. Nze and Onyemechi (2018) linked port

congestion to port dwell time, extra time on the voyage, delays, port turnaround time, and waiting time. Numerous concepts were developed to reflect port delay using different measures to tackle various bottlenecks in port operations. Despite extensive research, the literature lacks a universally accepted metric that comprehensively measures port delays while accounting for inter-port variability and the interplay of multiple factors. The reliance on absolute metrics such as port turnaround time and dwell time limits the ability to understand and address the systemic causes of delays. To address these gaps, the concept of **port time variability** has been proposed as a standardised metric for assessing port delays using the time-stamped AIS data on vessel movements. Port time variability is computed as a deviation from an expected or accepted condition or state (in this case, the average port time). Unlike traditional metrics, port time variability measures deviations from average port time, potentially incorporating both waiting and operational delays. Arguably, this concept indicates a form of port delay as it measures a temporary failing or slipping from a previous standard or depart from an accepted pattern or standard.

2.2. Port Delays Measurement and Metrics

Time is one of the central elements around which operations take place in any given port; therefore, port turnaround time and port dwell time continue to be general indicators for assessing port performance. The term port turnaround time refers to the time a vessel takes to arrive at the port, complete its cargo handling operations, and depart from the port (Ducruet et al., 2014). It is a composite measure encompassing various time-based components, including waiting, berthing, manoeuvring, and productive and idle time (Moon and Woo, 2014). Whereas port dwell time includes the time spent at various stages of cargo handling operations within the port, such as unloading, storage, customs clearance, and loading onto outbound vessels.

Some measures have captured operational inefficiency and delays, while others, such as port dwell time and port turnaround time, take a more holistic approach. Studies by Moon and Woo (2014); Sheikholeslami et al. (2014); UNCTAD (2018) have examined port delays through a wide range of time-based measures such as waiting time, manoeuvring time, berthing time, productive time, and idle

time. Some of these measures have captured operational inefficiency and delays. Whilst others such as Ducruet et al. (2014); Merckx (2005); Raballand et al. (2012); Slack et al. (2018) have applied more holistic concepts such as port dwell time and port turnaround time to measure the length of time a vessel spends at a port. Ducruet et al. (2014) measured port turnaround time as the average time a vessel needs to stay in port; On the other hand, Slack et al. (2018) simply computed port turnaround time as the length of time ships spends in port. Both widely applied concepts may not necessarily reflect port inefficiency or delay in port operations.

2.3 Determinants of Port Delays and Congestion

The current body of literature on port delay is extensive, yet inconclusive to ascertain key determinants and drivers and their compounded effects (Bai et al. 2022; Jiang et al. 2017; Peng et al. 2022; Pruyn et al. 2020). Various factors can influence port turnaround time. Lun et al. (2010) identify that low terminal productivity, including inefficiencies in cargo handling equipment, labour availability, and operational processes, can result in delays and longer turnaround times. Similarly, Moon and Woo (2014) reveal that inefficient port operations, such as delays in documentation, customs clearance, and cargo inspections, can affect port turnaround time. Slack et al. (2018) add that high yard congestion could delay locating and retrieving containers, leading to prolonged turnaround times. Notteboom (2006) notes that the increasing size of vessels in the shipping industry can affect port turnaround times. Larger vessel sizes may require more time for cargo handling operations due to increased volumes and complexities involved. In addition, Ducruet and Notteboom (2012) highlight the significance of berth availability and congestion concerning port turnaround time. Shortages of berths or berths that are congested with other vessels, can lead to delays in vessel arrivals and departures. Ships may be required to wait for their turn to access a berth, prolonging their overall turnaround time. On the other hand, port dwell time vary significantly depending on factors such as seasonal characteristics of products (Rodrigue and Notteboom, 2009), weather conditions, unexpected events (Maritime Traffic, 2019), availability of resources, gate operations (Kourounioti et al., 2016), port's geographical location, hinterland connections, intermodal transportation (Moini et al., 2012) all contribute to the duration containers spend at ports. The extended port dwell times negatively impact marine container shipping

operations, including unproductive movements, high yard storage occupancy, low container throughput, and increased trade logistics costs (Beuran et al., 2012).

Previous studies (Moini et al. 2012; Notteboom 2006; Peng et al. 2022) highlighted numerous port-related factors affecting port delay that include but are not limited to ageing physical infrastructure, inadequate port hinterland connectivity (Tongzon 2009; Gekara and Chhetri 2013), the unavailability of berths in peak times, the restricted maritime access routes (Meersman et al. 2012), increased container traffic, vessel upsizing (Fan et al. 2012), an unexpected waiting time (Nze and Onyemechi 2018), lower port productivity, and extreme weather conditions (Notteboom 2006), shortage of containers (UNCTAD 2021) and its knock-on effects on the wider port network (Jiang et al. 2017). Regression or optimisation methods are applied to either model the effect of factors on port delays or optimise port efficiency and performance. These studies have no doubt successfully achieved their research objectives; yet there is a lack of a broader theory development and simultaneous relationship testing. Knowing the complex interactions between port-related factors and port delays can help in making nuanced decisions to avoid avoidable demurrage costs, reduce loss time (Wang and Meng 2012), improve inventory management in the channel (Raballand et al. 2012), enhance port productivity (Nze and Onyemechi 2018) sustain reliability of liner schedules (Yap and Notteboom 2011), mitigate risks of CO2 emissions (Moon and Woo 2014), and retain shippers and consignees and long-term business sustainability.

Port delays are affected by a multitude of factors, as the delays could occur at different decoupling points in the port logistics operations. Notteboom (2006) reported four main sources that cause time delays in port, including unexpected waiting times before berthing or before starting loading/discharging (66.5%), a low level of port productivity (20.6%), unexpected waiting time for port-channel access (e.g., tidal windows, pilotage, and towage) (7.5%), and chance caused by bad weather at sea or on-route mechanical problems (5.3%). Likewise, based on the automatic identification system (AIS) data, Drewry (2022) observed that the total average vessel waiting time was longer than 4 hours in high-volume ports worldwide in 2021 and 2022. For this reason, Drewry (2022) presumed that congestion at ports would cause a delay in the following years. Table 1 presents the factors affecting

port delay and congestion in the current body of literature. These factors are identified from previous studies (Bai et al. 2021; Balliauw et al. 2020; Jiang et al. 2017; Meersman et al. 2012; Peng et al. 2022).

Table 1. A summary of major factors that affect port congestion.

Authors	Location scale	Method	Perspective	Factors
Bai et al. (2021)	Global	System dynamics	Carriers	Freight volume, port time, vessel speed and draft.
Balliauw et al. (2020)	Global	Geometric Brownian motion	Port authorities	Port infrastructure and port capacity.
Fan et al. (2012)	United States of America	An intermodal network flow model	Shippers and carriers	Port throughput, port capacity, the volume of import, and vessel sizes.
Jiang et al. (2017)	Global	Theoretical model	Shippers	Terminal capacity, speed, distance, and traffic volumes.
Ke et al. (2012)	Canadian	Graph model and analytic hierarchy process (AHP)	Port operators and carriers	Geographical location and port facilities.
Korinek and Sourdin (2011)	Global	Gravity model	Shippers and carriers	Logistics performance index and quality of port infrastructure.
Leachman and Jula (2011)	United States of America	Queuing model	Shippers and carriers	Queues at the terminals and queues outside the terminals.
Meersman et al. (2012)	Global	A survey	Shippers and carriers	Maritime access route, customs inspection, storage, berths availability, hinterland loading and unloading, hinterland connection, and terminal capacity.
Notteboom (2006)	Global	Trade-off analysis	Carriers	Terminal operations, port access, maritime passage, and chance.
Nze and Onyemechi (2018)	African	Regression analysis	Shippers and carriers	Cargo dwell time, transaction dwell time, operational dwell time, and storage dwell time.
Pelin et al. (2020)	Global	Analytic hierarchy process (AHP)	Shippers and carriers	Document procedures, ship traffic, port structure, port operation and management, strategy, and government policies.
Peng et al. (2022)	Global	Density-Based Spatial Clustering of Applications with Noise (DBSCAN)	Shippers and carriers	Port area, traffic volume, and turnaround time.
Pruyn et al. (2020)	Canadian	A Markov chain analysis (MCA)	Shippers and carriers	The days waiting time per port.
Slack (1985)	Global	Multiple regression analysis	Shippers and carriers	Berth length, water depth, number of granites, a total of TEUS, and vessel calls.
Talley (2006)	Global	Economic model	Shippers and carriers	Channel and berth accessibility, reliability entrance and departure gate reliability.

The causes for congestion at the ports are a combination of endogenous, exogenous, and subjective causes. Endogenous Factors internal to port operations. Port delays are significantly influenced by inefficiencies in port infrastructure, such as outdated equipment, inadequate berth availability, and insufficient capacity, which restrict operations and create bottlenecks (Notteboom, 2006; Jiang et al., 2017; Balliauw et al., 2020). Low terminal productivity, compounded by labor shortages and suboptimal operational processes, further exacerbates turnaround times (Lun et al., 2010). Delays in documentation, customs clearance, and inspections also contribute to operational inefficiencies, while high yard congestion slows container retrieval and disrupts workflows (Moon & Woo, 2014; Slack et al., 2018). Additionally, poor accessibility due to inadequate transport links hinders the seamless movement of cargo, amplifying delays and reducing overall port efficiency (Guy & Urli, 2006; Langen, 2007). Exogenous Factors are external to port operations. Port congestion is often exacerbated by increasing trade volumes and larger vessels, which place additional strain on resources and prolong cargo handling times (Fan et al., 2012; Notteboom, 2006; Peng et al., 2022). External factors such as adverse weather conditions, including storms and hurricanes, further delay vessel movements and operations (Li et al., 2015). Regulatory changes, including alterations to customs procedures or trade policies, disrupt port workflows, while workforce disruptions like labor strikes and shortages significantly reduce productivity (AbuAlhaol et al., 2018; Chen & Liu, 2016; Cullinane & Haralambides, 2021). Additionally, ports located in geographically challenging or poorly connected areas face delays due to limited accessibility and connectivity to major shipping routes (Lam & Dai, 2012).

Port delays are compounded by berth shortages and congestion, which force vessels to wait and extend turnaround times (Ducruet & Notteboom, 2012; Notteboom, 2006). Maritime access restrictions, such as tidal windows, pilotage, and towage requirements, further contribute to prolonged waiting times (Notteboom, 2006). Delays in intermodal transportation, driven by the availability and quality of inland transport modes, disrupt cargo movement during the exit phase (Raballand et al., 2012). Additionally, poor coordination among stakeholders—including port operators, shipping lines, customs authorities, and trucking companies—leads to operational inefficiencies and further delays (Fraser & Notteboom, 2014; Ghorbani et al., 2022).

3. Conceptual model and hypotheses development

Theoretical and conceptual models to explain port time variability or vessel delay at ports are immature and largely reflective of an embryonic development stage in maritime logistics. There are only a few attempts (Arvis et al. 2010; Notteboom 2006) to theorise port delays or inefficiency with limited empirical validation, generalisability, and interoperability. Arvis et al. (2010) developed a conceptual framework, grounded on the theory of vicious circle, to examine the vulnerability of logistics system performance in the context of landlocked nations. Founded on the theory of the vicious circle of poverty, proposed by Nurkse (1953) to illustrate lower levels of economic development, Arvis et al. (2010) applied the theory to systemic linkages between procedures and regulations and service quality and affordability in transit costs of being landlocked. Nurkse's theory (1953) incorporates both supply level and demand level where the former represents the vicious circle of "low income-low savings-low capital formation-low productivity-low output-low income"; whilst the latter reflects "low income-low purchasing power-low attractiveness of investment-low output-low income". Arvis et al. (2010) and later Rodrigue (2020) contextualised this theory to explain the nexus between logistics performance and trade facilitation.

In this study, a conceptual framework based on the logistics vicious and virtuous cycle theory is developed to explain the phenomenon of port time variability. The vicious circle of port time variability, as presented in Figure 1, is adapted from the seminal work of Arvis et al. (2010) to illustrate complex relationships between the factors linked to the negative feedback loops, leading to inefficiencies and delays. Such a setting forms a vicious circle where rent-seeking leads to poor quality of logistics services and unfavourable customs procedures and regulations. These factors inhibit investment in infrastructure resulting in the sustenance of a vicious cycle of rent-seeking and inferior service performance of ports. The key to improving port logistics services is a transition from a vicious towards a virtuous cycle.

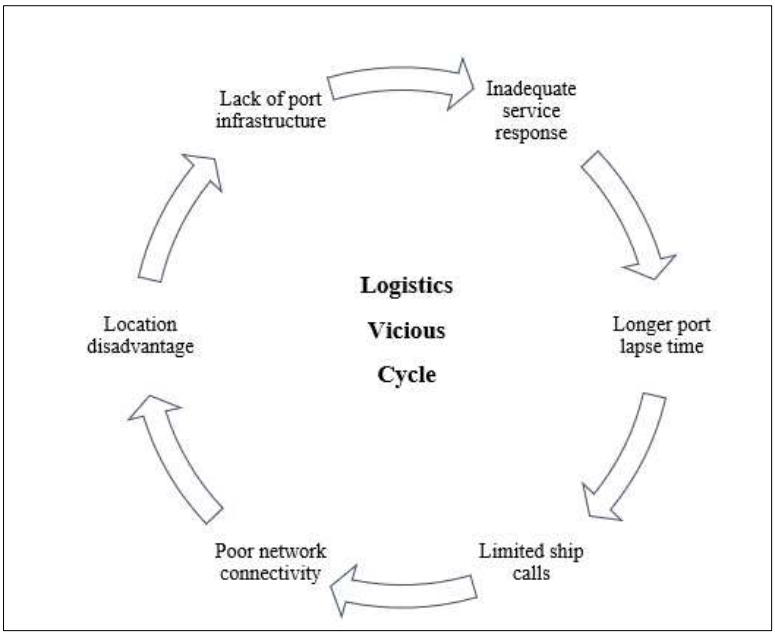


Figure 1. Vicious Cycle of Port time variability (adapted from Arvis et al. 2010; Rodrigue 2020).

Port time variability is subjected to a vicious cycle. For instance, a port with a locational disadvantage will attract low investment resulting in poor *port infrastructure* which can lead to delays in loading and unloading the cargo, resulting in the ship staying in port for too long and inhibiting the port's ability to provide *responsive services*. This inadequate service response will create inefficiencies resulting in a longer *port time variability*. The elevated port time variability is more likely to reduce the demand for the port services, which in turn *limits ship calls* resulting in port with *poor network connectivity* and a low degree of interconnectedness, consequently making port location less attractive to shipping liners. This reduced demand in tandem with elevated port time variability can lead to a lack of investment in port infrastructure, thus perpetuating the vicious cycle. To break this vicious cycle, it is therefore essential that proper investments are made to provide the adequate infrastructure that will enhance the service responsiveness, thereby reducing the port time variability, in turn leading to an improvement throughout the system

Adopting the vicious cycle model of logistics and reviewing the extant literature five broader factors are identified that influence port time variability. These factors include the quality of port infrastructure, location condition, service responsiveness, port network connectivity, and port dynamic flow. A

conceptual model of the hypothesised relationship among these factors is reflected in Figure 2 and the explanation for the relationships is discussed as follows. First, the quality of port infrastructure means the quality of port infrastructure to serve the vessels and transfer cargoes. Second, location conditions represent the physical geographic location of a port to accommodate ships and berthing functions. Third, service responsiveness represents the ability of a port to respond efficiently to provide logistics service to logistics companies. Fourth, port network connectivity is the degree to which a port is connected to or have access to other ports on the network. Fifth, port dynamic flow means the volume of the vessels departing and arriving at a port.

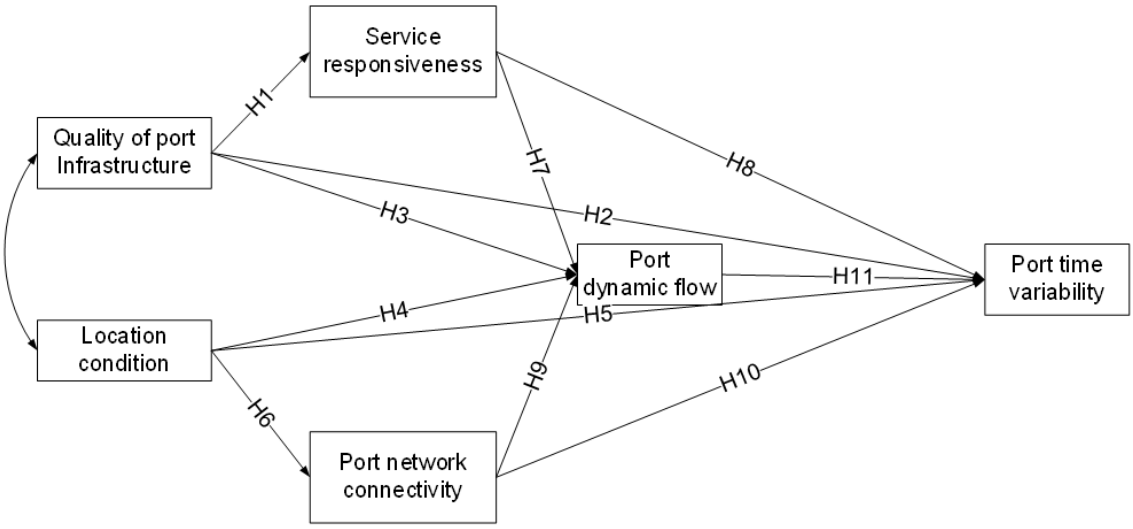


Figure 2. A conceptual model depicting the direction of causal relationships between constructs and port time variability.

Quality of port infrastructure represents the robustness of port infrastructure, such as the size of the terminal, the number of container berths, the quality of the crane, and the availability of intermodal transportation (Tongzon and Ganesalingam 1994). Previous empirical studies (Vega et al. 2019; Yudhistira and Sofiyandi 2018; Zhang et al. 2014) have proved that better port and logistic infrastructure improves port service responsiveness. Song et al. (2015) also stated that development in the quality of port infrastructure could reduce port congestion, whereas inadequate or poor port infrastructure may cause congestion at ports. In addition, the better quality of port infrastructure can attract carriers to operate at a port due to time economies, resulting in a dramatic increase in port flow

dynamics (Wang et al. 2020). A study by Zhu et al. (2021) confirmed that shipping lines prefer to call at the ports that offer better infrastructure. Thus, it can be hypothesised that.

H*$_1$: Quality of port infrastructure positively affects service responsiveness*

H*$_2$: Quality of port infrastructure negatively affects port time variability*

H*$_3$: Quality of port infrastructure positively affects port flow dynamic*

Location conditions can be defined as the location-related characteristics of a port, such as a harbour size, shelter afforded, channel depth, berth depth, and anchorage depth (Rodrigue 2020). Ding et al. (2019) reflected that a port with perfect location conditions could attract more vessels to berth. Wang and Cullinane (2016) added that better location conditions tend to enhance port dynamic flow and less waiting time. Notteboom (2016) supported the view that better location conditions can influence vessels to arrive on the scheduled time, especially for mega-containerships. In contrast, Ng and Liu (2014) found that the restricted location conditions can delay vessels arriving at the port. Bai et al. (2021) confirmed that physical limitations such as channel depth and quay length could bring increased difficulties to berthing operations, which contribute to a higher probability of causing a port delay.

H*$_4$: Location condition positively affects the port dynamic flow*

H*$_5$: Location condition positively affects port connectivity*

H*$_6$: Location condition negatively affects port time variability*

Service responsiveness refers to the ability of a port to provide quality service to port users, that is, shippers and carriers (World bank, 2018). Better service responsiveness tends to attract more carriers, thereby increasing port dynamic flows (Wilmsmeier 2015). Previous empirical work (Chen et al. 2022; Lee et al. 2018; Ren et al. 2018) supported the arguments that better service responsiveness can boost exports and port throughput. According to Balliauw et al. (2020), better service responsiveness can lead to less waiting time and less congestion. In addition, Chen and Liu (2016) believed that a port with abundant services and facilities could decrease delays in ports. Contrary, insufficient service responsiveness is the leading cause of long-time delays for container ships (Moini et al. 2012). Thus, it can be hypothesised that:

H*$_7$: Service responsiveness positively affects port flow dynamics*

***H_8**: Service responsiveness negatively affects port time variability*

Port network connectivity is related to the connectedness of a part to the container shipping port network (Parola et al. 2016). A port with a broad connection is likely to gravitate higher volume of vessel movements (Rodrigue 2020). Saeed et al. (2021) explored that improved maritime connectivity can lead to an increase in the number of ships called at a port. The UNCTAD (2021) reported that better connectivity could decrease the average time vessels spend in port. Jiang et al. (2014) also indicated that a port with a high level of connectivity may cause shorten the expected waiting time. Unlike, Lee and Lam (2015) commented that an increased volume of vessel arrivals and departures in a calling port might increase the probability of higher congestion. In the same vein, Peng et al. (2022) affirmed that the higher the frequency of ship arrivals, the greater the likelihood of ship delays. Thus, it can be hypothesised that:

***H_9**: Port network connectivity positively affects the port dynamic flow*

***H_{10}**: Port network connectivity negatively affects port time variability*

***H_{11}**: Port dynamic flow positively affects port time variability*

4. Methodology

4.1. Data sets used

In this study, three different datasets are used for analysis and modelling. These include Automatic Identification System (AIS) data, the World Bank, and the World Port Index of 401 ports in 119 countries. The AIS data was collected through an autonomous tracking system installed on ships to exchange navigational information. The transmission of data is electronically exchanged between AIS-receiving stations: onboard, ashore, or via satellite (AbuAlhaol et al. 2018). AIS data are of three types: static, dynamic, and voyage-related data. Static data provide vessel identification. Dynamic data are automatically updated from the vessel sensors connected to AIS. Voyage-related data need to be manually entered and updated during the voyage (IMO, 2002).

Port and country-level data are compiled from various sources. The first set of data relates to location conditions is collected from the World Port Index (The National Geospatial-Intelligence Agency, 2020).

These data describe the physical attributes of ports and terminals, including shelter afforded, harbour sizes, anchorage depth, channel depth, and cargo pier depth. The second set of data relates to the quality of port infrastructure which was obtained from the business's executive opinion survey (World Bank, 2018). The third set of data relates to service responsiveness and infrastructure quality, which were processed from the Logistics Performance Index (LPI) (World Bank, 2018). The LPI survey data provide information on how well the country is connected to the entire world logistically. There are six dimensions that are used to measure the LPI of a country that include customs, infrastructure, international shipments, logistics competence, tracking & tracing, and timeliness. Table 2 presents the list of variables used to model port time variability, along with descriptive statistics for those variables.

Table 2. Descriptive statistics of variables.

Constructs	Variables	S.D.	Min	Max	Skew	Kurtosis
Location condition	Shelter afforded (LC1)	0.90	1	5	-0.27	-0.33
	Harbour sizes (LC2)	1.08	1	5	-0.16	-0.77
	Anchorage depth (LC3)	4.32	1	5	-0.19	-0.68
	Channel depth (LC4)	3.59	1	5	-0.02	-0.49
	Cargo pier depth (LC5)	2.92	1	5	0.06	0.44
Port network connectivity	Accessibility (PNC1)	1.21	1	5	0.12	-0.39
	In degree (PNC2)	5.12	1	5	0.20	-0.27
	Out degree (PNC3)	4.98	1	5	0.19	-0.28
Port flow dynamic	Inflows (PFD1)	0.89	1	5	0.12	-0.39
	Outflows (PFD2)	1.12	1	5	0.12	-0.39
	Growth rate (PFD3)	0.95	1	5	0.03	-0.22
Quality of port infrastructure	Quality of port infrastructure (QPI1)	1.58	1	5	0.13	-0.26
	Infrastructure (QPI2)	0.96	1	5	0.05	-0.32
Services responsiveness	Logistics quality and competence (SR1)	0.92	1	5	0.05	-0.31
	Timeliness (SR2)	0.94	1	5	-0.01	-0.13
	Customs (SR3)	0.88	1	5	0.05	-0.32
Port time variability	Deviation from the average port time (PLT1)	0.39	1	5	0.01	-0.18
	Average port time (PLT2)	0.85	1	5	0.007	-0.17

4.2. Model variables and constructs

Port time variability is computed from the AIS data. Port time, the arrival and departure time of all the vessels, at a port is aggregated. The average port times of all vessels for each of the ports is then calculated. Hence, the unit of analysis is port instead of vessels for modelling port time variability. Port time variability is a measure of the relative dispersion of port time by comparing the standard deviation

to the mean. It indicates how much variation exists relative to the mean, useful for comparing datasets or units (e.g., comparing port time variability across ports with different average port times).

Five key factors impacting port time variability are computed, including location conditions, port network connectivity, port dynamic flow, quality of port infrastructure, and service responsiveness, as shown in Table 3. Location condition represents the physical geographic set-up of a port to accommodate ships and berthing functions and is made up of five variables. These variables are shelter afforded, harbour sizes, anchorage depth, channel depth, and cargo pier depth. A port's network connectivity is defined as the degree to which a port is connected to or has access to other ports on the network and is measured through three variables. These variables are accessibility, in-degree, and out-degree. Port dynamic flow is the volume of the inbound and outbound vessels departing and arriving at a port and consists of three variables, including inflow, outflow, and growth rate.

Quality of port infrastructure represents the condition of port facilities to serve the vessel and containerised cargo and is determined by two variables, including the quality of port and transport-related infrastructure. Service responsiveness represents the ability of a port to respond efficiently to provide logistics services to logistics companies and is measured by three variables, including logistics quality and competence, timeliness, and customs. A port time variability is the difference between the port's average berth time and the actual berth time for all the vessels. It is measured by two variables, which include average port time and deviation from the average port time.

Table 3. The computation of constructs and related variables.

Construct	Variables	Sources	Description	Formula
Port flow dynamic	Inflow	AIS	Total vessel inflows of a port (j).	$\sum_{j}^{N} T_j$
	Outflow	AIS	Total outflows of a port (i).	$\sum_{i}^{N} T_i$
	Growth rate	AIS	The percentage change in the inflow and outflow.	$\left(\frac{Tj-Ti}{Ti}\right) * 100$
Port network connectivity	In degree	AIS	The number of ties a port receives.	$S_i = C_D^w(i) = \sum_{j}^{N} Wij$
	Out degree	AIS	The number of ties a port sends.	$C_{D-in}^{w\alpha} = k_i^{in^{(1-\alpha)}} s_i^{in^{\alpha}}$
	Accessibility	AIS	The capacity of a location to be reached by, or to reach, different locations.	$A\,(P) = \sum_{i}^{n} P_i + \sum_{j}^{n} P_j/d_{ij}$

Construct	Variables	Sources	Description	Formula
Port time variability	Average port time	AIS	An average of the time between the arrival and departure of all ships at a port.	$\overline{x} = \frac{\sum x}{n}$
	Deviation from the average port time	AIS	A measure of a deviation from the average port t time.	$S = \sqrt{\frac{\sum_{[x-x^-]} 2}{n-1}}$
Location condition	Shelter afforded	World Port Index	The shelter afforded from wind, sea, swell.	
	Harbour sizes	World Port Index	The classification of harbour size based on area, facilities, and wharf space.	
	Anchorage depth	World Port Index	The least depth in the best anchorage.	
	Channel depth	World Port Index	The deepest channel in the best channel.	
	Cargo pier depth	World Port Index	The greatest depth alongside the respective wharf/pier.	
Quality of port infrastructure	Quality of port infrastructure	World Bank	The measurement of business executives' perception of the country's port facilities.	
	Infrastructure	World Bank	The quality of trade and transport-related infrastructure.	
Services responsiveness	Logistics quality and competence	World Bank	An evaluation of the competence and quality of logistics services.	
	Timeliness	World Bank	The timeliness of shipments arriving at their destination within the scheduled or expected delivery time.	
	Customs	World Bank	The efficiency of the clearance process by border control agencies.	

5. Results and Analyses

5.1. Construct reliability and validity

This study applied the maximum likelihood method (MLE), given that the multivariate normality assumptions were met. Table 4 presents the factor loadings, squared multiple correlation (SMC), cronbach's alpha (α), composite reliability (CR), and average variance extracted (AVE) of the model. All the factor loadings are above 0.7, squared multiple correlation (SMC) values are above 0.5, and average variance extracted (AVE) values are above 0.5. This supports the adequate convergent validity of the model. The value of χ^2/DF is 2.34 less than a threshold of 3, indicating model fit is acceptable (Kline 2016). Other goodness of fit statistics are also well supported and are consistent with the model fit, such as Comparative Fit Index (CFI) = 0.98, Incremental Fit Index (IFI) = 0.95, Tucker Lewis Index (TLI) = 0.97, Normed Fit Index (NFI) = 0.96, are all above 0.95 and Standardised Root Mean Square Residual (SRMR) = 0.03 that is less than a threshold of 0.05 (Collier 2020).

The findings indicate that the Cronbach's alpha (α) values for all constructs are greater than 0.70 in this study, which is well above the acceptable reliability. It is also found that the composite reliability for all the constructs is above 0.70, which is well within the acceptable threshold. A construct's distinctness and ability to properly reflect the phenomenon that are not captured by other constructs is evidenced by examining discriminant validity (Collier 2020). This study maintains discriminant validity by demonstrating that AVE values are greater than the inter-factor squared correlation coefficients, as shown in Table 4.

Table 4. Summary results of the measurement model.

Constructs	Items	Factor loadings	SMC (R^2)	Cronbach's alpha (α)	CR	AVE
Location condition	LC1	0.88	0.77	0.84	0.92	0.79
	LC2	0.87	0.76			
	LC3	0.94	0.88			
	LC4	0.93	0.86			
	LC5	0.83	0.69			
Port network connectivity	PNC1	0.89	0.79	0.94	0.80	0.70
	PNC2	0.84	0.71			
	PNC3	0.77	0.59			
Port flow dynamic	PFD1	0.92	0.85	0.86	0.82	0.73
	PFD2	0.78	0.61			
	PFD3	0.85	0.72			
Quality of port infrastructure	QPI1	0.81	0.66	0.81	0.67	0.62
	QPI2	0.76	0.58			
Services responsiveness	SR1	0.79	0.62	0.96	0.83	0.76
	SR2	0.95	0.90			
	SR3	0.88	0.77			
Port time variability	PLT1	0.81	0.66	0.87	0.89	0.61
	PLT2	0.75	0.56			

5.2. Results and Analysis

The results of the final model are presented in Figure 3 and Table 5. The finding shows a significant positive effect of the quality of port infrastructure on service responsiveness *($\beta = 0.22$; $t = 12.84$, $p < 0.01$)*. This implies that if the port facilities are of a higher standard, then the service provided will be more efficient. Location conditions were found to have a positive effect on port network connectivity *($\beta = 0.42$; $t = 13.17$, $p < 0.01$).* It is corroborated by the finding that an optimal port location can lead to a heightened level of interconnection between port networks. The results also indicate that the quality of port infrastructure, location conditions, and service responsiveness have a significant negative impact on port time variability respectively *($\beta = -0.21$; $t = 17.49$, $p < 0.01$), ($\beta = -0.27$; $t = 21.07$, $p < 0.01$),*

(β = -0.18; t = 10.78, p < 0.01). This implies that the reduction in port turnaround time can be attributed to the high-quality port infrastructure and location advantages of port services.

Furthermore, the quality of port infrastructure, location conditions, and port network connectivity were found to have a positive impact on port dynamic flow respectively *(β = 0.21; t = 19.21, p < 0.01), (β = 0.34; t = 22.61, p < 0.01), (β = 0.13; t = 9.56, p < 0.01).* This reflects that the high-level of service responsiveness, advantageous location, and optimal port facilities are likely to be the contributing factors to the large number of vessels arriving and departing at the port. The port dynamic flow was found to have a significant positive impact on port time variability (*β = 0.41; t = 13.45, p < 0.01*), suggesting that a large number of vessels arriving and departing at a calling port may likely increase the port time variability. However, the impact of service responsiveness on port dynamic flow *(β = 0.18; t = 1.94, p > 0.01* and port connectivity on port time variability *(β = 0.11; t = 2.72, p > 0.01)* were found to be insignificant.

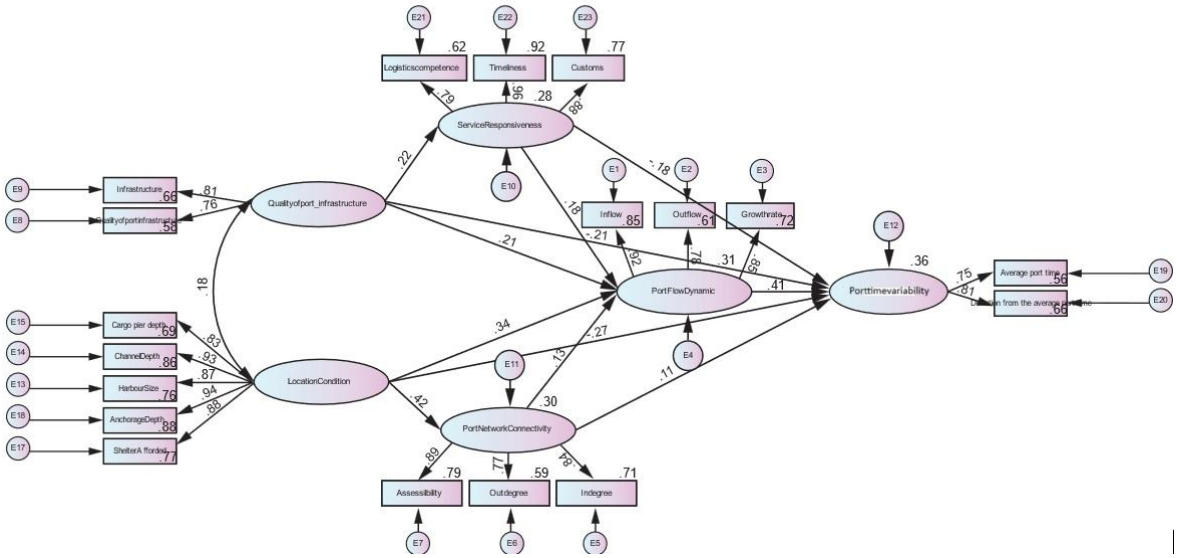


Figure 3. Full structural model results.

Table 5. Results of the full structural model

Hypothesised Relationships	Standardised Estimates (β)	t-value (C.R.)	Hypothesis Supported
H1: Quality of port infrastructure → Service responsiveness	0.22	12.84	Supported
H2: Quality of port infrastructure → Port time variability	-0.21	17.49	Supported
H3: Quality of port infrastructure → Port dynamic flow	0.21	19.21	Supported
H4: Location condition → Port dynamic flow	0.34	22.61	Supported
H5: Location condition → Port time variability	-0.27	21.07	Supported

Hypothesised Relationships	Standardised Estimates (β)	t-value (C.R.)	Hypothesis Supported
H6: Location condition → Port network connectivity	0.42	13.17	Supported
H7: Service responsiveness → Port dynamic flow	0.18	0.92	Not supported
H8: Service responsiveness → Port time variability	-0.18	10.78	Supported
H9: Port network connectivity → Port dynamic flow	0.13	9.56	Supported
H10: Port network connectivity → Port time variability	0.11	1.22	Not supported
H11: Port dynamic flow → Port time variability	0.41	13.45	Supported
Squared Multiple Correlation (R^2) :			
Service responsiveness	0.28		
Port network connectiviy	0.30		
Port dynamic flow	0.31		
Port time variability	0.36		
Model Fit Statistics :			
χ^2 = 225.34, df = 105, p < 0.01, CFI = 0.98, IFI = 0.96, NFI =0.97, TLI= 0.95, RMSEA = 0.037			

5.2.1 Mediation Effects

The results show a significant direct effect of the quality of port infrastructure on service responsiveness (H1), port time variability (H2), and service responsiveness on port time variability (H8). However, this also indicates a possible indirect effect of the quality of port infrastructure on port time variability via service responsiveness. As a result, a bias-corrected bootstrap confidence approach was used to test for indirect paths, with 2000 bootstrap samples. A significant test result indicates a mediation effect ($\beta = 0.321$ and $p<0.01$). This suggests that service responsiveness partially mediates the relationship between the quality of port infrastructure and port time variability.

The results also show a significant direct effect of the quality of port infrastructure on port time variability (H2), port dynamic flow (H3), and port dynamic flow on port time variability (H11). Hence, it is likely that the indirect effect of the quality of port infrastructure on port time variability via port dynamic flow exists. To evaluate this effect, a bias-corrected bootstrap confidence technique was used, which included 2000 bootstrap samples. A significant test result indicates that port dynamic flow partially mediates the relationship between the quality of port infrastructure and port time variability ($\beta = 0.384$ and $p<0.01$).

Similarly, the findings also show that location condition has a significant direct effect on port dynamic flow (H4), port time variability (H9), and port dynamic flow on port time variability (H11). This leads us to conclude that the indirect effect of location conditions on port time variability through

port dynamic flow could be conceivable. To affirm the mediation effect, bias-corrected bootstrap confidence approach was employed, with 2000 bootstrap samples. As the test results were statistically significant ($\beta = 0.412$ and $p<0.01$), it is evident that port dynamic flow partially mediates the relationship between location condition and port time variability.

Lastly, the findings demonstrate a significant direct effect of location conditions on port time variability (H5), port network connectivity (H6), port network connectivity on port dynamic flow (H9), and port dynamic flow on port time variability (H11). Consequently, it is possible that the serial indirect effects of location condition on port time variability via port network connectivity and port dynamic flow can be established. To check for indirect paths, the bias-corrected bootstrap confidence approach was used with 2000 bootstrap samples. A significant test result indicates a serial mediation effect ($\beta = 0.195$ and $p<0.01$), which implies that port network connectivity and port dynamic flow partially mediates the relationship between location condition and port time variability.

Table 6. Test for mediation using a bootstrap analysis with 95% confidence interval.

Relationships	Indirect Effect	Confidence Interval		p-value	Conclusion
		Low	High		
Quality of port infrastructure → Services responsiveness → Port time variability	0.321	0.143	0.424	< 0.01	Partial mediation
Quality of port infrastructure → port dynamic flow → port time variability	0.384	0.235	0.561	< 0.01	Partial mediation
Location conditions → Port dynamic flow → Port time variability	0.412	0.214	0.623	< 0.01	Partial mediation
Location condition → Port network connectivity → Port dynamic flow → Port time variability	0.195	0.175	0.324	< 0.01	Partial mediation

Note: Unstandardised coefficients reported.

6. Policy Implications

There are numerous policy implications of the findings of this study. More broadly, the evidence generated informs port authorities to improve the management of port operations and strategic planning for future investment in port infrastructure. Ship owners will benefit from the findings in judging the future choices of ports and their connected maritime shipping routes. It may also help regulators in devising a long-term strategy and implementing new policies to stimulate containerised trade through

strategic alliances or monetary incentives. Aligned to the key findings, the following policy implications are presented.

6.1 The quality of port infrastructure and the emergence of fourth-generation ports

The quality of port infrastructure has a positive impact on service responsiveness. Policymakers could thus focus on improving the quality of port infrastructure to enhance service responsiveness. Previous studies showed that countries with better port infrastructure also exhibit efficient customs procedures, which is one of the components of service responsiveness. For instance, Singapore, Malaysia, and Japan have been successful in improving the quality of port infrastructure and maintaining excellent and efficient customs procedures (Vidya and Taghizadeh-Hesary 2021). Moreover, a good quality port infrastructure facilitates and improves logistic activities.

With excellent port infrastructures world's leading ports, such as the port of Rotterdam, port of Antwerp, port of Barcelona, and port of Panama, have been successful in providing logistics and value-added activities within the port area. To gain a competitive advantage, the world's top ports are emerging as fourth-generation ports as logistics platforms. And for this purpose, improving the quality of port infrastructure is crucial. Given that the service gets better if the infrastructure is good, therefore, to further enhance efficient port operation/services, they may adopt a Single Window System, which allows traders to submit all import, export, and transit information required by regulatory agencies via a single electronic gateway. It will be of benefit to port authorities and regulators by cutting costs by reducing delays, faster clearance, and more effective and efficient deployment of resources.

6.2 Improvements in location conditions to enhance port network connectivity

The location advantage of a port can forms a broader port network. With excellent location conditions such as harbor size, anchorage, and channel depths, the top maritime economies in the world (China, the USA, Japan, Singapore, and Germany) have developed excellent port network connectivity. These strong economies are also among the top-ten best maritime-connected countries in the world (UNCTAD 2018). The geographical location of ports is naturally determined; however, it is possible to improve the location condition by enhancing other attributes. For instance, several ports in the USA, such as Miami, New York, and Savannah, did the dredging to expand the channel depth (Rodrigue

2020). Other ports that invested in the port's expansion are the port of Jacksonville, the port of Miami, the port of Mobile, Alabama, and the port of Long Beach. To further enhance the port network, port authorities may develop freight corridors to neighbour countries and promote new trade routes.

6.3 Strategies to reduce port time variability and improve port dynamic flow

It was also found that there is a negative relationship between location conditions and port time variability. In response, it would be interesting to encourage carriers and port operators to establish their commercial shipping operations through tax exemptions, spatial expansion of a port, and network-related functional expansion. Further, service responsiveness has contributed to the decline in port time variability; thereby it is useful for port authorities to propose mobile integrated functions in IT systems and adopt cloud-based technology. These can provide transparency on shipments, reduced handovers, waiting times, and handling costs. This study found that port network connectivity has a positive impact on port dynamic flow. To further enhance vessel flows, port operators may provide an added incentive for carriers to attract businesses with less connected and accessible ports by establishing Free Trade Zones.

6.4 Need for port governance model transformation

Ports' infrastructure development and improvement of location conditions require substantial expenditure, which the governments usually finance under service and tool port models. However, governments, especially in developing countries, might not have enough resources to cover these expenditures or face hurdles such as political and economic policies, which prefer other areas than port development. Moreover, the public sector often has a limited interest in increasing ports' efficiency and profitability (The World Bank, 2007). To overcome this, it is recommended that policymakers and port authorities, especially in developing economies, switch the port governance model from tool and service port to the landlord port model, which involves the private sector's participation in ports' development and expansion. In addition to this, vertical integration among ports and other stakeholders (for instance, shipping lines) and horizontal integration among ports are recommended to develop and expand ports' capacity.

6.5. Importance of application of big data analysis in maritime logistics

The growing interest in big data analysis in supply chain management has revolutionized this field, and its application has resulted in several benefits such as reduction in operational cost, adoption of better supply chains strategies such as agility, innovation, and value creation for the final customer to improve their satisfaction (Nguyen et al. 2018). Despite this growing interest and awareness about the feasibility of big data analysis, its application in the supply chain, including the maritime sector, is limited. This study is one of the few studies in the maritime field which applies extensive data extracted from different sources to explore the port-specific factors affecting ports' time variability and thus raises the importance of big data analysis for sound policy recommendations.

It is recommended that the stakeholders in the maritime supply chain should collaborate to collect and share extensive data for research analysis and policy implications. The drastic advancement in information and communication technologies has simplified the big data collection procedure. However, collaborative efforts among players are still essential to extract quality data from other parts of the maritime supply chain and gather it in one or few platforms to make it easily accessible for researchers and practitioners.

7. Conclusion

In conclusion, this study highlighted port delay as a major challenge associated with container liner shipping and the root causes of port delays are multidimensional and complex. The utilisation of AIS data, however, provided a better insight into the effect of location advantage and inter-port connectivity on port time variability at a global scale. A new framework is developed to theorise and measure the relationships between the key factors and port time variability. The results highlight the significant contribution of geographical location, port accessibility, port connectivity, and port infrastructure in mitigating the time-related risks associated with port time variability. This paper concludes that: i) the quality of port infrastructure has a significant impact on service responsiveness; ii) location conditions tend to affect port dynamic flows and port network connectivity; iii) service responsiveness is likely to impact on port time variability; and iv) port network connectivity and port dynamic flow partially mediate the relationship between location conditions and port time variability.

This study contributes to the current body of knowledge in three different ways. First is the adoption of a holistic approach to model the complexity at a global scale to enhance a better understanding of port time variability. Second is the utilisation of AIS data, which is collated from real-time tracking of ships, to analyse and map port dynamics and complex flow networks to model port time variability. This in turn has added quantitative vigour and depth to the existing theoretical models. Third is the application of SEM to develop and examine the complex interactions between port-related factors and port time variability.

There are, however, a few limitations of the method adopted in this study. Addressing them can help set out the agenda for future research. The first limitation is data aggregation, whereby the data at a vessel level is aggregated to a port level. This process may have resulted in the loss of finer granularity and details, the inclusion of which may provide deeper insights onto the complexity of factors affecting vessel movement patterns and delays at ports or in-transit. The second is the use of data on port infrastructure and service responsiveness at the country level. This is important for countries with multiple ports representing significant variability in port infrastructure service quality. The final limitation is the time-stamped AIS data, which may not accurately reflect real-time relay of information on vessel movements.

Future research will collect and collate more details port level service responsiveness and port infrastructure data to enable analysis of port time variability at a global level. A further study will explore the use of machine learning and other advanced AI techniques to identify movement patterns and relationships within the data and uncover new insights into the factors that influence vessel movements and port congestion. Additionally, future research will also investigate the potential use of vessel level AIS data to provide more accurate and up-to-date information on vessel movements and port conditions, which would enable real-time modelling of port time variability and decision-making process related to berth allocation, ship scheduling and operational planning.

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