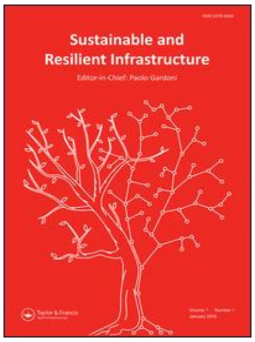

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REVIEW ARTICLE

Port disruption impact on the maritime supply chain: a literature review

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ABSTRACT

Maritime transportation systems are responsible for the transportation of the vast majority of global overseas trade. Ports are fundamental agents of the maritime transportation system, being the point of entry and exit of most imported and exported goods. Ports are also important nodes in intermodal transportation systems, making the connection between maritime, rail, and road transportation. Nonetheless, the study of the impacts of maritime transportation and port disruptions in the literature is still in its early stages. Similarly, port resilience and intermodal transportation resilience considering maritime transportation have not yet received significant attention from academic researchers. This article provides a review of the existing literature in maritime supply chain and port disruptions. The goal is to contribute to the literature by presenting the topics that have been addressed and identifying gaps of knowledge that can be explored.

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Resilience; maritime transportation system; port disruption

1. Introduction

Maritime transportation systems are as economically important as they are complex. Over 90% of the global trade is transported by sea (International Maritime Organization, 2018) and the world fleet is continuously growing, with over 93 thousand commercial vessels registered in 2017. This represents a capacity of more than 1.86 billion deadweight tons (Asariotis et al., 2016). In the United States alone, the maritime transportation system is responsible for more than 23 million jobs, supports over 99% of the volume of oversea trades, and the total economic impact of ports (direct and indirect) exceeds $4.5 trillion dollars annually (American Association of Port Authorities, 2015; Aylward et al., 2016; Touzinsky et al., 2018).

Most ports are located in low-lying coastal areas or at mouths of rivers, exposing them to a variety of environmental hazards, such as tropical storms, which bring extreme winds, flooding, and storm surge. Climate change impacts in the form of sea-level rise, increased storm intensity, and increased flooding, aggravate these hazards and reveal ports‘ vulnerabilities (Becker et al., 2012; Repetto et al., 2017; Touzinsky et al., 2018).

Despite its undeniable importance to global trade and transportation, studies focused on port disruptions and on improving port resilience are still sparse, showing that the topics have not yet received substantial attention in the literature (Gharehgozli et al., 2016). To the best of our knowledge, the most recent works reviewing maritime supply chain disruption and risk management were conducted by Madhusudan and Ganapathy (2011), Oztanriseven et al. (2014), and Salleh et al. (2015).

Madhusudan and Ganapathy (2011) performed a thorough investigation of research on disaster resilience of transportation infrastructure and seaports. Their work covers papers published until 2011 in the areas of disaster in general, disaster resilience, transportation infrastructure resilience, and port resilience. They conclude that there is a significant amount of work on disaster resilience in terms of infrastructure disasters and community resilience. Work related to port resilience or disaster resilience of port linked intermodal transportation, on the other hand, is scarce. More recently, Oztanriseven et al. (2014) reviewed applications of system dynamics in the maritime transportation system. According to the authors, system dynamic models are able to depict the complexity of the maritime transportation system and should be used to better understand and improve the maritime transportation system. Finally, Salleh et al. (2015) reviewed the literature related to supply chain risk management in the container liner shipping industry.

This literature review goes beyond that of the previous work in that it identifies and addresses the impacts of a disruption to multiple agents in the system and includes significant literature on the impacts of

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port disruption on maritime supply chains. Among the topics reviewed are the identification of the agents affected directly or indirectly by a port disruption and the impacts of a port shutdown to different stakeholders. This article also reviews port and maritime supply chain resilience, including both quantitative and qualitative methods. Finally, literature in maritime intermodal transportation is also reviewed.

The remainder of this paper is organized as follows: Section 2 explores work on port and maritime supply chain disruptions, focusing on the identification of main stakeholders and the study of maritime supply chain uncertainty and its impact on stakeholders; Section 3 refers to port resilience literature, emphasizing resilience actions taken by stakeholders; Section 4 presents literature available on maritime intermodal transportation; finally, Section 5 presents our concluding remarks and future research suggestions.

2. Maritime supply chain and port disruption impacts

Most literature available on maritime transportation systems and port disruptions apply analytical methods and simulation models to liner shipping network reliability and container terminals. Areas such as the integration between ports and other modes of transport, as well as the entire maritime supply chain are limited (Acciaro & Serra, 2013; Berle, 2012). The following sections present studies that (i) identify port stakeholders and (ii) address the sources of uncertainty in the maritime supply chain that may lead to port disruptions and identify the impacts of these disruptions to specific stakeholders.

2.1. Agents of a maritime supply chain: port primary stakeholders

Ports are intricate operational systems and include multiple stakeholders. The vast network of stakeholders includes, but is not limited to, terminal operators, shippers, federal, state and local government representatives, environmental agencies and non-governmental organizations, academic researchers, as well as the surrounding communities (Becker & Caldwell, 2015; Mostashari et al., 2011; Shaw et al., 2017). These stakeholders commonly have different, if not competing, interests, such as higher revenue, increased customer satisfaction, or reduced environmental impacts (Notteboom, 2004; Panayides, 2006).

According to Gharehgozli et al. (2016), protecting ports from adverse weather impacts while also considering all stakeholders and variables involved is a ‘wicked problem’ – a problem characterized by being difficult or impossible to solve due to incomplete, contradictory, and changing requirements that are often difficult to recognize (Gharehgozli et al., 2016; Head & Alford, 2015).

It is possible to study a port through the lens of the stakeholder cluster (Becker & Caldwell, 2015; De Langen, 2004; Gharehgozli et al., 2016; Lam et al., 2013; Winkelmans & Notteboom, 2007). Clusters are commonly used by strategic management scholars to analyze systems by identifying groups of stakeholders with common interests (Freeman, 1984). Based on the idea of clusters, some authors define the stakeholders of a port as any group or individual who can affect or is affected by the achievement of the port’s objectives (Gharehgozli et al., 2016). Other authors (Becker et al., 2013; Becker & Caldwell, 2015) include in the port stakeholder concept the key stakeholders that have an interest in the functioning of a port and can somehow contribute, either in planning or decision-making, to the port.

In general management, stakeholders may be clustered into three categories: internal, external, or interface. Internal stakeholders include employees and middle managers. External stakeholders include the local community, federal government, suppliers, competitors, and customers. Finally, interface stakeholders are represented by a corporation’s board of directors and its auditors (Savage et al., 1991). An alternative stakeholder framework, proposed by Clarkson (1995) while evaluating corporate social performance and the relationship between corporations and society, consists of grouping stakeholders into primary and secondary classes. The former is comprised of stakeholders who have a formal relationship with and a direct economic impact upon the organization. The latter includes stakeholders that affect or are affected by the corporation’s operations, but are not essential for the continuity of these operations.

In maritime transportation supply chain, stakeholders are commonly clustered into two primary categories: external and internal stakeholders (Becker & Caldwell, 2015; De Langen, 2006; Denktas-Sakar & Karatas-Cetin, 2012; Winkelmans & Notteboom, 2007). Becker and Caldwell (2015) define internal stakeholders as those who constitute parts of the port authority organization and are generally most concerned with return on investment, shareholder value and creation of wealth. The authors subcategorized the external stakeholders into four other groups: economic/contractual, public policy, community/environmental, and academic/research. Economic/contractual stakeholders are involved in port operations and are represented by shippers, tenants, trucking companies, insurers, and others. Public policy stakeholders are further divided into local, state, and federal. They include government agencies that are responsible for transportation and economic affairs, environmental agencies, planning departments, and emergency management agency. Community/environmental stakeholders consist of environmental groups, neighboring residents, community groups, and even the general public. Finally, academic/research stakeholders are an important group, since they often contribute with relevant information for the port planning process. This cluster includes organizations and non-governmental groups that either conduct their work independently or are contracted by another category of stakeholder (Becker & Caldwell, 2015).

T. Notteboom and Winkelmans (2002) proposed a classification where stakeholders are divided into four groups: internal stakeholders, economic/contractual external stakeholders, public policy stakeholders, and community stakeholders. Denktas-Sakar and Karatas-Cetin (2012) argued that the last three stakeholder categories could be grouped together into a single category of external stakeholders, resulting in the aforementioned internal and external stakeholder categorization. While studying the stakeholders‘ perspective for sustainable development of a port city, Lam and Yap (2019) divided port stakeholders similarly to T. Notteboom and Winkelmans (2002). The four groups identified by the authors are internal stakeholders, public sector, market players/corporate body, and community/interest groups. They determined the level of influence held by each group of stakeholders in making decisions and promoting reforms in favor of sustainable development.

In a somewhat similar approach to Clarkson (1995), Gharehgozli et al. (2016) divided port stakeholders focusing on the activities performed by each group. The authors classified stakeholders in two groups: those who directly use, regulate, maintain, and police the port, and those who indirectly benefit or are otherwise affected by the port’s activities.

While the majority of researchers cluster port stakeholders into internal and external groups, we observe that the choice of the paradigm should be driven by the research question of interest and the granularity of the problem. There is no single correct cluster method. Stakeholders‘ interest and alignments differ according to the problem being addressed and the diverse clustering approaches allow researchers to focus on the appropriate elements for any given scenario.

From the literature, it is possible to determine the set of stakeholders that are commonly identified by most authors (see Table 1). Through time, since the early 2000s, one can observe a tendency of research to address a more holistic view, with a broader variety of stakeholders included in each study. Figure 1 is a simple representation of the maritime supply chain agents most commonly addressed in the literature: *vessels, ports, inland shippers*, and *manufacturers*.

Table 1. Stakeholders in the literature.

Author	Port Authority and Terminal Operators	Vessels and shipping companies	Shippers (manufacturers)	Intermodal logistic providers	Government	Community	Researchers
Notteboom and Winkelmans (2002)	✓	✓	✓	✓	✓	✓	
Notteboom (2004)	✓	✓	✓	✓			
Barnes and Oloruntoba (2005)	✓	✓	✓	✓	✓		
De Langen (2006)		✓	✓		✓	✓	
Berle et al. (2011)	✓	✓			✓		
Mostashari et al. (2011)	✓				✓		
Dinwoodie et al. (2012)	✓	✓			✓	✓	✓
Denktas-Sakar and Karatas-Cetin (2012)	✓	✓	✓	✓	✓	✓	
Lam et al. (2013)	✓	✓	✓	✓	✓	✓	
Park and Lim (2013)	✓	✓			✓	✓	
Christiansen et al. (2013)	✓	✓	✓				
Becker et al. (2013)	✓	✓	✓	✓	✓	✓	✓
Becker and Caldwell (2015)	✓	✓	✓	✓	✓	✓	✓
Lam and Bai (2016)	✓	✓	✓		✓		
Gharehgozli et al. (2016)	✓	✓	✓	✓	✓	✓	✓
Vilko et al. (2019)	✓	✓		✓	✓		
Shaw et al. (2017)	✓	✓	✓	✓	✓	✓	✓
Lam and Yap (2019)	✓	✓	✓	✓	✓	✓	✓

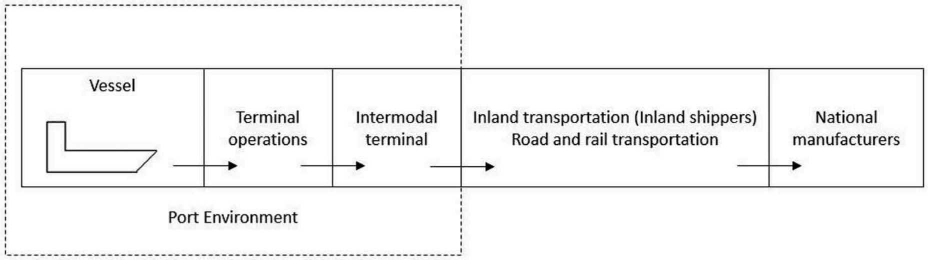

Figure 1. Port primary stakeholders.

Christiansen et al. (2013) classifies *vessels* into three categories: tramp, liner, and industrial. Tramp ships operate as taxis, owned by the so called carriers and rented out by those to the shippers. It commonly operates from one port to others, with flexibility on its schedule, and following the demand of cargo owners. Liner ships, on the other hand, operate as buses: they have a fixed route and schedule. Liner ships usually carry cargo from many different shippers, meaning, each shipper uses only a portion of the liner ship capacity. Finally, industrial shipping is responsible solely for in-house traffic (Tran and Haasis (2015)).

Ports are responsible for loading and unloading cargo from incoming and outgoing vessels, as well as for temporary storage of cargo. Ports are only a part of the operation of moving goods through a supply chain. Before being loaded (unloaded) to (from) the ship, the goods are transferred using inland transportation, that may be rail or road.

Inland shippers are the agents responsible for the movement of goods inland. Traditionally, inland shippers are third-party companies, hired by manufacturers to deliver finished goods or pick up raw material. However, it is not uncommon for large manufacturers to manage their own inland transportation.

Finally, the last represented stakeholders are *national manufacturers*. Manufacturers may import their supply chain's input through the port, may export their finished goods through the port, or both. In either one of these situations, the manufacturer will be impacted by a port disruption.

2.2. Sources of uncertainty and impacts to stakeholders

According to Knight (1921), the distinction between risk and uncertainty relies on the existence of probability. The term *risk* refers to situations in which probabilities associated to events are available. Meanwhile, *uncertainty* is used to describe situations in which information is too imprecise or unreliable to be represented by probabilities. Knight's definitions are commonly used in decision theory and economics (LeRoy & Singell, 1987; Mousavi & Gigerenzer, 2014; Runde, 1998; Russell & Taylor, 2014; Tversky & Fox, 1995).

In risk assessment and reliability engineering, however, these definitions should be used with caution since not all authors agree. Some authors argue that uncertainty is inherent to risk and thus safety should be addressed with the goal of both risk and uncertainty reduction (Möller & Hansson, 2008). Other researchers believe that a broader risk perspective is required and that uncertainty should replace the probability component in the concept of risk (Aven, 2010, 2011, 2012). A more comprehensive definition of risk is presented in Gardoni and Murphy (2014), where the authors define risk along three dimensions: the probability of occurrence, the potential consequences of an occurrence, and the inherent source of the risk (e.g., negligence, natural hazard, etc.)

When considering specific areas of research, one can be more specific along defining the relevant components of risk. For example, in a global supply chain, Chopra and Meindl (2013) identified nine different categories of risk that need to be taken into account: disruptions, delays, systems risk, forecast risk, intellectual property risk, procurement risk, receivables risk, inventory risk, and capacity risk.

In maritime supply chains, commonly identified sources of uncertainty are weather, ground transportation, and information sharing. Some natural hazards, such as hurricanes and tropical storms, are continuously monitored. As time passes and they approach the coast, the uncertainty about the future evolution of the storm disappears but not about the consequences (Liberatore et al., 2013). Even if it was possible to know for sure the category of a hurricane on the Saffir-Simpson Hurricane Wind Scale before it hit, the range of wind speed within a category is wide enough that the storm impacts vary. Ground transportation network also represents a significant source of uncertainty. Ground transportation network uncertainties include capacity, availability, and reliability. The final source of uncertainty that is frequently pointed out is related to information sharing throughout the network. The size, complexity, and number of stakeholders all contribute to make effective communication a challenge in the port environment (Caris et al., 2013; Shaw et al., 2017). After a disaster, information sharing becomes both more crucial and more challenging. When an event takes place, it is likely that power will go out for extended periods of time, which interfere, if not completely disrupt, communication. This obstruction, combined with the fact that human behavior may become unpredictable after a disaster, might cause the flow of information to become compromised to the point of total lack of communication (Smythe, 2013).

Risks and uncertainties can cause port delays and port inoperability, consequently leading to maritime supply chain disruptions. For example, if there is a possibility that a railroad leading to a port may be obstructed due to potential landslides caused by heavy rain, trains could not able to reach the port to be loaded with incoming cargo from ships. The port has a limited storage space for cargo and may become overcrowded if not managed properly. Therefore, faced with a potential railroad disruption, the port must make the decision to continue to unload cargo from vessels or not. If the port decides to suspend loading and unloading activities until further information on the railroad condition is gathered, docked vessels that are not unloaded will be delayed. Similarly, other intermodal transportation systems will also be impacted by port operations delay. This is just one example of the cascading effects that may impact port operations.

Table 2. Impacts of port unreliability and disruptions to stakeholders.

Author	Port	Manufacturers	Vessels
Rosoff and Von Winterfeldt (2007)	✓		
J. Park (2008)	✓		
Jung et al. (2009)	✓		
Pant et al. (2011)	✓		
MacKenzie et al. (2012)	✓		
Lam and Yip (2012)	✓		
Rose and Wei (2013)	✓		
Y. Zhang and Lam (2015)	✓		
Thekdi and Santos (2016)	✓		
Lewis et al. (2006)		✓	
Figliozzi and Zhang (2010, January)		✓	
Loh and Van Thai (2015a)		✓	
Yang et al. (2005)			✓
Notteboom (2006)			✓
Qi and Song (2012)			✓
Qi and Song (2012)			✓
Cervinska (2012)			✓
Brouer et al. (2013)			✓
Rodrigue and Notteboom (2013)			✓
Wang et al. (2014)			✓
Tran and Haasis (2015)			✓

Rose and Wei (2013) divided the impacts of a port shutdown into three levels: *port level, macroeconomic level*, and *total impacts*. On the *port level*, common impacts are disruption of imports and exports as well as disruption of port activities. At the *macroeconomic level*, possible impacts are intermediate good shortfalls, final goods shortfalls, and reduction in final demand. Finally, the *total impacts* level consists in national impacts that expand from the port region as well as permanent loss of port business.

The following sections review the literature on the impacts of port unreliability and disruptions to three stakeholders: ports, domestic manufacturers, and vessels. A list of the reviewed literature focused on the impacts of port disruptions to stakeholders is provided in Table 2.

2.2.1. Impacts to ports

Multiple authors (Jung et al., 2009; MacKenzie et al., 2012; Pant et al., 2011; J. Park, 2008; Rose & Wei, 2013; Thekdi & Santos, 2016) used an input-output modeling approach to estimate the economic impacts of port disruptions. Pant et al. (2011) quantify the impact of port disruptions across interdependent industries by combining the multi-regional inoperability input-output model to a simulation model of the operations of an inland port. Similarly, Thekdi and Santos (2016) measured the economic impacts of sudden disruptions to port operations by combining scenario analysis and interdependency modeling. Rosoff and Von Winterfeldt (2007) and J. Park (2008) focused on man-made risks, evaluating the economic impact of a terrorist attack and shutdown of the port of Los Angeles/Long Beach. Beach. Rose and Wei (2013) estimated the total economic impact of a seaport disruption by combining demand-driven and supply driven input-output analysis, as well as including resilience through adjustments for each case studied.

Lam and Yip (2012) applied a stochastic timed Petri Net approach to model and analyze the impact of a port disruption on supply chains, while Y. Zhang and Lam (2015) evaluated the economic losses of port disruptions by taking into account both the daily cargo throughput of the port and the weather. The likelihood of a disruption was evaluated by Y. Zhang and Lam (2015) based on historic data of the ports, while the throughput estimation was given by a regression analysis. The total economic loss calculated was then split into loss to the shippers, loss to the carriers, and loss to the ports in terms of income and reputation.

2.2.2. Impacts to domestic manufacturers

Domestic manufacturers are also impacted by disruptions in ports and maritime transportations systems.

Lewis et al. (2006) developed a model capable of quantifying the costs faced by a global supply chain firm that makes use of a seaport subject to unexpected closure. A Markov decision model with uncertain lead times was used to determine the cost-minimizing inventory management policy. Figliozzi and Zhang (2010, January) interviewed logistics and supply chain managers from a group of 30 companies based in Sydney, Australia. The researchers focused on supply chain disruptions caused by an international maritime transportation element. Figliozzi and Zhang (2010, January) gained a better understanding of the causes, implications, and costs of a supply chain disruption from a company's perspective. The disruption costs indicated by the interviewed managers were lost sales, expediting costs, loss of reputation, and impacts to the company's cash flow. More recently, Loh and Van Thai (2015a) measured the impact of a port-related threat on supply chains faced by a manufacturer in Singapore by comparing the total costs, warehousing costs, and transportation costs for four different disruption scenarios.

2.2.3. Impacts to vessels

Although vessels can be classified in three different categories (tramp, industrial, and liners), this review focus on liner shippers, as these are the most commonly studied types of vessels on the impact of port disruption to maritime shippers. As previously stated, liner shipping operations are different from other shipping operations, in the sense that they have a fixed itinerary and schedule. For that reason, ideal liner service networks have low operating costs, high frequencies, fast transit times, and both tight and reliable voyage schedules. Liner shipping most commonly transports containers. Container transport systems are characterized by tight time schedules. Therefore, when planning routes and schedules, liner services must maintain a high degree of schedule reliability (Notteboom, 2006; Rodrigue & Notteboom, 2013).

Port-related uncertainty is the primary source of volatility and unreliability on vessels schedules, leading to economic impacts to shippers. Moreover, global transport networks are growing in both size and complexity, making the design and operation of liner services a challenging task (Notteboom, 2006; Qi & Song, 2012). While there is extensive research on route scheduling, port selection, and fleet size and scheduling regarding the liner shipping industry (Tran & Haasis, 2015; Wang et al., 2014), work focused on the impact of a disruption in liner shipping operations is still scarce.

Notteboom (2006) explored potential costs experienced by liner shippers and their clients, due to port unreliability. From the liner shippers perspective, the authors identified potential costs in the form of time loss, loss of customer, additional operating costs, additional port fees and tariffs, and increased fuel consumption. For the liner clients, delay may result in increased logistics cost, in the form of extra inventory and transportation costs, additional production costs, and potential product losses. The authors also explored the causes of schedule unreliability in the liner shipping industry and provided measures and planning tools available to shipping lines to address the issue. Notteboom (2006) classified the causes of delays into four categories: terminal operations, port access, maritime passages, and chance. The first and second groups are the ones of interest in this work. The first group, terminal operations, refers to port or terminal congestion before berthing or before starting the loading or unloading operations. Meanwhile, the second group, port access, refers to disruption in a port's access channel. This may happen for multiple reasons, such as irregularities in pilotage, low availability of pilots or tug boats, delays at sea locks, or access channel availability related to tidal windows.

Identifying potential risks and solutions are important steps to minimize the impacts suffered by the shippers due to port uncertainties and disruptions. Yang et al. (2005) developed a risk assessment framework for container lines supply chains based on the Formal Safety Assessment methodology. The developed framework is summarized in five steps: vulnerability identification, quantified estimation of risks associated with the identified vulnerability, development of risk control options, cost and benefit analysis, and recommendation for decision-making. Qi and Song (2012) evaluated the impacts of port-related uncertainty on vessels schedules in liner shipping routes, focusing on minimizing fuel emissions. The authors formulated and solved the optimal vessel scheduling problem, in which both delay and fuel costs were considered, using simulation-based stochastic approximation methods. Cervinska (2012) assessed the vulnerability of intercontinental ports and estimated the impact of port closures on the total supply chain cost from a liner shipping perspective through the formulation of different optimization models.

Finally, Brouer et al. (2013) proposed a formulation for dealing with disruptions in liner shipping named Vessel Schedule Recovery Problem based on the airline industry. The three recovery modes considered on their model are speed adjustment, port call omission, and port call swap. These actions can potentially lower costs by allowing the maintenance of slow-steaming policy, while also decreasing delay costs in a liner shipping network. The Brouer et al. (2013) formulation is particularly interesting given that there are many similarities between maritime and airway transportation. We speculate that there is more to be learned from the airline industry that could be applied to maritime transportation problems.

3. Port resilience

Hollnagel et al. (2007) define resilience 'as the inherent capacity of a system to adjust its functioning prior to or following changes and disturbances so that it can sustain operations even after a major mishap or in the face of continuous disruptions stress.' Mansouri et al. (2009a) and Kurapati et al. (2015) both define resilience in the context of a maritime supply chain as a function of system's vulnerability and its capacity to recover to a sufficient level of service within an acceptable time frame after a disruption takes place. Similarly, in Nair et al. (2010), resilience accounts for both the innate reliability of a system and the ability of mitigating negative effects through quick recovery actions.

Supply chains involving port operations are particularly complex and vulnerable to both internal and external disruptions. Moreover, port-related disruption can trigger a cascade effect that can potentially affect the entire supply chain, as well as impacting economical and societal well-being of its surroundings (Kurapati et al., 2015). Therefore, increasing global supply chain resilience is closely related to assessing port vulnerability (Barnes & Oloruntoba, 2005; John et al., 2014; Loh & Van Thai, 2015a).

Common resilience actions proposed by authors to minimize the impact of a port disruption from a manufacturer perspective are the use of inventories and input substitution (Chopra & Meindl, 2013; Rose & Wei, 2013; Unnikrishnan & Figliozzi, 2011). Other authors suggest the promotion of structural integrity to increase resilience, through the development of physically stronger infrastructure systems during the design and construction phases (Croope, 2010; Omer et al., 2012). Creating modularity in systems, increasing staffing in safety-critical areas and promoting training to increase knowledge, flexibility, and redundancy in the system are also mentioned in the literature (John et al., 2016; Mansouri et al., 2010; Omer et al., 2012).

The actions mentioned above, even though useful when dealing with risks and uncertainty, may not be enough to address the magnitude of the impacts of a port disruption. In the following sections, resilience assessment approaches are analyzed following a classification scheme suggested by Hosseini et al. (2016). First, work on qualitative assessment of maritime supply chain resilience is presented, consisting of conceptual papers and frameworks. Next, literature regarding quantitative assessment methods is reviewed. This section includes probabilistic and deterministic approaches, risk assessment methods, optimization models, simulation models, and fuzzy logic models. Lastly, a brief review of port resilience in the light of climate change is presented.

3.1. Qualitative assessment of maritime supply chain resilience

Conceptual frameworks constitute the majority of qualitative approaches proposed to assess maritime supply chain resilience.

According to Barnes and Oloruntoba (2005), the intricate interaction and complex interdependency between the elements of maritime supply chains result in an inherently vulnerable system. To examine maritime supply chain vulnerability, the authors defined two classifications of vulnerability. Type I refers to vulnerability emerging from operational complexity within a port, including both port infrastructure and operators. Type II refers to the vulnerability of maritime movements, where the port is simply a node of the system. According to the authors, considering both types of vulnerability and their interdependencies can promote a better understanding of the system for future crises.

As explained previously, Gharehgozli et al. (2016) classified the problem of port resilience as a 'wicked problem'. Gharehgozli et al. (2016) work, above all, had the goal of changing the way that the port resilience problem is looked at. By presenting the port resilience in the wicked problem context, the authors aim to change the decision-making and policy-making approaches used by port managers. From the presented perspective, port managers should make decisions in terms of mitigation and minimization of the consequences of a disruption. The authors also emphasized that the problem cannot be solved overnight, rather, it should be mitigated overtime with the collaboration of stakeholders.

Mansouri et al. (2009b) developed a framework based on risk analysis and management methodologies that aids in the identification of elements of uncertainty in maritime infrastructure and transportation systems. Their framework consisted of three phases: application of risk assessment methodology to identify, analyze and prioritize risks; utilization of a cause-and-effect diagram methodology to create a tree of events and effects; and at last, application of a decision tree analysis methodology to assess the strategies and their value for the system. Mansouri et al. (2010) later applied a similar framework to port infrastructure systems.

Berle et al. (2011) proposed a structured formal vulnerability assessment (FVA) methodology to evaluate the vulnerability of a maritime supply chain. According to the authors, the methodology allows a clear and systematic identification and mitigation of risks in the maritime transportation network.

Hsieh (2014) evaluated seven vulnerability factors derived from the literature and previous disasters applying geographic information systems. The produced model aimed to assist decision makers in obtaining a comprehensive understanding of port risk. Moreover, the risk analysis was to be used to help decision-makers understand the vulnerable system they are dealing with and reduce disaster risks by choosing successful strategies of disaster prevention and preparedness.

Mostashari et al. (2011) proposed the so-called Cognitive Process Architecture Framework (CPAF) to help seaport stakeholders sense changes, perceive operational scenarios, choose response alternatives based on trade-offs, and monitor the implementation of the responses. The authors believed that the great variety of stakeholders in seaports can easily produce fragmented information flows that undermine its ability of a systemic response to disruption events.

Gharehgozli et al. (2016) developed a conceptual framework for developing resilience strategies for ports in the context of adverse weather events. The authors defend that, due to the dynamic nature and constant change of the problem, mitigation is the best way to approach the problem. The developed framework consists of the following steps: data collection and analysis, stakeholder analysis, resilience strategies development, and strategies implementation.

Due to its complexity and high levels of uncertainty, John et al. (2016) proposed that seaport operations should be broken down to facilitate the investigation of resilience strategies. The authors pointed out that different risk categories affect different stakeholders and developed a list of the most common risk events and the most significant causes of these events. They separated the risk events in five categories: operational risk factors, which included port equipment failure, vessel accident and cargo spillage; security risk factors, such as sabotage and terrorist attacks; technical risk factors, consisting of lack of equipment maintenance, lack of navigational aid maintenance, as well as lack of IT system and dredging maintenance; organizational risk factors, for example, labor unrest or congestion at the storage area, berth or gate; and, finally, natural risks factors, which include geologic, hydrologic and atmospheric events (John et al., 2014, 2016).

Finally, Loh and Van Thai (2015b) conducted interviews with professionals from the port management sector, as well as port users, to identify the most common port-related supply chain threats. Based on these interviews, the authors proposed a practical management model with the intent of increasing port resilience. Lam and Bai (2016) also conducted interviews in order to develop a quality function deployment approach to improve maritime supply chain resilience. They interviewed containers liners and cargo shippers in order to be able to take both customer requirements and maritime risks into account when prioritizing different resilience solutions.

Authors frequently classify ports as a system-of-system, due to their complexity, and suggest that they should be analyzed using System Dynamics or Systems Thinking methods. In terms of disruptions on the maritime transportation supply chain, multiple authors utilized system dynamics to model the uncertainties and complexities of those types of disruption (Kwesi-Buor et al., 2016; Oztanriseven et al., 2014; Yeo et al., 2013).

Yeo et al. (2013) used system dynamics to evaluate the impact that security procedures have on the performance of seaports. More specifically, the authors analyze the relationship between seaport security levels and container throughput. Their results show that increasing port security has a ripple effect on the productivity level of the entire port. Similarly, Kwesi-Buor et al. (2016) used System Dynamics modeling to analyze the impacts of policy interventions on the ability of different maritime agents to mitigate risks and recover from disruptions. Their model demonstrated that Disaster Preparedness levels are dependent, among other factors, on port activities and attitude towards risk prevention.

Mansouri et al. (2009c) also approached the maritime transportation system from a system of systems point of view. The authors applied systems thinking methodologies and its systemic tools to study the critical properties of the system. According to the authors, applying a systems thinking approach can help stakeholders have a better understanding about the system and empower them to solve problems that may arise in a systemic way.

3.2. Quantitative assessment of maritime supply chain resilience

In this section, a review of quantitative assessment methods of port resilience is provided. These include quantitative risk assessment methods, simulation models, decision support, fuzzy assessments, among others.

In maritime transportation systems and maritime supply chain, risk assessment is frequently performed by researchers with a wide variety of goals (Goerlandt & Montewka, 2015). Gasparotti and Rusu (2016) utilized risk assessment to identify, manage, and reduce risks in the transport of petroleum products at sea, focusing on the environmental impacts of maritime transportation accidents. J. Zhang et al. (2016) constructed a Bayesian belief network model for risk assessment and prediction of the consequences of different types of accidents in the Tiajian port. Soares and Teixeira (2001) assessed the structural safety of ships at sea, while Li et al. (2012) reviewed quantitative risk assessment models for vessels sailing in maritime waterways.

The utilization of risk assessment methods to address and improve maritime supply chain and port resilience is less frequent. According to Aven (2017), resilience assessment and management can be performed without performing risk assessments, but both can be supported and even improved with risk assessment techniques. The author used redundancy as an example for their claims, arguing that adding redundancy to a system does not require assessing specific events and associated risk.

Bichou (2008) identified event tree analysis, Markov process, failure mode and effects, and fault tree analysis as the major hazard analysis tools used in the literature of risk assessment in maritime transportation systems. Mokhtari et al. (2011) developed a risk assessment method consisting of a generic bow-tie-based risk analysis combined with both Fault Tree Analysis and Event Tree Analysis to evaluate risk factors. Later, Mokhtari et al. (2012) proposed a new methodology for risk evaluation for seaport stakeholders based on fuzzy set theory and evidential reasoning.

In their work, Berle et al. (2013) combined risk assessment methods and inventory routing simulation of a maritime supply chain. It aimed to systematically address the vulnerability in a maritime transportation system using a formal vulnerability assessment approach. Simulations with heuristic-based tools allow the authors to quantify the impact of the disruption scenarios, as well as the mitigation measures.

John et al. (2014) believed that the traditional risk modeling approaches cannot address uncertainty effectively and are, therefore, inappropriate to address the complexity of seaport operations risk assessment. To better address uncertainty in seaport operations, the authors proposed a methodology using fuzzy analytical hierarchy process and evidential reasoning. Later, John et al. (2016) used Bayesian belief network (BBN) to assess the influencing factors leading to disruption of operations. According to the authors, differently than other approaches for risk analysis, BBN has the ability to address randomness and capture non-linear causal relationships in complex systems. The authors also used a Fuzzy Analytical Hierarchy Process to evaluate the relative influence of each influencing variable.

Ship rerouting is a mitigation strategy that is proposed by multiple authors. Unnikrishnan and Figliozzi (2011) proposed rerouting on their model through an online freight network assignment model. They proposed utilizing real-time tracking technology to find the best recourse options for the users in order to minimize transportation costs while also avoiding costly delays and disruptions. The method could also be used to estimate network flows and predict the behavior of freight decision makers under a disruption. The authors addressed uncertainty by applying their model to different scenarios with different weather impacts and port operating conditions.

Martagan et al. (2009) developed a simulation model capable of making rerouting decisions with the goal of minimizing the impact of crisis conditions on a supply chain. They performed statistical analysis to illustrate how the simulation model can be used by port decision makers. The system performance was measured through the creation of five different scenarios, each with different percentages of ships being rerouted to different ports when a port in Texas is under disruption. Each scenario was compared against a normal scenario (without disruption) and statistical tests were performed to determine the significance of the changes in terms of queue length and average time of a container in the system.

Lee and Farahmand (2013) used discrete-event simulation to explore the feasible paths before and during port disruptions on the West Coast of the United States. The model compared fully and partially disrupted scenarios to the port current operations.

Omer et al. (2012) suggested a quantitative assessment of resilience for a maritime transportation system based on key performance measures of the system. Resilience is measured as the ratio between the original output of the system (prior to the disruption) to the output after the disruption. The three identified resilience metrics are tonnage resilience, time resilience, and cost resilience. After the identification, the system is modeled using optimization techniques and a system dynamics model, where the objective function of the network optimization problem is to maximize the total flow on the network links.

Paul and Maloni (2010) developed a decision support system that aims to optimize the movement of cargo through a port network during a disaster. The developed algorithm allocates ships to ports maximizing the use of network capacity, while considering inland transportation, port and inventory costs. Port capacities are updated dynamically, in order to reflect the congestion conditions during the disaster.

Baker et al. (2012) used a dynamic decision model to minimize the loss of revenue a port may suffer during a hurricane by determining when a port shutdown should be ordered. A port is the agent that suffers the most with the disruption, since it not only loses revenue, but also incurs the cost of preparation. Due to the uncertainty of a hurricane path, finding the right moment to perform the port shutdown not only reduces the costs, but also avoids potential damage in case the preparation is not correctly made. Wendler-Bosco and Nicholson (2018, May) extended their work by adding the perspective of incoming cargo vessels to the problem. In the newly formulated problem, vessels seek to minimize the impact suffered from a hurricane landfall by making the choice between rerouting to a port outside the hurricane's path or waiting for the storm to pass and the port to reopen. The first option takes into account extra fuel and inland transportation costs incurred by the shipper, while the second option includes possible extra labor and delay costs. The authors formulated the problems as Markov decision processes and solved using a backward-induction dynamic programming.

Ship rerouting is an alternative to avoid delays due to port disruptions. However, it has multiple constraints associated with it, including: dock availability at the rerouted port, loading and unloading equipment availability at the port, cost of last minute docking and unloading, fuel availability onboard to complete the rerouting, cost of increased fuel consumption, and inland transportation network availability. Although the goal of rerouting is ultimately to minimize delay costs while the port returns to its normal operations, the aforementioned costs can easily outweigh rerouting benefits, especially if the rerouting is an unpremeditated decision. Existing papers account for many of these costs, but none takes all these aspects into consideration.

3.3. Port resilience and climate change

Climate change is causing weather events to become more intense every year, and ports are specially vulnerable to its impacts, such as sea-level rise, stronger storm surges and increased coastal flood (Becker et al. (2013)). Moreover, port cities are commonly important concentrations for population, with many of the most populated cities in the world being port cities. Therefore, dealing with extreme weather impacts in ports is not only an economical issue but also a social issue (Hanson et al. (2011)).

Different reasons encouraged different ports to seek climate resilient structures. In the case of the Port of Rotterdam (Netherlands), the reason for addressing the vulnerability of the port structure to climate change was the need to deal with the city's extreme vulnerability. In order to do so, the port joined forces with other stakeholders with the ultimate goal of making the city one of the safest port cities in the world and fully resilient to climate impacts (Pijnappels et al., 2010). Meanwhile, in Australia, the reason behind resilience enhancement of the Sydney Port and Port Kembla was the fear that climate change might impact the successful operations of the port sector; and in the Port of New York and New Jersey the reason was actually a response to a poor ranking in an Organization for Economic Co-operation and Development (OECD) study (McEvoy & Mullett, 2013; O'Keeffe et al., 84). However, most ports around the world are still unaware of the latent hazards of climate change or are slowly starting to acknowledge the necessity of investments in port resilience (Becker et al., 2013).

O'Keeffe et al. (84) conducted interviews with 70 senior managements of the maritime sector in Ireland, with the goal of understanding and identifying the preparedness of the sector to build adaptive capacity to adapt to climate change. The authors determined that, even though most interviewees were aware of the importance of environmental management of the port sector and most perceived the impact of climate changes on their lives, few actually comprehended the importance of mitigation and adaptation actions to climate change in the port sector.

There is a dearth of climate change related to port resilience literature. The limited research that does exist primarily focuses on particular ports. While such work presents significant findings for the specific case studies involved, it is difficult or impossible to extend the work as a basis for general climate-change motivated operation policies, frameworks, or guidelines.

4. Ports as part of an intermodal transportation network

Intermodal transportation refers to the transportation of a person or a load from an origin to a destination, through a sequence of two or more transportation modes. The transfer between two modes is performed at an intermodal terminal. Similarly, when addressing freight rather than people, intermodal freight transportation refers to a multimodal chain of container-transportation services (Cho et al., 2012; Crainic &

Kim, 2007; García et al., 2013; Macharis & Bontekoning, 2004). In an intermodal transport chain, it is usual that the shortest possible length is traveled by road, due to its higher cost. Most of the route is traveled by rail, ocean-going vessel or inland waterway (Macharis & Bontekoning, 2004).

Globalization is transforming ports from simple bridges between land and sea to important providers, responsible for complex logistics networks through the usage of intermodal transportation networks (Coulter, 2002; Panayides & Song, 2008). Intermodal transport operations in maritime ports are commonly located at container terminals, being divided into seaside operations, storage operations, and landside operations. On the landside, containers are loaded to or unloaded from trucks or trains. Similarly, on the seaside, containers are loaded to or unloaded from vessels. Storage operations refer to the transportation and storing of containers at the yard (Kurapati et al., 2015).

The tendency of increased integration between land and sea operations emerges from the understanding of the necessity of having a holistic container terminal operation (Loh & Van Thai, 2015a). This increasing importance has been attracting the attention of researches progressively, as studies related to containerization and intermodal transportation networks involving ports are beginning to emerge. However, there is still a massive gap between the amount of studies focused solely on rail and road intermodal transportation and the ones incorporating the maritime sector (SteadieSeifi et al., 2014).

Caris et al. (2013) performed a literature review where they identify intermodal research topics and determine gaps in the literature regarding decision support systems for intermodal transport. The authors were able to identify trends among the research papers. Three trends stood out: the development of models in a dynamic context, the introduction of environmental concerns, and the application of Operations Research techniques innovatively. The main difficulties regarding decision support models for intermodal transport identified by the authors in the literature refer to data availability and sharing, network size and computational time, and incorporation of all the agents in the decision support tools (Caris et al., 2013).

The following sections provide a literature review on containerization, resilience actions, and the utilization of quantitative methods to address intermodal transportation problems.

4.1. Containerization

Containerization is the name given to the transportation of cargo between different transportation modes through the use of standardized containers, eliminating the need for re-handling its contents (Rickett, 2013). A significant part of the international movement of goods is supported by containerized intermodal transportation and efficient container movement is fundamental for an overall efficient intermodal supply chain. Containerized transportation is also timely, reliable, and economical. Containers transportation equipment are standardized, meaning movements and handling can be performed efficiently. Containers are also considered a safe transportation method in terms of cargo loss and damage (Crainic & Kim, 2007).

Transportation of cargo with containers is the foundation of globalization and international trade. Containerization is a key mechanism when providing a global transportation with high quality and low price (Notteboom, 2006). The utilization of containers improves supply chain efficiency and reliability. Proof of these benefits is the growth rates of container transportation in the last century (Acciaro & Serra, 2013; Parola & Sciomachen, 2005). Container transport is a highly synchronized process and, if a segment of the container transportation does not function accordingly, the entire chain will be affected (Rodrigue & Notteboom, 2013).

To accommodate container ships and container handling, ports and container terminals have been renewed or built all over the world. Following the trend, containerization is increasingly receiving attention from the literature. Topics of interest include container vessels scheduling and operational planning and control in container terminals. The second category includes problems as berth scheduling, container crane scheduling, stowage planning and sequencing, storage activities in the yard, and allocation of yard cranes and transporters (Crainic & Kim, 2007).

4.2. Resilience actions

Work in intermodal transportation network considering seaports as part of the network are still far behind when compared to intermodal networks consisting solely of railways and roads (SteadieSeifi et al. (2014)). Similarly, research focused on intermodal transportation network resilience including maritime transportation are scarce. This section provides a review of the existing literature on the topic.

An action that is widely accepted among authors in terms of resilience in intermodal transportation networks refers to information sharing (Caris et al., 2013; Kurapati et al., 2015; Shaw et al., 2017). Due to the presence of multiple agents, an intermodal transport requires more data exchange than an unimodal transport system. Data exchange is a very sensitive feature in any network, and becomes especially problematic when multiple agents, with sometimes conflicting preferences, are involved (Caris et al., 2013; Shaw et al., 2017). Kurapati et al. (2015) used a simulation game to bring awareness to the fact that communication, information sharing, and plan alignment among main stakeholders within a container terminal is severely overlooked.

Nair et al. (2010) proposed an intermodal resilience framework that can be applied for any intermodal component and has the ability to quantify the component's level of vulnerability, being a useful analysis tool for decision makers.

Al-Khaled (2013) sought to facilitate routing and rerouting options in the case of a network disruption. They did so by establishing models and solution approaches with the goal of determining the criticality of transportation infrastructures. The authors developed models for different disrupted transportation networks: two for railroad networks and one for an intermodal system. The models built by the authors take into account the congestion effects that are likely to happen after a disaster takes place.

4.3. Quantitative methods in intermodal transportation

The use of Operations Research (OR) in intermodal transportation is still in its early stages (Crainic & Kim, 2007; García et al., 2013).

Large intermodal transportation network problems usually cannot be solved in a timely manner using traditional operations research techniques. The combinatorial explosion of these problems is one of its main difficulties when trying to obtain the optimal solution. García et al. (2013) addressed this problem by decomposing the intermodal transportation problem into two subproblems and solving it with a new hybrid approach. The authors developed a combination of linear programming and automated planning. Linear programming is used to optimally solve the assignments subproblem, while automated planning solved the selection of the best transportation mode for the problem (García et al., 2013).

García et al. (2013) developed a framework that combined the minimum cost flow problem on a intermodal freight network and three types of economies of scale: quantity, distance, and vehicle size. The authors solve the problem using a proposed genetic algorithm. Cho et al. (2012) developed an optimal transport algorithm for intermodal transport using dynamic programming to solve a weighted constrained shortest path problem. Finally, Iannone (2012) developed an optimization model to analyze the economics of container logistics systems beyond ports. The author focused on seaports at the Campania region, in Italy, and aimed to evaluate possible economic advantages of utilizing regional intermodal facilities and intermodal solutions for inland distributions.

Simulation models were used by multiple authors to gain a better understanding of intermodal supply chains. Vilko and Hallikas (2012) observed the Finnish intermodal maritime supply chain to identify and categorize the risks existent in the supply chain. The authors conducted interviews with members of different stages of the intermodal maritime supply chain and worked with them in identifying the risks and categorizing the risk effects. Once the risk probabilities and impacts were determined based on the interviews, the authors implemented a Monte Carlo simulation model to investigate the impacts that risk events had in terms of delay in the supply chain.

Abadi et al. (2009) developed three simulation models with the goal of understanding the movement of goods at a port. Similarly, Burgholzer et al. (2013) used an event-driven and agent-based traffic micro simulation model to analyze intermodal transport networks. The authors used real-life data to model a transport network, including the agents of the network and their decisions in the event of a disruption. The models aided planners and operators in the identification of critical portions of the network and make decisions to reduce network vulnerability.

5. Concluding remarks

Ports are extremely important agents in a global supply chain, being responsible for transporting a large percentage of the world's freight. The large amount of cargo moved daily through ports, added to the presence of multiple stakeholders, make the job of securing port operations especially complex. Moreover, due to their location, ports are especially vulnerable to weather events, such as hurricanes, storm surges, and flooding.

The objective of this paper is to review the existing literature on the impact of port disruptions in the maritime supply chain. This article reviews the existing agents on the maritime supply chain and the economic impacts they suffer in light of a port disruption. The literature on port resilience is also examined. Finally, intermodal transportation systems that account for maritime transportation nodes are reviewed.

It is clear that the number of studies available on port disruption is small when compared to the disruption of other agents in transportation systems. The lack of attention received is even more puzzling when considering the cargo volume traded daily at ports and the economic impact that port operations have to the global economy.

Several researchers have proposed qualitative frameworks and strategies to improve maritime supply chain resilience and address port vulnerabilities. Commonly, the motivation is to help port managers and stakeholders with the decision-making process during disruptive events. Upon review, we find considerable overlap among the proposed frameworks along with the significant repetition of ideas. Research to unify these frameworks into a general standard would help reduce redundancy and promote novel developments in the area.

This review also reveals that, even though there are quite a few quantitative port resilience methodologies, no author simultaneously considers more than a few possible resilience actions which are available in the literature. Ship rerouting, which is an alternative explored by various authors, has significant difficulties associated with it and is not always a viable option, especially in the case of short-term disruptions. Moreover, we find that port sustainability and port resilience to climate change are important topics that are understudied. While most of the existing quantitative work relating to climate change is characterized by case studies, with significant findings for the specific ports or port groups present in the study, the literature lacks guidelines that can be applied generally.

Finally, it is evident that maritime supply chain intermodal network resilience modeling is still in its early stages and has much room for improvement. This is especially clear when compared to railways and roads intermodal networks. Containerized intermodal transportation is the mode used to move a significant parcel of cargo, especially international cargo. Yet, studies including the maritime transportation portion of it are limited.

With respect to future research directions, we note that the existing literature on maritime supply chain resilience is dominated by qualitative concepts. We believe that more quantitative approaches would improve the rigor and clarity of the methodologies. There is a gap regarding the formulation of comprehensive ship rerouting problems, including all possible costs that may arise from the rerouting decision. Detailed analysis can improve decision-support and identify guidelines for determining when ship rerouting should be performed. Furthermore, there is a deficiency of analytical frameworks addressing port resilience in the context of climate change. An equally important research suggestion is in the maritime intermodal transportation area. As previously stated, port disruption's can cause cascading effects to the entire supply chain. There are insufficient studies to properly understand and address these effects. Helpful information and guidelines that could arise from resilience-related research in this area include improved models for intermodal operations planning, optimal intermodal node allocations, and intermodal capacity planning.

In summary, ports are significant components of the U.S. economy accounting for trillions of dollars in economic activity each year. Given their location along coastlines, they are susceptible to natural hazards such as hurricanes and storm surge, which are expected to intensify in the future due to climate change. Filling the research gaps identified in this study will help further the science relating to port and maritime supply chain resiliency.

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