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# Vulnerability of international freight flows to shipping network disruptions: A multiplex network perspective

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ABSTRACT

As freight flows through global supply chains intensify, dependence upon maritime transportation increases. This paper explores the risks that international freight flows are exposed to as a function of the multiple complex structure of liner shipping networks. Based on network modelling of over 80 networks and simulation of attacks to seven strategic nodes in the Americas, the paper shows that the vulnerability of international freight flows to disruptions in maritime transportation services varies according to the country of origin of such flows and the role that the country plays in the multi-layered maritime transportation network.

## 1. Introduction

During the second half of the twentieth century, international trade in goods grew twice as fast as world output, driven by globalisation, trade liberalisation, delocalisation of production activities, vertical integration, lower transportation costs and the use of information technologies in international business and production (Blonigen and Wilson, 2013). Supply chains became more international and complex, encompassing numerous actors, processes, products and locations (Myers et al., 2006; Creazza et al., 2010; Wagner and Neshat, 2010; Christopher and Holweg, 2011). In this context, a variety of risks threatens to disrupt the smooth flow of international materials and final products along supply chains, with severe potential consequences for international business (Bogataj and Bogataj, 2007; Tang and Musa, 2011). Each day that a product is delayed reduces the possibility of it being traded by 1% (6% when products are time-sensitive) (Djankov et al., 2010) and reduces its value by 0.8% (Hummels and Schaur, 2013).

Among the main risks global supply chains face are disruptions in the flow of goods transported internationally. Lack of adequate infrastructure and transport services, failure of critical infrastructure, adverse weather conditions, cumbersome customs processes, and labor conflicts, among others, can increase logistics costs and raise uncertainty in already complex environments. As a result, the efficiency of the international transport chain has become critical for supply risk management and performance. Among transport modes, the literature in this regard has paid particular attention to the international shipping mode. Indeed, maritime transportation is the dominant mode of transport in international trade, with around 80% of global trade by volume and over 70% of global trade by value carried by sea and handled by ports worldwide (UNCTAD, 2015). These large shares suggest that ports (as nodes) and shipping services (as links) play an important role in many global supply chains (Notteboom and Rodrigue, 2005; Mangan et al., 2008; Panayides and Song, 2008). Because of this, a large body of literature advocates for port-supply chain integration, suggesting that sharing information between a port and other supply chain actors contributes to reduced order cycle times, a cut in inventories and more flexible systems (Panayides and Song, 2013; Woo et al., 2013).

Despite this increasing attention and the relevance of maritime transportation for global supply chains, the extent to which the

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configuration of liner shipping networks may affect the international flow of materials and final products remains largely unexplored. Literature in the areas of Transport Geography and Transport Economics that analysed the characteristics of transport networks showed that the structure of shipping routes does not entirely overlap trade patterns (Ducruet and Notteboom, 2012; Calatayud et al., 2017). In this context, the research question investigated in this paper can thus be summarised as 'to what extent does the specific configuration of shipping networks create risks for international freight flows. Indeed, the strategies of shipping lines and the different positions that ports and countries may have in the maritime network can play an important role in smoothing or hampering international freight flows across global supply chains. The contribution of this paper to the literature is twofold: (1) it uncovers the structure of liner shipping networks and the risks they may pose to international freight flows, and (2) it does so by applying multiple complex network analysis, a technique that scholars recently started applying to air transportation, but that still remains largely underused in maritime transportation. The results of this paper may be useful not only for researchers, but also for practitioners in both private and public sectors. Having a better understanding on the risks that the structure of liner shipping networks may pose to international trade flows may help design more efficient risk management strategies for international freight flows, as well as provide input for transportation, trade and infrastructure investment strategies in the public sector.

The paper is organised as follows: Section 2 presents the literature review; Section 3 presents the methodology; Section 4 presents the results and discusses the implications for academic research and policy-making; and Section 5 presents the conclusions of this research.

## 2. Literature review

Risks can be defined as the combination of the probability of occurrence of an event and its negative consequences (Holton, 2004). In the context of international freight, this could mean any risk that prevents goods with origin in a given country from reaching their destination markets. With the accelerated growth of international trade and the emergence of global supply chains, dependency on transportation has increased (Tang and Musa, 2011). Among transportation modes, shipping has emerged as the backbone of globalisation and international trade (Creazza et al., 2010). While the development of containerization has certainly allowed countries and firms to improve efficiency and reliability in their international trading links, it has exposed them to a new type of risk: disruptions in maritime transport networks (Acciaro and Serra, 2013). Adverse weather conditions, natural disasters, terrorist attacks, regulatory barriers, and changes in shipping companies' strategies are among the main factors that can create disruptions in maritime transportation (Ducruet et al., 2010; Earnest et al., 2012). For example, the decision following the 2011 Fukushima Daiichi disaster to close the ports of Yokohama and Tokyo led Japanese exports, and particularly its auto parts supply chains to a halt that cost Toyota alone an estimated US$73 million per day with knock-on effects to automobile manufacturers around the world (Earnest et al., 2012). More recently, the filing for bankruptcy of Hanjin shipping line – the world's seventh-largest container line – in August 2016 created confusion in ports and firms around the world. Millions of dollars' worth of merchandise sat on vessels seized on behalf of creditors, denied entry to ports or left unable to dock, while firms tried to make alternative arrangements to meet contractual obligations with their clients and minimise the financial impact of supply chain disruptions (The Guardian, 2016).

Given the importance of maritime transportation for the smooth flow of international trade and the efficient performance of global supply chains, the structure of shipping transportation business and the strategies adopted by liner shipping companies have drawn the attention of both supply chain and transportation researchers (Lam and Yap, 2011). According to the literature that explored the determinants of port choice for liner shipping services, port choice is a function of the overall network cost and performance (Mangan et al., 2001; Ducruet and Notteboom, 2012). Shipping lines face a trade-off between the requirements of the customers, who demand direct services between ports of origin and destination of their products, and operational cost considerations leading shipping companies to optimise ship utilisation and take advantage of scale economies in vessel size (Feng et al., 2012). Balancing the trade-off between supply and demand, shipping companies design their service routes in terms of: (i) the liner service type, (ii) the number and order of port calls in combination with the actual port selection process, (iii) vessel speed, (iv) frequency and (v) vessel size and fleet mix (Notteboom, 2006; Christiansen et al., 2013).

With the aim of improving efficiency and profitability, many shipping companies have adopted the strategy of hub-and-spoke networks, where the lowest cost for the entire network is achieved by routing via hubs, the use of different types of vessels in the network for optimal ship utilisation, and the amalgamation of flows to benefit from scale economies in maritime transportation (Fremont and Soppe, 2004; Fremont, 2007; Imai et al., 2009; Gelareh et al., 2010; Meng and Wang, 2011; Moon et al., 2015). The hub-and-spoke configuration has created a hierarchy among ports, with shipping companies having different functions in the network. Among these are ports dedicated to transhipment and/or relay/interlining, located in strategic geographic positions, which multiply shipping options and improve connectivity within the network through their pivotal role in regional hub-and-spoke networks (Ducruet and Notteboom, 2012; Ducruet, 2017).

Research on the structure of maritime networks and liner shipping strategies has benefited from the adoption of network analysis where, with the assistance of advanced analytical software, maritime connections are abstracted into graphs made of nodes and links. Elements of graph theory are used to uncover the properties and laws governing maritime networks, as well as their internal efficiencies and vulnerabilities (Ducruet and Lugo, 2013), improving available knowledge in the field obtained using other methods like gravity models (Kaluza et al., 2010) or variables such as total traffic volume (Xu et al., 2015). Indeed, studies applying network analysis showed that the container shipping network shared the characteristics of other networks found in nature and sciences: (i) it was a scale-free network, where a limited number of nodes were highly connected and links among nodes were distributed according to a power-law distribution (Barabasi and Albert, 1999); (ii) it was a 'small-world' network, with high cluster densities among nodes (Watts and Strogatz, 1998); and (iii) a giant component could be found in the network, to which almost all nodes belonged to. In