ACHIEVING ENVIRONMENTAL SECURITY IN SHIPPING AND PORTS: A STUDY OF THE ROBUSTNESS OF THE MARITIME NETWORK AGAINST ADVERSE ENVIRONMENTAL DISASTERS

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Abstract. In view of the huge operational and policy challenges imposed by global climate change effects; achieving environmental sustainability in international shipping and port operations requires the development of relevant analytical tools for vulnerability assessment and management including for service and routing decisions. However, little or no work to-date has addressed the vulnerability of the international shipping and port network, in particular with regards its robustness and reliability against adverse climate change impacts such as rising temperatures and sea levels, inundation and flooding, and other extreme weather conditions. In this paper, ports and scheduled Trans-Atlantic liner services between West Europe and North America are modeled as the nodes and links of a global shipping network. Following recent work in complex network theory, the properties of the shipping network are examined here in the context of environmental sustainability with a particular focus on the vulnerability and robustness of the shipping and port network to adverse climate change effects. Generic frameworks and a hypothetical case study are presented to identify critical nodes where failure would lead to a wider collapse of the network or change in service and routing decisions.

Keywords International Shipping, Port Operations, Environmental security, Climate Change Impacts, Risk Analysis, Network Reliability, Network Robustness

1. Introduction

Ports are critical infrastructure resources and serve a key role in the transportation of freight and people. With more than 80% of international trade by volume is being carried by sea, ports are vital for seaborne trade and international commerce. In 2011, world ports handled over 8.7 billion tons of estimated international seaborne trade of goods loaded (UNCTAD, 2012). In the container traffic alone, the world's container trade in 2011 was estimated at around 1.4 billion tons corresponding to a global container ports' throughput of 578.2 million twenty-foot equivalent units (TEU) (UNCTAD, 2012).

In view of the adverse impacts of global climate changes, the robustness and reliability of the global shipping network against node failures should become a high priority. Research to date has focused on greenhouse gas (GHG) emissions from international shipping and on relevant mitigation strategies including through technology, operational, policy, and regulatory instruments. Equally, the effects of climate change and their implications on low lying port infrastructure and related communities need to be properly addressed and analysed. A joint OECD/UNCTAD report identified several world ports as particularly vulnerable to rising sea levels and coastal flooding, with the top 10 most vulnerable port cities in terms of population exposure being Alexandria, Ho Chi Minh City, Guangzhou, Miami, Mumbai, Kolkata, New Orleans, New York, Osaka-Kobe, and Shanghai (UNCTAD, 2009b).

Current maritime transport and port systems and have been designed to respond to an extensive set of market and operational requirements, but their robustness and reliability vis-à-vis node failures have for long been taken for granted. Examples of the causes of node failure in ports and shipping include industrial strikes, safety and security incidents, and extreme climate and weather conditions. In the context of global climate change impacts, scientific and empirical evidence shows that the traditionally low-frequency / high-consequence events such as Tsunamis and Hurricanes are becoming more frequent and even more severe, hence adding a new dimension and further amplifying environmental risks and impacts in ports. A further complication in the assessment and management of climate change risks stems from the network structure of the global shipping and port networks. The current topology of maritime transport networks consists of a series of highly interdependent nodes and links whereby a failure in any node is likely to have major cascading effects on other nodes and on the reliability of the global network as a whole.

This study proposes to investigate the robustness properties of the global maritime transport and port network against adverse impacts of climate change. We focus on container shipping routes linking European and North-American seaports and use the complex network theory to simulate the impacts of environmental-led node failure on network resilience and reliability. The paper reports on several aspects of linking climate change incidents with port robustness and network failure including such aspects as risk modeling and assessment, mitigation and disaster recovery, and robust network planning and design.

The remainder of the paper is structured as follows. Section 2 reviews the conventional methods of environmental risk assessment and management in shipping and ports, and highlights their shortcomings in the context of global climate change threats and impacts. Section 3 reviews the network architecture of global marine transport systems, in particular the organization and structure of container shipping and port operations. Section 4 describes the dataset and the model starting by outlining the theoretical backgrounds of the complex network theory before reporting the results of the simulation case study. Section 5 concludes with summaries and suggestions for future research.

2. Environmental Risk Analysis in Shipping and Ports

2.1. System's Safety Approach to Environmental Risks and Hazard Analysis

The conventional approach to risk defines it as being the chance, in quantifiable terms, of an accident or adverse occurrence. It therefore combines a probabilistic measure of the occurrence of an event with a measure of the consequence, or impact, of that event. The process of risk assessment and management is generally based on three sets of sequenced and inter-related activities as outlined below.

- The assessment of risk in terms of what can go wrong, the probability of it going wrong, and the possible consequences,

- The management of risk in terms of what can be done, the options and trade-offs available between the costs, the benefits and the risks, and

- The impact of risk management decisions and policies on future options and undertakings.

Performing each set of activity requires multi-perspective analysis and modeling of all conceivable sources and impacts of risks as well as viable options for decision making and management. The empiricist approach is to regard accidents as random events whose frequency is influenced by certain factors. Under this approach, the immediate cause of an accident is known in the system safety literature as a hazardous event. A hazardous event has both causes and consequences. The sum of the consequences constitutes the size of the accident. Hazardous events range in frequency and severity from high-frequency low-consequence events which tend to be routine and well reported, to low-frequency high-consequence events which tend to be rare but more complex. Several analytical tools have been developed for hazard analysis. The choice of tool depends on (i) whether the causes or the consequences of a hazardous event are to be analyzed, and on (ii) whether the techniques used take into consideration or not the sequence of the causes or consequences.

Table1: Major Hazard Analysis tools

	Consequence analysis	Cause analysis
Sequence dependent	*Event Tree Analysis*	*Markov Process*
Sequence independent	*Failure Mode and Effects*	*Fault Tree Analysis*

The causes of a hazardous event are usually represented by a fault tree, which is a logical process that examines all potential incidents leading up to a critical incident. A popular methodology that relates the occurrence and sequence of different types of incidents is the fault tree analysis (FTA). Under the FTA, a mathematical model is fitted to past accident data in order to identify the most influential factors (top events) and estimate their effects on the accident rate. The model is then used to predict the likelihood of future accidents. The extent to which the tree is developed (from top to basic events) is usually governed by the availability of data with which to calculate the frequencies of the causes at the extremities of the tree, so that these may be assigned likelihoods. From these, the likelihood of the top event is deduced.

FTA has a number of limitations. For instance, the approach assumes that the causes are random and statistically independent but certain common causes can lead to correlations in event probabilities which violate the independence assumptions and could exaggerate the likelihood of an event fault. In a similar vein, missed or unrecorded causes may equally bias the calculated likelihood of a hazardous event. Another shortcoming of the fault tree analysis is the assumption that the sequence of causes is not relevant. Where the sequence does matter, Markov-chain techniques may be applied.

The consequences of a hazardous event may be analyzed using an event tree. Event tree analysis (ETA) is a logical process that works the opposite way of FTA by focusing on events that could occur after a critical accident. Under ETA, a statistical analysis of past accidents is performed to estimate the consequences of each type of accident in order to predict risk and consequences of future accidents. The event tree approach implies that the events following the initial accident, if they occur, follow a particular sequence. Where a particular sequence is not implied, 'Failure Modes and Effects' Analysis' may be used. This technique seeks to identify the different failure modes that could occur in a system and the effects that these failures would have on the system as a whole.

2.2. Applications in Environmental Risk Management of Ports and Shipping

Most of the general tools described above have been successfully applied across most areas environmental management in shipping and ports, with the Formal Safety Assessment (FSA) being the most standardized framework of risk analysis in regulated maritime systems. The FSA was first developed by the UK Maritime and Coast Guard Agency (MCA) and later incorporated into the International Maritime Organization (IMO) interim guidelines for safety assessment (IMO, 1997). The FSA methodology consists of a five-step process: hazards identification, risk assessment, risk management, cost-benefit analysis, and decision making.

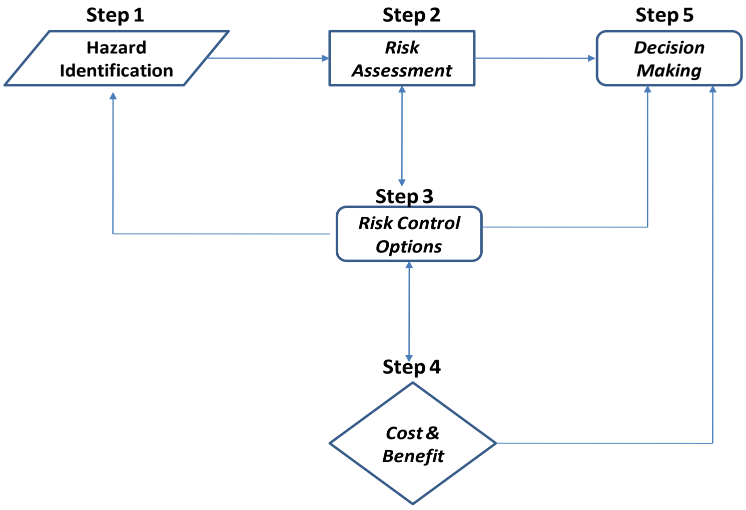


Figure 1: FSA Methodology (adapted by the author from IMO, 1997)

Despite the variety analytical tools available, the FSA and other conventional risk assessment models involve a substantial element of subjective judgment for both the causes and the consequences. The assumption of randomness of the causes of hazardous events is particularly problematic for low frequency high consequence events such as environmental disasters. As a result of global climate changes, the traditionally low-frequency high-consequence environmental events are predicted to become more frequent and even more severe. Moreover, there is a growing debate on (i) the premise and extent of randomness of environmental disasters caused by changes in global eco-systems, and (ii) the assumption that the sequence and interdependency of the causes of such disasters is not relevant. On the other hand, any analytical tool for risk assessment and management requires that the boundaries, components, and functioning of the system under study are well established. However, this is not always evident in shipping and ports given the combination of several elements related to vehicle (ship), facility (port), cargo, equipment, communication, labor and other exogenous factors. Since both the causes and the consequences of eco-system changes are global in nature, it would be difficult to place spatial or geographical boundaries on environmental maritime or port systems.

The calculation of the consequences of an environmental accident can also be subjective. Once identified, the level of seriousness of a hazard or an event should be traced down as far as relevant, and should account for various types of impacts; human, environmental, economic, social and cultural. An important element in any valuation method of decision making is the cost of preventing a fatality (CPF) and other principal losses in transport and infrastructure, a key component of which stems from human casualties that is fatalities and injuries. In most countries, specific regulatory frameworks set out the value of preventing a fatality (VPF) and other values for the prevention of injuries on transport infrastructure. For example, the UK currently operates with a VPF of a just over £1.38 million while the USA uses a VPF figure of around $6 million. This variation may stem from differences in methodologies of calculations, social priorities and values, or other reasons. A major issue with regard climate change risks and impacts is how to collectively define and quantify the value of preserving global eco-systems and preventing environmental disasters. Even if a standard VPF from changes in global eco-systems is achieved, such value is based on life saving rather than observable market transactions of risk reduction. Most economists believe that VPF valuations should be based on the preferences of those who benefit from preventive environmental measures and who also pay for them, either directly or through taxation. In the context of casualty prevention, these preferences are often measured using the willingness to pay *(*WTP) approach, that is the amount that the average member of the general public is willing to pay to reduce the level of risk to the average victim. The WTP approach has been extensively used in the context of international transport and maritime safety, but no global consensus exists on the use of the methodology in the context of climate change and environmental security.

A further difficulty stems from the dissimilarity between stakeholders' perceptions as to the allocation and distribution of the costs and benefits associated with a precautionary policy decision or a risk management program. Page (1978) has described some of these problems in the context of environmental risk management:

- Poor knowledge of the processes that determine the probability and impact of risk.
- Potential for catastrophic loss in that the occurrence of an environmental disaster would engender great individual, corporate, and societal losses.
- Combination of low subjective probability, high uncertainty, and lack of consensus.
- Rarity of the occurrence of similar events with only few estimates based on historical figures.
- Unclear pattern regarding the value, allocation, transfer and distribution of costs and benefits among both participating and non-participating parties.

The primary aim of environmental risk assessment models in shipping and ports is to assess the level of environmental security within and across the international maritime network. From the above discussion, we pointed out the limitations of conventional risk models at providing an integrated and effective approach to global climate change threats, risks, and impacts. In particular, when assessing system's risk and reliability to environmental risk, conventional approaches seem to overlook the network structure and interdependencies of port and shipping operations as well as the global dimension of climate change risks and impacts.

3. Reliability and Network Structure of Global Maritime Operations

Most transport and freight distribution systems follow a node-link network structure, although the nature and properties of the network differ greatly between and within systems. From an engineering and operations perspective, ports are a central node of the maritime and intermodal transport networks. Mathematically, a transport network can be represented by a graph consisting of a set of *links* (edges) and a set of *nodes* (vertices). The links represent the transport movements between the nodes, which in turn represent points, e.g. ports, in space and sometimes in time as well. A *path* is a collection of links and nodes specifying both the route and the mode(s) of transport. In the graph theory, a network is pure when only topology and connectivity properties are considered. When flow properties are considered as well, a network is then referred to as a flow network, in which case capacity constraints and other related factors become key features of network analysis.

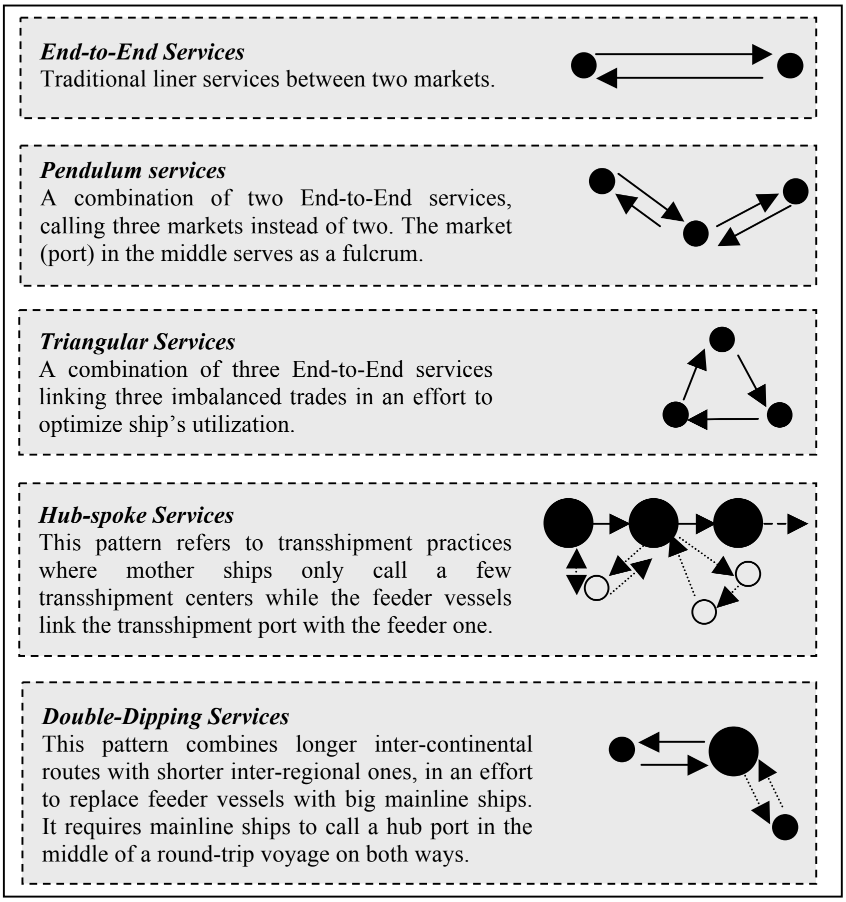


Figure 2: Description of selected operational patterns of liner shipping

Traditionally, international shipping networks have followed a trade-led pattern where new routes are designed and operated to link two or multiple markets, ideally on the basis of a balanced traffic. In container shipping, much of world's containerships' capacity is deployed to serve within one or a combination of the three major trade lanes; the trans-pacific, the trans-Atlantic and the Europe-Asia routes. The routes are normally those between two trade markets (supply and demand) with a range of ports being visited at either side of the route. Trade routes or lanes ideally link two or multiple markets based on an equitable traffic pattern and any other relevant requirements. However, traffic and operational constraints, regarding traffic type and volume, route distance and seasonal variations, containership's size and capacity, etc.; have both led shipping lines to develop new operational patterns in an effort to optimize ship's utilization and efficiency (see Figure 2).

The study of the topology of port and shipping networks is relevant to the analysis of maritime environmental risks and impacts, but the literature on the subject is relatively scarce. Traditionally, port and maritime network patterns have evolved from micro-level and fragmented decisions that do not always consider global network performance and system-wide impacts. With evolving complex shipping networks and the urgent need of global environmental sustainability, network design and analysis of port and shipping operations require a new approach and systemization.

Another area of interest in network analysis is network reliability which aims at studying the vulnerability and robustness of a transportation network including topics of connectivity, link failure, disruption and redundancy, vulnerability and security. A widely accepted definition of reliability is the one provided by Wakabayashi and Lida (1992) who define reliability as '*the probability of a device performing its purpose adequately for the period of time under the operating conditions encountered*'. Obviously, the extent to which a system or device is reliable depends on the interests and perceptions of different users, for instance between those who focus on cost reliability versus those who favor time reliability, or simply between high risk averse users versus less risk averse users.

The potential sources of disruption to port networks are numerous, ranging from routine events such as congestion and equipment failure to exceptional disasters such as earthquakes, hurricanes, and other environmental accidents. The cause, scale, impact, and frequency of such events vary extensively, but it is possible to design and manage port systems and operations in ways that enhance the predictability of such events, minimize the disruptions they may cause, and improve the robustness and redundancy of the maritime networks against such disruptions. Here, the concept of risk assessment and management becomes a key element in the study of a system's reliability. As described earlier, risk assessment and evaluation is a well-established engineering process for identifying hazards, their probabilities and consequences, assessing the acceptability of risks, and taking remedial actions to address unacceptable risks. Vulnerability is another concept closely related to risk in that it encompasses both probability and consequences. Generally, vulnerability is defined as the likelihood of severe adverse consequences. Therefore, vulnerability may be interpreted as the opposite to reliability.

Superior system's design and redundancy improves network reliability. For instance, developing systems and processes of quick recovery and resilience in the event of failure reduces the adverse consequences of disruption. Even though, research to date only looked at different but fragmented areas of maritime network robustness including such aspects as system vulnerability, risk avoidance, mitigation strategies and supply chain resilience. In the context of environmental security, available models of risk assessment and management, only identify risk elements based on logical mapping of internal processes, but there has been no applied research on the robustness of the shipping network link (route) and node (port/terminal) topology, quite apart from the perspective of the complex network theory.

4. Analysis of the Robustness of the Maritime Network against Environmental Disasters

4.1. Background to the Complex Network Theory

The theory of complex networks is a fast growing field of applied mathematics. Having its roots in the random graph model by Erdös and Ranyi (1959), interest in the field has been sparked by the recent development of the small-world and scale-free models by Watts and Strogatz (1998). Studies on the subject have shown interesting results in fields as diverse as ecology and social science, possibly the most famous being the discovery that on average only six degrees of separation exist between any two people selected at random. Networks such as the air travel grid, road and subway systems have been analyzed this way (Angeloudis and Fisk, 2006; Albert et al, 2002, Dunne et al, 2002), but the technique has yet to find application in other major transportation networks. There has been parallel interest in the application of complex networks theory to supply chain topologies, regarding such aspects as robustness, resilience and agility (Swaminathan et al., 1998; Thadakamalla et al., 2004). Nevertheless, few applications of the theory in the context of environmental security of maritime operations exist.

In a landmark study, Newman and Watts (1999) propose the "small world" model where the edges are added randomly between vertices without removing others in the ring lattice. Networks produced by this process have a smaller average shortest path length compared to a similar random graph network. A major property of small worlds is an increased clustering coefficient, which is used to quantify the tendency of nodes in various parts of the network to form interconnected groups with many links within them, but only few between them.

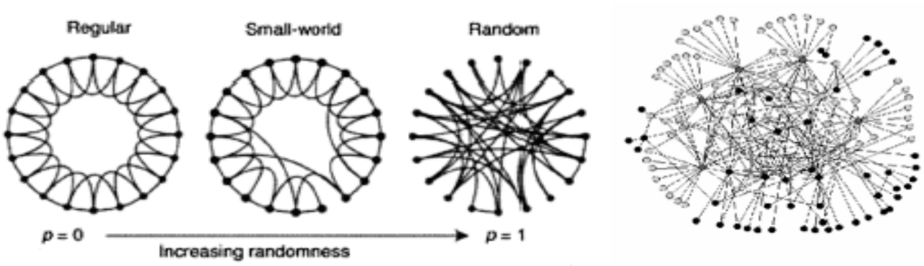


Figure 3: Illustration of the small-world rewiring procedure (Watts and Strogatz, 1998)

Scale-free networks were introduced by Barabasi and Albert (1999) in order to explain the behavior of many real world systems (like the WWW) that could not be adequately modeled as random networks. According to the model, the number of links k originating from a given node adheres to a power law $P(k) \sim k^{-\gamma}$, which for large networks is free of a characteristic scale. This effectively means that some nodes will have an exceptionally large number of links when compared to the vast majority of nodes in the network. Scale-free network are thought to be created by a process of preferential attachment whereby new nodes will be more likely to be linked to existing nodes with a higher degree (number of links) in order to benefit from their increased connectivity to other parts of the network.

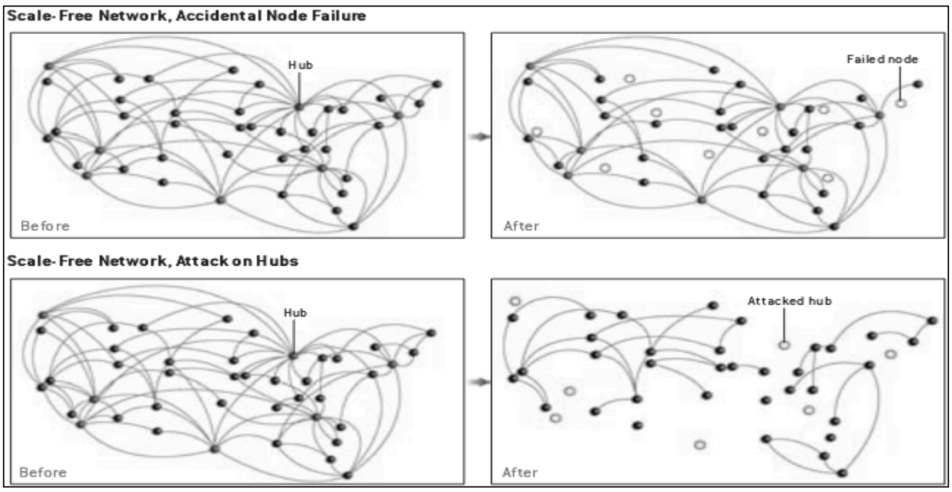


Figure 4: Node failure scenarios in scale free networks. (From Albert et. al, 2003)

Soon after the initial publications of the two network types in the late 1990s, a movement began among researchers to model real world networks. When studying scale-free networks, more emphasis is given to their robustness against errors and robustness against failures, which effectively represent two different strategies of node removal. In the investigation of error robustness, the underlying assumption is that nodes to be removed are selected at random in order to simulate the likely impact of evenly distributed operational errors on the network's robustness. Regarding attack robustness, the modeler must hold sufficient prior information about the system, which is then targeted strategically with a view to maximizing the impact. Scale-free networks exhibit an exceptional degree of robustness against random node failures due to the dominance of few hubs over their topology. The situation is reversed in the case of intentional attacks, since major hubs are relatively easy to identify. Nonetheless, we are not aware of any application of complex networks theory to environmental security in shipping and ports.

4.2. Dataset and Model Assumptions

The aim of the modeling process was to create a relatively precise model of the global container liner shipping network. A database was built using the information on the 2021 fleet deployment and liner schedules as posted on individual websites of global shipping lines, ports and relevant web-based information providers such as *Containerization International*. Due to the large scale and scope of the global shipping network, we decided to limit the analysis at this stage to the liner routes linking West Europe to North America. One should emphasize however that many Trans-Atlantic routes are part of a wider global network such as round-the-world trips, and as such they are fully included in the model.

Figure 5 depicts the shipping network generated by in-house modeling software that was developed for the purpose of complex network modeling. The route inputs on the network are in the form of ports of call sequences for each route. Through combining these sequences with port data, we generated the network shown below, where each port is represented as a circular node, and the links between ports represent shipping trips.

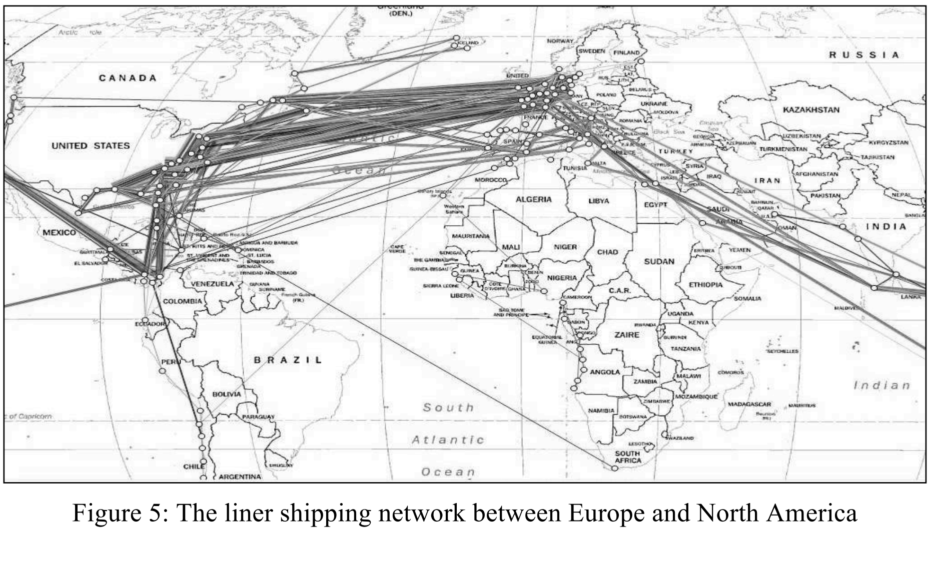
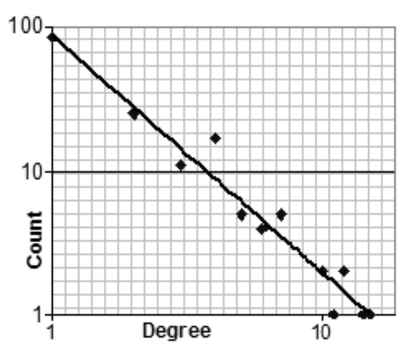


Figure 5: The liner shipping network between Europe and North America

4.3. Network Structure

The network generated has 159 nodes, a size much smaller than databases generated by previous studies such as for power grids, the Internet or the air travel network. In a network of such a small size, it is difficult to observe well defined features of the common network models. Nevertheless, the behavior of the network can still be identified by examining the different properties attached to it. Among these, the degree distribution of the model is a property of particular interest. Basically, a node degree denotes the number of connections each node is linked to. However, due to the fact that more than one service may provide a path between two ports, it makes more sense to consider as degree the number of neighbors that a port has as shown in Figure 5.



Degree	Count
15	1
14	1
12	2
11	1
10	2
7	5
6	4
5	5
4	17
3	11
2	25
1	85

Figure 5: Degree distribution of the liner network between Europe and N. America

Regarding the remaining complex network properties of the model, it was found to have an average path between any two nodes of approximately 6 stops, a clustering coefficient of 0.0278, and a network diameter (maximum number of stops between any two nodes) of 28. Further tests can be run in order to determine the busy nodes on the network. The table below presents a selection of the most heavily used nodes under different definitions of heavy use. Operational Paths refer to the number of optimum paths between any two ports in the network.

Table 2: Critical nodes and under various definitions of network vulnerability

Station	Neighbors	Links	Operational Paths
Antwerp	15	152	5239
Bremerhaven	7	124	903
Charleston	12	174	3661
Felixstowe	7	35	216
Halifax	7	47	1585
Hamburg	7	78	387
Le Havre	11	112	1891
Manzanillo	10	54	3900
Miami	6	54	2092
Montreal	10	64	1653
New York	12	144	2745
Rotterdam	14	156	5371

4.4. Analysis and Results

Simulations of random environmental disasters using these results targeted the busiest nodes and assessed the impact of environmental risks on the network. After the occurrence of a hazardous event in an individual node, the state of the network is re-assessed in order to identify the most vulnerable port that would also constitute the next vulnerability node. Further analysis can performed to evaluate the impact of various events on the network as a whole, for instance by determining how container shipments would have to be rerouted to account for the defective node, and by identifying a new minimum cost path given the current situation. Through this procedure, optimal container routes and points of re-routing can be recalculated, and the resulting state of the network is compared to the original one, before the events. As such, shipment rerouting, necessary to avoid currently infeasible paths are identified. Using these results, we can get an estimate of the additional load borne by different parts of the network in its current state, by calculating the changes in the number of container routes passing through each node.

The figure below provides a visualization of this process. The arrow points at the Port of New York/ New Jersey, which is closed due to an imaginary environmental disaster, while in dark circles are the indirectly affected ports that will face the highest extra routing load so that containers will reach their destinations without being handled in the affected Port of New York. As shown in the figure below, the most heavily affected ports are Montreal, Charleston, Miami, Rotterdam, Le Havre, and Antwerp, along with several ports lying in the Far East (Singapore, Shanghai and Pusan) which are affected to a smaller but not negligible extent. The wide distribution of the indirectly affected nodes illustrates the global impact of the closure of NY/NJ port.

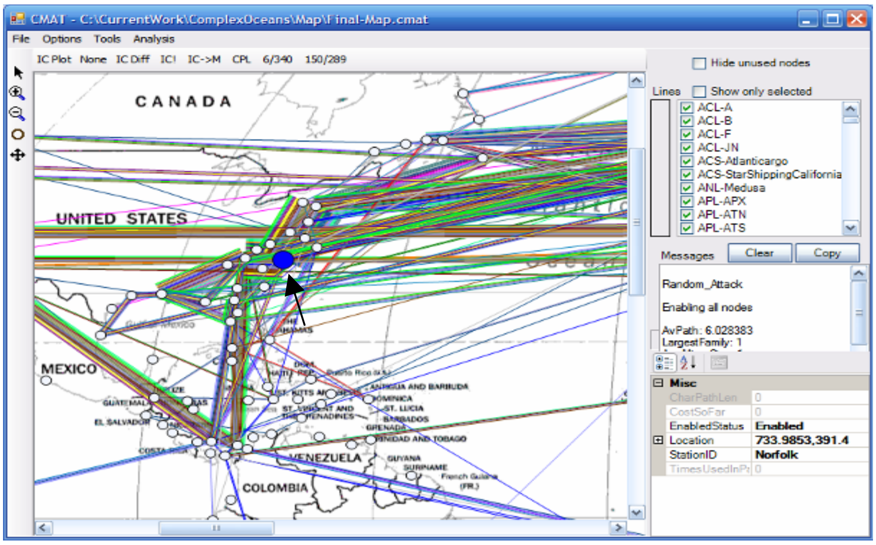


Figure 6: Visualization of impact of network events

It is worth mentioning that our process at this stage does not take into account the processing capacity of the ports, and assumes that indirectly affected ports will be able to process the additional load. The repercussions would be even wider if, more realistically, capacity is taken into account. Modeling capacity is one of the medium-term goals of this project.

5. Conclusion and Future Research

This paper starts by reviewing the development, application and adequacy of existing risk assessment and management models to environmental risks and impacts in maritime and port settings. In particular, we examine the problematical issues of risk perception, value and impact, and discuss the limitations of conventional risk models in providing an integrated and effective approach to risk assessment and management in the context of global environmental security and eco-system sustainability. The paper followed by providing a brief discussion of network reliability and its applications in shipping and ports. The complex network theory was introduced, and its potential applications for modeling liner shipping networks for the purpose of environmental security were then reviewed.

In order to investigate robustness properties of the global maritime network against global environmental risks and impacts, we modeled and simulate the impacts of random node failures on network resilience and reliability. For the purpose of this paper, we modeled only a section of the global shipping network, namely the Trans-Atlantic network, has been analyzed. The analysis of the Europe-North America maritime network properties has shown that it relates closely to generic scale free networks with an average path of approximately 6 port stops. Simulation of both random and intentional disasters has revealed that the most critical nodes are not necessarily the busiest ones, and that some ports may be more heavily affected than others, with impacts stretching to ports located beyond the Trans-Atlantic network studied in this paper. More analysis is needed to fully understand the structure, network properties and robustness of the global shipping network against adverse impacts of environmental disasters, but the study reported in this paper can shed some light on how the complex networks theory can be as useful for the analysis of shipping routes with a view of designing a robust transport network against more frequent and severe environmental disasters.

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