MODELLING THE EFFECTS OF PORT DISRUPTIONS: ASSESSMENT OF DISASTER IMPACTS USING A COST-BASED CONTAINER FLOW ASSIGNMENT IN LINER SHIPPING NETWORKS

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ABSTRACT

In recent years, the increasing levels of interdependence between ports and logistic networks have underlined the importance of an integrated approach toward the formulation of resilience strategies to address disruptive events along the supply chain. Nonetheless, the variety of actors and processes within modern supply chains, and the complexity of associated relationships have previously led to the development of simulation-based models, whose application has been largely compromised by their dependency on extensive and complex sets of data.

This paper lays the basis for the application of optimization techniques, less dependent on complex data sets, in order to assess the impacts of disruptive events on the container liner shipping network. It provides a categorization of port failure factors, differentiating between systemic and external disruptions, and investigating their impact of port components; it proposes the application of a container assignment model that minimizes the expected container routing costs and presents a case-study application to a set of South-East Asian ports along the Asia to Europe route, developing a range of scenarios related to the consequences of seismic and conflict hazards.

Keywords: Logistics, Network resilience, Container assignment model, Maritime transport
1. Introduction

We live in the era of globalization and large-scale outsourcing manufacturing – this has accorded container terminals a critical role in modern society: they are the hubs through which the majority of the world cargo flows among transport modes and international jurisdictions. As such, their performance and resilience is not merely defined by their internal processes but are from their position on the various supply chains that they serve.

At the same time, fierce regional competition within the ports industry has led to the desire to increase market competitiveness, which is usually defined as the capacity to respond reliably to variations of service demand, and uphold stringent commercial and regulatory requirements for punctuality, information transparency, and security (1-2). Relative operational costs are driven down as operators seek to exploit economies of scale through denser stacking strategies and automated handling equipment, capable of operating round the clock with minimal downtime.

Furthermore, in most cases, the increasing levels of integration between ports and complex supply chains have resulted in the selection of ports by shippers based on the performance of landside infrastructure and access to hinterland. As such, port choice has become less discretionary and progressively dependent on the minimization of total logistic costs and maximisation of suppliers’ and customers’ profit.

While the effects of market cycles (3) on the overall stability of these networks have been the subject of extensive research over the years, what is less known is how the overall maritime transport system is likely to be affected by major incidents that are not related to market processes. Examples of such threats include natural disasters (such as earthquakes, tsunamis and floods) as well as armed conflict and political tensions. While some of the work that has been carried out in the past would still be applicable for the analysis of such scenarios, a range of new modelling and analysis techniques would have to be developed in order to accurately represent the particular nature of the events involved and the impacts they may have on the actors involved in maritime supply chains. To meet this requirement, this study seeks to establish a quantitative modelling framework for the analysis of disrupted liner shipping networks, building upon earlier work by Bell et al. (4) on cost-based container flow assignment.

The remainder of this paper is structured in 5 sections: the second section provides a preliminary insight into the concept of port resilience and the effects of supply chain disruptions, including a literature survey of previous work. The following section explores the possible factors that relate to port failure and reflects on how these stand to affect different terminal components. The cost-based assignment model that forms the core of the disruption analysis framework developed is described in Section 4, with an original case-study focusing on the Southeast Asia to Europe route outlined in Section 5. The final section of the paper focuses on a set of disaster scenarios taking place in Indo-China and includes a discussion on the outcomes of the analysis.

2. Background - port resilience and effects of disruptions on the supply chain

The high degree of interdependence between the ports and shipping industries bestows container terminals with a critical status among the various supply chain components - any service interruption has the potential to lead to cascading failures that will disrupt significant portions of large-scale distribution networks. Several studies that use simulation techniques to address this issue can be found in research literature: Martagan et al., (5) developed a simulation model for the determination
of alternative freight routes in case of supply chain disruptions. On this occasion, the U.S. port system
network was implemented as a statistical model, using travel, waiting and operational times as
performance measures. Similarly, Paul and Maloni (6) proposed an algorithm capable of optimising
shipment routes in real-time, using regression-based parametric models.
Recent simulation experiments have been trying to deal with the concept of resilience using aggregate
parameters: Chen and Miller-Hooks (7) developed a quantitative resilience index, expressed as the
fraction of demand that can be satisfied post-disruption, under a given amount of resources and a
given level of service. The index takes into account the random link interactions by using Monte
Carlo simulation and solving them through Benders decomposition. An application of this index is
performed by Nair and Miller-Hooks (8) for the case of Swinoujcie port (Poland); instead of
applying the measure of resilience to a network of ports, it is down-scaled to the port-level and used
in order to understand the strength and efficiency of a multi-terminal port by considering the relation
between its component and their recovery ability.
Simulation-based models are largely compromised by their dependency on extensive and complex
sets of data. Since such detailed datasets are not readily available for a significant number of cases,
more recent research efforts are focusing on the development of optimisation-based analytical models
that can operate with simpler datasets yet capable of delivering reliable results using computationally
efficient programs.
Starting with early linear programming applications to the container fleets management problems (9),
different optimisation techniques have been applied to the problem of container flows allocation, from
minimum cost flow model (10) to integer programming models including empty container
management (11). The study outlined on this paper continues and expands the research on
optimisation-based models, proposing an application of the cost-based assignment model recently
developed by Bell et al. (4) in order to assess the impacts of port disruptions in a liner shipping
network. The latter model has a series of features that make it particularly suitable for the
requirements of this study: in the first instance, cost dimension is used to model the distribution of
flows and aggregates a range of dependencies such as operational costs, container rental cost,
depreciation and travel time (based on travel frequency and capacity). As such it can be used to model
possible variations in costs and times that occur on the aftermath of port disruptions. Secondly, it
includes both port capacity and link capacity constraints, that can capture operational limitations in
liner shipping networks. Finally, the virtual network approach (12), combined with route capacity
constraints, provides an accurate representation of liner services and the possibility of multi-leg
connections between pairs of ports allows the simulation of re-routing in case of port closures.

3. Classification of port disruptions

A clear assessment of potential threats and operational risks is a crucial aspect of port planning, and
allows port operators to develop mitigation strategies, control procedures and implementable recovery
actions. Mansouri et al. (13) developed a schematic inventory of the main factors involved in port
failures, comprising four sub-families: natural factors; technological factors; human factors;
organizational factors. This classification facilitates the distinction between systemic disruptions and
external disruptions, described in the following paragraphs.

3.1 Systemic disruptions
It is well established that ports are sensitive to systemic disruptions, traced to the volatility of liner
shipping schedules, market cycles and their role within various supply chains (14). These types of
disruptions are usually linked to risks arising from two main sources: coordination between supply and demand; disruption to normal procurement and distribution practices.

Examples from the liner shipping industry include significant changes in port rotations due to surge of empty containers to be repositioned or cascading effects of vessels displaced from major trade routes. Imbalances between supply and demand can result from unpredictable changes affecting volume forecasts such as abrupt price variations, new technologies in the market or variations in consumer preferences. Each of these events can convey time delays and other disturbances, propagating along the supply stream.

Furthermore, the increasingly global extension of the trade network affects its resiliency by removing safety buffers in the supply chains in order to lower costs. The complexity of the interactions between logistics, supply and trade channels converging in a port system results in liabilities that cannot be investigated by analysing the three channels independently. The need for comprehensive supply chain risk management frameworks has been repeatedly recognised, but yet not addressed. This is mainly due to the fact that stakeholders in ports and maritime industries tend to adopt an operational perspective on vulnerabilities, focusing on frequent events instead of low-frequency high-impact scenarios (15).

3.2 External disruptions

Causes of potential external disruptions differ among ports – these can depend upon the nature of operations taking place, morphology of the surrounding environment and geopolitical stability of the wider region. During the planning phase, engineering decisions that relate to port location and design would acknowledge the conditions of the natural substrate and the constraints posed by the nature of equipment and yard layouts to be used in the terminal.

Natural factors, the largest sub-family of external factors, include hydrologic, geologic, seismic and atmospheric risks; are generally the less predictable and manageable by port planners. Coastal engineering works are carried out to prevent excessive water agitation within harbours. However, the return periods that are used for design purposes rarely cater for the extreme wave heights seen in recent natural disasters that involved tsunamis, therefore leaving facilities exposed (for an extensive description on port development procedures see 2).

Other significant liabilities are determined by the intrinsic features of a port as a complex system, i.e. by the interaction of manpower and technical equipment, governed by organizational structures and information flows. In the first instance, the influence of human behaviour on port disruptions can be accidental or intentional. Accidental disruptions are mostly caused by workers errors: such events are largely unpredictable, but their impact can be reduced through staff training, standardization of procedures, application of control checks and automation of routine actions.

Intentional human influence spans from strike actions to damages and sabotages. Strikes can reduce the operational throughput of a port in two ways: directly, by reducing the service level of the infrastructure; indirectly, by causing ship-owners to re-route temporarily their services to other destinations. Widespread concerns on security issues have been growing over the last few years, drawing attention to terrorist attacks and sabotages; (16-18).

Lastly, the larger and more analysed family of port disruptions relates to technical failures, errors and interferences. The complexity of port systems requires continuous and multifaceted interactions between its components, operated and supervised either by automated controls or by workers. Innovation and large adoption of Terminal Operating Systems (TOS) have been drastically reducing the incidence of errors and accidents, but technical disruptions still represents the most common distress to ports’ regular functionality.
All the above mentioned events do not necessarily have the same level of impact on the functionality of a port system: some may only affect specific services, while others would generate different levels of failure depending on the area of the port against which they take action. Most of the factors described entail a direct effect on port functionality. It is worth to mention that many of the disruptions affecting port systems are indirect, determined by upstream or downstream interruptions on the transport network that links the terminal with its hinterland.

Previous work by Loh & Thai (19) examined the inoperability of road and rail infrastructure, as generated by the effects of congestion, accidents, atmospheric or hydrogeological hazards, and assessed the potential that these have to induce anomalies in the flow of containers from/to the port. Table 1 provides an overview of possible disruption effects and the corresponding components of a container terminal that stand to be affected.

Section 6 of this paper will focus on two categories of external factors, due to the intrinsic features of the selected case-study area in Asia: seismic hazards and conflict hazards. These categories were selected to illustrate the potential disruptive effects of natural and man-made in the liner shipping network.

4. Application of the cost-based assignment model

As indicated in section 2, in order to assess the effects of port disruptions, the network model considered in this study consist of the following components based on earlier work on cost-based assignment carried out by Bell et al. (4):

- Routes – itineraries followed by a liner services, composed of sequenced ports of call
- Links – direct connections between two ports provided by a scheduled routes
- Legs – sets of links connecting two ports, performed by a single route
- Paths – sets of one or more consecutive legs

The following assumptions and simplifications are adopted in the cost-based assignment model:

- A single container type is considered, with a fixed set of daily rent and handling costs: this enables the aggregation of data on container flows and liner service capacities.
- Liner services are defined through service frequencies, scheduled ports of call and capacity. Each of these features is fixed and independent from other services.
- Surcharges applied by shipping liners and port operators when respectively link and port capacity are reached, so that the rise in prices leads to redistribution in the demand.

The cost functions included in the model comprise of the various container-associated costs (handling costs, container renting costs and depreciation costs), whereas ship operation-associated costs (fuel expenditures, charter costs and port levies) do not have any influence on the assignment of flows. In this application, the model regards only flows of full containers, without addressing the repositioning of empty containers.
### TABLE 1. Categorisation of disruptive consequences on port components

<table>
<thead>
<tr>
<th>Factor</th>
<th>Entrance Channels</th>
<th>Harbour</th>
<th>Quay</th>
<th>Yard</th>
<th>Terminal Operating Centre</th>
<th>Custom/Security Checks</th>
<th>Intermodal connections (rail, road, pipelines)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural Factors</strong></td>
<td>Geo-seismic Hazard</td>
<td>Tsunami waves block the access to entry channels; earthquakes cause collapse of containing banks</td>
<td>Earthquakes and waves cause collapse of containing banks</td>
<td>Damages to banks and mooring equipment; impossibility to use cranes;</td>
<td>Earthquakes and tsunamis make container stacks fall down; damages to gantry cranes and impossibility to use straddle carriers or other vehicles. Water and mud invading the area</td>
<td>Damages to communication, power grid; earthquakes cause collapse of buildings or force evacuation, interrupting work routine</td>
<td>Earthquakes and tsunami waves damage the infrastructure, preventing cargoes from being shipped and causing overload in storage; collapse of pipelines leads to spill overs</td>
</tr>
<tr>
<td></td>
<td>Atmospheric Hazard</td>
<td>Strong winds from cyclones/hurricanes can intensify waves in shallow waters</td>
<td>Icing in shallow waters causes problems in mooring/unmooring; strong winds cause movements</td>
<td>Damages to cranes or impossibility to use them, due to strong winds; icing can make surface inoperable for trolleys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrologic Hazard</td>
<td>Coastal erosion gradually reduces the protection secured by banks; movement of detriti reduces depth; floods makes impossible to berth or removes the installed moorings</td>
<td>Unloading operations are made impossible by floods: container cannot be transported through trolleys or straddle carriers</td>
<td>Floods make yard surface inoperable for trolleys and damage containers; refrigerated container linked with electricity cannot be maintained</td>
<td>Floods cause inoperability of centres, by preventing workers from using the facilities or damaging the technological services (communication, energy)</td>
<td></td>
<td>Erosions and flooding cause landslides and breakdowns along the lines, impeding inbound/outbound flows.</td>
</tr>
<tr>
<td><strong>Human Factors</strong></td>
<td>Human Errors</td>
<td>Error in scheduling leads to congestion; wrong manoeuvres can increase berthing times or cause ships to block channels</td>
<td>Errors in unloading containers, and moving them to the yard can delays and damages; errors in mooring operations cause damages to infrastructure, equipment and third parties</td>
<td>Errors in coordinating activities or supervising the actions of the Terminal Operating System</td>
<td>Accidental oversights in security checks can bring dangerous goods within the port</td>
<td>Connection and interchange errors within the intermodal areas cause delays; errors in scheduling</td>
<td></td>
</tr>
<tr>
<td><strong>Industry Actions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Terrorist Attacks</strong></td>
<td>Maritime sabotages and hijackings may be cause of damages to port infrastructures</td>
<td>Hazardous content in containers may be harmful for equipment/workers and cause interruption of operations. Storage tanks with oil and other combustibles may be targeted by terrorists</td>
<td></td>
<td>Computer hacking attacks can violate security systems and sabotage the routine operations</td>
<td>Hazardous or dubious materials, even if not directly harmful, require extraordinary controls and can interrupt the normal flow of cargoes</td>
<td>Hazardous content in containers may be harmful for equipment/workers. Tanks with oil and other combustibles may be targeted by terrorists</td>
<td></td>
</tr>
<tr>
<td><strong>Technological Factors</strong></td>
<td>Maritime Accidents</td>
<td>Improper manoeuvring or lack of coordination can cause accidents between ships or blockages</td>
<td></td>
<td>Queuing procedures and coordination can be cause of accidents or congestion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interface Issues</td>
<td></td>
<td>Coordination issues between container liners and terminal operators</td>
<td>Issues on quayside interface and on rail/road interfaces; possible lack of communication along the supply chain (over / under capacity).</td>
<td>Interface issues can be generated by errors in the Operating System</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Failures to Computer Network, Control Systems</td>
<td></td>
<td></td>
<td>Computer network failures reducing the functionality of the Terminal Operating System have impact on the whole port; Particularly: the queuing procedures for ship arriving at the port; the organization of unloading operations and storage, the coordination with the intermodal road and rail facilities. Errors in the design or usage of control and surveillance tools, such as the Managing Information System (MIS) and Decision Support System (DSS) can fail the detection of problems throughout the terminal.</td>
<td></td>
<td></td>
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<tr>
<td><strong>Organizational Factors</strong></td>
<td></td>
<td></td>
<td></td>
<td>Delays in authorization procedures, organization of intervention and recovery planning affects the response to disastrous events, worsening their effect. Poor training acts as a second level of disruption, worsening a critical condition initiated by other factors. The inability of workers and technicians to cope with the difficulties of an emergency can lead to imprecise or wrong behaviours that lengthen the recovery process.</td>
<td></td>
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</tbody>
</table>
M. Novati, P. Achurra-Gonzalez, R. Foulser-Piggott, G. Bowman, M.G.H. Bell, P. Angeloudis

Notation:

1. $c_a$  Sailing time on leg a, including loading/unloading
2. $x_{as}^f$  Flow of full containers on leg a, en route to destination s
3. $t_{rs}^f$  Flow of full containers from origin r to destination s
4. $f_a$  Frequency of sailing on leg a
5. $w_{is}^f$  Expected dwell time at port I for full containers en route to destination s
6. $k_i$  Maximum throughput of port i
7. $CHC_n^t$  Cargo handling cost per container for a leg of type t, on route n
8. $CR_n$  Rental cost per unit time per container
9. $DV_i$  Depreciation per unit time per full container
10. $N$  Set of routes
11. $T$  Set of leg types
12. $A$  Set of legs
13. $A_n^t$  Set of legs of type t, on route n
14. $A_i^+$  Set of legs entering port i
15. $A_i^-$  Set of legs leaving port i
16. $I$  Set of ports
17. $O$  Set of origin ports
18. $D$  Set of destination ports
19. $RC_n$  Capacity of route n

Leg types T are origin-to-destination (o-d); origin-to-transhipment (o-t); transhipment-to-transhipment (t-t); and transhipment-to-destination (t-d). The following conventions are used to simplify the notation (4):

\[ x_{a+}^f = \sum_{s \in D} x_{as}^f \]  
\[ w_{i+}^f = \sum_{i \in I} \sum_{s \in D} w_{is}^f \]

The assignment model is thus governed by an objective function that minimizes total costs:

\[ p_0: \min x_{as} \left( \sum_{n \in N} \sum_{t \in T} \sum_{a \in A_n^t} CHC_n^t (x_a^f) + \left( \sum_{a \in A} x_a^f c_a + w_{i+}^f \right) (CR + DV) \right) \]

subject to a set of constraints:

\[ \sum_{a \in A_i^+} x_{as}^f - \sum_{a \in A_i^-} x_{as}^f = b_{is}^f \quad \text{for all } i \in I, s \in D \]  
\[ x_{as}^f \leq w_{is}^f f_a \quad \text{for all } a \in A_i^-, i \neq s \in I, s \in D \]  
\[ k_i \geq \sum_{a \in A_i^+} x_{as}^f + \sum_{a \in A_i^-} x_{as}^f \quad \text{for all } a \in A_i^-, i \in I \]  
\[ RC_n \geq \sum_{a \in A} x_{a+}^f + \sum_{a \in A_i^+} x_{a+}^f \quad \text{for all } i \in I \]  
\[ x_{as}^f \geq 0 \quad \text{for all } a \in A, s \in D \]  
\[ b_{is}^f = \begin{cases} -t_{rs}^f & \text{if } i = r \in O \\ t_{rs}^f & \text{if } i = s \in D \\ 0 & \text{otherwise} \end{cases} \]
Constraint (4) enforces container conservation; constraint (5) ensures that the delay at ports is at least as large as the inverse of the combined service frequency, differentiating by destination; constraints (6) and (7) respectively guarantee that port and route capacities are not exceeded; (8) is a non-negativity constraint and (9) represents the set of origin/destination constraints.

5. Problem instance definition and calibration – An application to the South East Asia

The following two sections seek to demonstrate the applicability of the cost-based assignment model for disruption analysis. The case study in this paper focuses on the Asia-Europe trade lane, and assesses the vulnerability of ports in South East Asia, namely Singapore, Port Kelang (Malaysia), Jakarta/Tanjung Priok and Belawan (Indonesia). Liner service calls beyond this region are represented using two port group centroids, namely Southeast Asia and Europe. This region was selected for its susceptibility to impacts of earthquake and conflict scenarios, as presented in section 6. The analysis will therefore assess how container flows stand to be redistributed across ports in the region examined, should any loss of functionality occur at any one of the nodes.

Singapore, Port Klang and Belawan operate in close proximity to the Malacca Straights, which are regarded as the most crucial bottleneck in the Asia-Europe trade lane. As such disruptions affecting services in these areas have the potential to significantly affect shipping operations across the entire global liner shipping network.

The Southeast Asian centroid collectively represents ports located in East Indonesia, East Indochinese Peninsula, Vietnam and Philippines. Given its location, Tanjung Perak (the second largest port of Indonesia) was selected to represent the actual geographical location of the centroid. Jakarta/Tanjung Priok, the main port of Indonesia, has been considered separately from the group, due to its role as a transhipment hub between Southeast Asia and routes toward Europe. The European centroids comprise of hubs in the North-Atlantic and Hanseatic area, i.e. Le Havre, Felixstowe, Southampton, Thamesport, Antwerp, Zeebrugge, Rotterdam, Hamburg and Bremerhaven. In this case, Rotterdam has been adopted as the physical location of the centroid, given its role as one of the major European ports.

5.1 Data sources

One of the most important difficulties encountered by maritime transport analysts is that accurate data on international trade volumes, schedules, port capacities and operational throughputs are notoriously difficult to source due to commercial sensitivities and the complexity of liner shipping patterns. For the purposes of this case study, input data for the model were generated using the most up-to-date figures available for liner services passing through the Indochinese ports of Singapore, Port Kelang, Jakarta and Belawan. This preliminary approximation leaves room for refinements that will be addressed in future work, but do not compromise the practical availability of the model. External factors that may influence supply and demand were not considered, therefore leading to the assumption that cargo flows would not be affected by disruptions and that ports and maritime infrastructure would be expected to cope despite a (partial) loss of operational capacity.

The four ports representing the core of the case study network are all positioned among the top 100 in the world in terms of yearly throughput, with the exception of Belawan. Liner service capacity constraints and port call data were populated using data from Containerisation International (20). No
throughput capacity constraints are applied to the “Southeast Asia” and “Europe” nodes, given their status as port group centroids.

Port capacities used in the model were calculated based on port throughput data, and in a way that they reflect the weekly capacity allocated to the sub-network under investigation (data for each port are reported in Table 2).

\[ k_i = \frac{n_i}{N_i} K_i \]

Where:

- \( k_i \): Weekly capacity allocated to the sub-network at port \( i \)
- \( n_i \): Number of weekly liner services within the sub-network to/from port \( i \)
- \( K_i \): Total weekly capacity at port \( i \)
- \( N_i \): Total number of weekly liner services to/from port \( i \)

**TABLE 2. Port figures and estimation of weekly port capacity**

<table>
<thead>
<tr>
<th>Port</th>
<th>( K_i ) [TEUs]</th>
<th>( N_i )</th>
<th>( n_i )</th>
<th>( k_i ) [TEUs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>513,000</td>
<td>288</td>
<td>7</td>
<td>14,500</td>
</tr>
<tr>
<td>P</td>
<td>163,000</td>
<td>124</td>
<td>5</td>
<td>7,500</td>
</tr>
<tr>
<td>J</td>
<td>120,000</td>
<td>27</td>
<td>2</td>
<td>9,000</td>
</tr>
<tr>
<td>B</td>
<td>15,500</td>
<td>8</td>
<td>4</td>
<td>7,500</td>
</tr>
</tbody>
</table>

Five services are set up in this model, defined in a way that reflects the actual pattern of container flows among ports in the region. Ship sizes and speeds used in the model are similar to those used by actual liner services that follow such patterns. Figure 1 demonstrates the structure of the model used in the analysis. Despite its relative simplicity it is deemed to provide a sufficient level of detail for this stage of the analysis, and is capable of demonstrating the features of the cost-based container assignment model.

As shown in Figure 1, services 1, 2 and 3 correspond to the weekly Asia-to-Europe liner service loops that are offered by major shipping alliances. Vessels in these services fall within the Post-Panamax range, with an average size of 8,000 TEUs (27). Services 4 and 5 represent regional services, offered weekly with an average ship size of 4,000 TEUs. Vessels across all services in the model are assumed to operate at 20 knots.

Liner service costs used in the model are in accordance to the values and pricing structures used in previous studies by Bell et al. (4, 22). Different port container handling costs are used in cases of direct shipping and transhipment, while average cargo values for loaded containers were statistically inferred using net worth values and TEU flows in the Asia to Europe route, as reported in trade databases (23-25). Rental and depreciation costs for containers were set in accordance to the value inserted in the referenced application of cost-based assignment model, i.e. based on the average values for the Far East - Europe trade lane (as shown in Table 3).
FIGURE 1. Scheme of the network and services characteristics

TABLE 3. Cost of loading/unloading, rental and depreciation costs for containers

<table>
<thead>
<tr>
<th>Cost of loading/unloading</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading at origin and unloading at destination</td>
<td>400 $/TEU</td>
</tr>
<tr>
<td>Loading at origin and unloading at transhipment port</td>
<td>350 $/TEU</td>
</tr>
<tr>
<td>Loading at transhipment port and unloading at destination</td>
<td>350 $/TEU</td>
</tr>
<tr>
<td>Loading and unloading at transhipment port</td>
<td>300 $/TEU</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rental and depreciation costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value of cargo shipped per container</td>
<td>40,000 $/TEU</td>
</tr>
<tr>
<td>Rental cost for full/empty container</td>
<td>4.5 $/TEU/day</td>
</tr>
<tr>
<td>Rate of depreciation for a full container</td>
<td>20 $/TEU/day</td>
</tr>
</tbody>
</table>

The container flow origin-destination matrix used in this problem instance assumes that the bulk of cargo originates on the endpoints of the Asia to Europe corridors, with the ports that are explicitly included in the model being used mostly for transhipment purposes. This is in accordance to annual regional trade figures reported by UN Comtrade (23).

6. Development and application of disruption scenarios

The use of event scenarios assists the estimation of impact and increases understanding of, in this case, rare events and the effects they have on critical systems and infrastructure. Two kinds of external disruptions were used in this study: an earthquake (chosen to illustrate the effects of natural hazards) and an act of war (illustrating human-made disruptions). Systematic disruptions would not be examined in this paper but the methodology applicable for those cases would be similar. Natural hazard scenarios utilise established statistical methods to determine a return period, which connects likelihood of loss with probability of severity. Human-made scenarios are developed deterministically, and rely on the combination of qualitative and quantitative data to approximate levels of severity and likelihood. In this paper an earthquake scenario and a war scenario affecting the
port network are considered. The two cases stand to affect the examined port system in different ways, the characteristics of which are illustrated in the section below.

6.1 Earthquake scenarios
For an earthquake scenario, we consider the seismic hazard at a port (probability of a certain level of ground shaking) and the vulnerability of the port (likelihood of damage to the port due to ground shaking). In many international building codes, the seismic hazard to be considered in the design of earthquake-resistant structures is defined as a level of ground shaking with a 2% probability of exceedance in 50 years (a 2475 year return period). The level of ground shaking is measured using spectral acceleration (Sa). Spectral acceleration with a 1 second period (S1) is roughly equivalent to peak ground acceleration (PGA). The values for the ports in the network are obtained from the USGS Worldwide Seismic Design Maps. The vulnerability of ports is measured using a Quality of Port Infrastructure rating, which measures business executives' perceptions of their country's port facilities (26). The rating ranges from 1 to 7, with a higher score indicating better development of port infrastructure. These data are obtained from the Global Earthquake Model (GEM) report on socio-economic vulnerability indicators for earthquake impacts (26).

The earthquake scenario was developed using the 1995 Hanshin-Awaji Earthquake impacts on the Port of Kobe as a case study. According to the USGS, the Port of Kobe experienced a PGA = 0.315g (27). The vulnerability of ports rating in Japan is 5.2 (28-29). It should be noted that this rating is from 2014 and port vulnerability in Japan in 1995 may have been higher (<5.2) and earthquake impacts resulted in considerable improvements to port infrastructure to reduce vulnerability to earthquakes. The port accounted for 10% of Japan’s import and export trade and handled 30% of Japan’s container cargo throughput. The port was particularly important for Western Japan as it handled roughly 65% of imports and exports for Kinki, Hyogo and Chugoku and 80% of exports from Shikoku. After the earthquake struck, the port was virtually closed. The first berth for container traffic reopened 2 months after the event and by April, the total trade amounted to only 40% of the previous year. Cargo traffic was diverted to alternative ports, where the main beneficiaries were domestic ports with 50% of container cargo rerouted to Yokohama and 40% to Tokyo and Osaka.

In the port network presented in this paper, two earthquake scenarios similar in impacts to the 1995 Hanshin-Awaji Earthquake are possible, affecting the ports of Jakarta or Belawan. An earthquake in Jakarta or Belawan with a 2475 year return period has a spectral acceleration, S1 = 0.33g (28-29). Using the conversion equations of Worden et al. (30), this gives a shaking intensity (MMI) = 7.7. Jakarta could therefore experience ground-shaking of a similar level to that experienced in Kobe. Jakarta is rated as more vulnerable in the GEM study than Japanese ports (GEM rating = 3.6) and could potentially suffer more damage and therefore take longer to rebuild than the Port of Kobe, increasing recovery time to return the port to its normal operations. A suggested level of disruption is similar to that experienced at the Port of Kobe: the port of Jakarta or the port of Belawan are estimated to be closed for container cargo for 2 months (equivalent to Kobe disruption). After 3 months, 40% of available port container handling capacity is restored. The system is expected to recover fully after 1 year (with 100% of original capacity being available). The sets of parameters applied in order to generate these scenarios can be found in Table 4.
### TABLE 4. Summary of scenarios and related parameters

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Event</th>
<th>Timeframe</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base case</strong></td>
<td>all ports and routes working at standard operational level</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Earthquake in Jakarta</strong></td>
<td>a) Immediately after the event</td>
<td>0% port capacity</td>
<td>-50% leg capacity to/from J +200% sailing time to/from J</td>
</tr>
<tr>
<td></td>
<td>b) 3 months after the event</td>
<td>40% port capacity</td>
<td>-50% leg capacity to/from J +100% sailing time to/from J</td>
</tr>
<tr>
<td><strong>Earthquake in Belawan</strong></td>
<td>a) Immediately after the event</td>
<td>0% port capacity</td>
<td>-50% leg capacity to/from B +200% sailing time to/from B</td>
</tr>
<tr>
<td></td>
<td>b) 3 months after the event</td>
<td>40% port capacity</td>
<td>-50% leg capacity to/from B +100% sailing time to/from B</td>
</tr>
<tr>
<td><strong>Earthquake involving both ports</strong></td>
<td>a) Immediately after the event</td>
<td>0% port capacity</td>
<td>-25% leg capacity to/from J, B +200% sailing time to/from J, B</td>
</tr>
<tr>
<td></td>
<td>b) 3 months after the event</td>
<td>40% port capacity</td>
<td>-25% leg capacity to/from J, B +100% sailing time to/from J, B</td>
</tr>
<tr>
<td><strong>War affecting flows in the South China Sea</strong></td>
<td>a) Severe consequences</td>
<td>-50% leg capacity on leg A-S +200% sailing time on leg A-S</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b) Mild consequences</td>
<td>-25% leg capacity on leg A-S +100% sailing time on leg A-S</td>
<td></td>
</tr>
</tbody>
</table>

### 6.2 War scenarios

Developing a war scenario involved historical analysis, the assessment of current ‘areas of tension’, and consideration of current military theory and recent war-gaming exercises. The hypothetical China-Japan war scenario builds on historical tensions and geographical disputes. Claims of sovereignty of the Senkaku/Diaoyu Islands in the East China Sea and the targeting of naval assets triggers the conflict. Direct action on either country is limited, although military targets in China and Japan’s power infrastructure are targeted in missile strikes. One of the areas most affected, and the focal point of this study, is the impact on shipping. An initial naval blockade surrounds the islands, disrupting shipping routes through the East China Sea. As the conflict escalates, the blockade zone increases to an area of over 250,000 square kilometres, extending from the north-east of Taiwan to the south-west of the Island of Kyushu. As other nations become involved in a naval standoff, the blockade zone expands further, encompassing Taiwan, access to China, and Hong Kong, from the South China Sea, and the Sea of Japan.

In this extreme scenario, where the conflict lasts 9 months, and takes a further 3 months to manage the stand-down of forces, international trading is severely restricted: foreign direct investment decreases by 70% and imports and exports suffer 90% reduction for the belligerent nations. While the main ports of South-East Asia (Kaohsiung, Tokyo, Busan, Shanghai, and Hong Kong), would maintain almost full capacity through the conflict, the level of activity would be minimal. Manufacturing organisations, particularly foreign-owned entities in China and Japan, would halt operations, through political pressure, safety concerns, or because exporting became impossible as container yards fill. Perhaps the greatest impact on a functioning port would be to the Port of Singapore, which would become a global bottleneck, as trade was restricted to the conflict zone (see Table 4).
6.3 Application of the model: assumptions and results

Four alternative outcomes of the above mentioned scenarios are developed and tested through the model. Scenario assumptions and results are reported in Table 4 and Table 5 respectively. The consequences of earthquakes are modelled not only by reducing the capacity of ports, but also affecting the route capacity on legs involving the disrupted port and the costs of shipping through those routes. From the results provided below it can be seen that transport demand on the Asia to Europe corridor is normally satisfied by the three liner services (base case), without need for intra-network transhipments.

When one or more ports are disrupted, or the cost of shipping through a particular route is increased by time elongations, the flows are redistributed by the model in order to minimize total costs. The variations in total costs from the base case are sensible, ranging from +7.7% in scenario 3b to +19.9% in scenario 4a, as shown in Table 6. The service leg linking the port of Singapore to the rest of South East Asia is shown to be the most sensible component of the network.

7. Conclusions and further work

This paper outlined the development of a novel approach for the vulnerability of a multi-port system against natural and man-made disruptions, using the cost-based container flow assignment technique. The South East Asia to Europe corridor has been investigated, due to its global strategic importance and the potential of consequences that a chain effect of failures might generate. Data on previous events and hazard forecasts were used to develop the two scenarios presented in this study, which were eventually translated into operational functionality indexes and recovery intervals.

For the purposes of this research, the case-study example focused on the impacts of port failures on a number of container liner shipping services, abstracting it from the wider chain of relations that it holds with the rest of the global network and within the multimodal logistic grid.

This case study demonstrates the applicability of the cost-based assignment model to improve the understanding of effects of disruptive events. The linear program allows an extension of this model to wider networks, efficiently solvable with the help of LP solvers. Due to its exemplifying purpose, the preliminary simulation makes large use of secondary data, leaving room for further refinements in selection of data sources and calibration inputs.

A fully developed application of the container assignment model could provide shipping lines and logistics providers with a tool for the simulation of hazardous events, allowing them to estimate the operational and financial consequences of flow redistributions. Moreover, it would help port authorities in evaluating the robustness of networks, the associated strategic importance of container terminals and the connected risks, supporting decision making processes and orientating investments on port infrastructures.
**TABLE 5.** Scenarios outcomes: total costs (variation from base case in brackets) and flows

<table>
<thead>
<tr>
<th>Scenario 0</th>
<th>Total Cost: $ 24,398,500</th>
</tr>
</thead>
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<tr>
<td>Origin</td>
<td>Destination</td>
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<tr>
<td>Asia</td>
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</tr>
<tr>
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<td>Europe</td>
</tr>
<tr>
<td>Asia</td>
<td>Europe</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 1a - Total Cost: $ 28,640,000 (+17.3%)</th>
<th>Scenario 1b - Total Cost: $ 27,579,000 (+13.0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>Belawan</td>
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<tr>
<td>Asia</td>
<td>Singapore</td>
</tr>
<tr>
<td>Asia</td>
<td>Europe</td>
</tr>
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</tr>
<tr>
<td>Asia</td>
<td>Singapore</td>
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<tr>
<td>Asia</td>
<td>Port Klang</td>
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<td>Asia</td>
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<td>Jakarta</td>
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<td>Asia</td>
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<td>Port Klang</td>
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<td>Belawan</td>
<td>Port Klang</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2a - Total Cost: $ 27,866,500 (+14.2%)</th>
<th>Scenario 2b - Total Cost: $ 26,694,500 (+9.4%)</th>
</tr>
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<tbody>
<tr>
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<tr>
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<td>Singapore</td>
<td>Port Klang</td>
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<table>
<thead>
<tr>
<th>Scenario 3a - Total Cost: $ 28,754,500 (+17.8%)</th>
<th>Scenario 3b - Total Cost: $ 26,289,000 (+7.7%)</th>
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<tbody>
<tr>
<td>Asia</td>
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</table>

<table>
<thead>
<tr>
<th>Scenario 4a - Total Cost: $ 29,260,000 (+19.9%)</th>
<th>Scenario 4b - Total Cost: $ 24,845,500 (+1.8%)</th>
</tr>
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<tbody>
<tr>
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References


