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Achurra-Gonzalez, Pablo E.; Novati, Matteo; Foulser-Piggott, Roxane; Graham, Daniel J.; Bowman, Gary; Bell, Michael G H; Angeloudis, Panagiotis

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Pablo E. Achurra-Gonzalez*

Centre for Transport Studies, Department of Civil and Environmental Engineering,
Skempton Building, South Kensington Campus, Imperial College London, London SW7 2BU, UK
Tel: +44 20 7594 2706 Email: p.achurra-gonzalez13@imperial.ac.uk

Matteo Novati

Steer Davies Gleave Ltd.
28-32 Upper Ground, London SE1 9PD, UK
Tel: +44 20 7910 5527 Email: matteo.novati@sdgworld.net

Roxane Foulser-Piggott

Faculty of Business, Bond University,
14 University Drive, Robina QLD 4226, Australia
Tel +61 7 559 52266 Email: rfoulser@bond.edu.au

Daniel J. Graham

Centre for Transport Studies, Department of Civil and Environmental Engineering,
Skempton Building, South Kensington Campus, Imperial College London, London SW7 2BU, UK
Tel: +44 20 7594 6088 Email: d.j.graham@imperial.ac.uk

Gary Bowman

Faculty of Business, Bond University,
14 University Drive, Robina QLD 4226, Australia
Tel +61 (7) 5595 1161 Email: gbowman@bond.edu.au

Michael G. H. Bell

C13 - St James Campus, Institute of Transport and Logistics Studies (ITLS)
University of Sydney Business School, The University of Sydney, Australia
Tel: +61 0291141816 Email: michael.bell@sydney.edu.au

Panagiotis Angeloudis

Centre for Transport Studies, Department of Civil and Environmental Engineering,
Skempton Building, South Kensington Campus, Imperial College London, London SW7 2BU, UK
Tel: +44 20 7594 5986 Email: p.angeloudis@imperial.ac.uk

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*Corresponding Author

Abstract

Understanding how container routing stands to be impacted by different scenarios of liner shipping network perturbations such as natural disasters or new major infrastructure developments is of key importance for decision-making in the liner shipping industry. The variety of actors and processes within modern supply chains and the complexity of their relationships have previously led to the development of simulation-based models, whose application has been largely compromised by their dependency on extensive and often confidential sets of data. This study proposes the application of optimisation techniques less dependent on complex data sets in order to develop a quantitative framework to assess the impacts of disruptive events on liner shipping networks. We provide a categorization of liner network perturbations, differentiating between systemic and external and formulate a container assignment model that minimises routing costs extending previous implementations to allow feasible solutions when routing capacity is reduced below transport demand. We develop a base case network for the Southeast Asia to Europe liner shipping trade and review of accidents related to port disruptions for two scenarios of seismic and political conflict hazards. Numerical results identify alternative routing paths and costs in the aftermath of port disruptions scenarios and suggest higher vulnerability of intra-regional connectivity.

Keywords: Liner shipping; Network perturbations; Port disruption accidents, Container assignment model

1 Introduction

While the effects of market cycles (Stopford, 2009) on the overall stability of liner shipping networks have been the subject of extensive research over the years, what is less known is how the overall liner shipping transport system can be affected by perturbations to the established network topology caused by events such as infrastructure developments, natural disasters or armed conflicts. These perturbations are important because they could significantly alter transportation capabilities between regions or result in accidents that can cause loss of life, injuries, economic loss or damage to the environment (Mullai and Paulsson, 2011). Therefore, understanding the impact of liner shipping perturbations on container cargo routing and their potential related accidents is crucial for decision-makers in the maritime industry who strive at being better prepare for these events.

It is unrealistic to expect remove all uncertainty related to the potential effects of the above-mentioned events. However, this uncertainty can be reduced applying quantitative frameworks that model container routing under hypothetical scenarios of network perturbations and examining historical records of accidents related to the events evaluated. Such frameworks, however, are not simple to formulate. The variety of actors and processes within modern supply chains, and the complexity of their relationships have previously led to the development of simulation-based container models whose, application have been largely compromised by their dependency on extensive and complex sets of data which are generally not available in a many cases and regions.

One of the earliest attempts to simulate maritime container flows at a global scale was the Container World project (Newton, 2008; Bell et al., 2011). This study proposed a simulation approach in which every ship, port, liner service, shipping line, truck and rail operator was represented by a separate agent. The network was built using actual port rotations published by ocean carriers. Containers were transported via each of the agents operating based on their individual set of parameters. Although the model provided a framework for global-scale container routing, it proved to be too data intensive in an competitive industry reluctant to share the data required to maintain the model (Bell et al., 2011). This limitation hampers the application of such model for scenario analysis in regions where the required data is not available.

Alternative research efforts have focused on the development of optimisation-based models that can operate with simpler datasets yet are capable of delivering reliable results using computationally efficient mathematical programs. The network used in these models can be built from published ocean carrier schedules (Zurheide and Fischer, 2012) or computed from a liner shipping network design problem (Agarwal and Ergun, 2008). The objectives in the optimisation-based literature range between minimisation of routing costs (Wang et al., 2013), minimisation of sailing time (Bell et al., 2011), maximisation of profit from an ocean carrier point of view (Ting and Tzeng, 2004) and maximisation of volumes transported (Song et al., 2005). Tran and Haasis (2013) provide a comprehensive review of previous optimisation-based works including additional relevant features such as empty container repositioning, deterministic or stochastic shipping demand, and container routing problems in time extended networks.

This study seeks to contribute to the application of optimisation-based models for the analysis of liner shipping cargo flows affected by network perturbations, building upon earlier work by Bell et al. (2013) on cost-based container assignment. The proposed application of this model minimises expected container routing costs in order to assess changes in container cargo flows under scenarios of seismic and conflict hazards affecting the Southeast Asia to Europe trades. We examine previous studies of past similar disruptions in order to discuss their potential related accidents and network parameters affected in the aftermath of the disruption scenarios presented.

The cost-based assignment model has a series of features that make it suitable for the requirements of this study: First, the cost dimension is used to model the distribution of flows and aggregates a range of dependencies such as container handling and rental cost, cargo depreciation, and transit time. As such it can be used to model possible variations in costs and times that occur on the aftermath of port disruptions. Second, it includes both port capacity and link capacity constraints that can capture disrupted operational parameters in liner shipping networks. Third, the model uses a virtual network approach (Jourquin et al., 2008) which provides an accurate representation of liner shipping operations and allows to skip disrupted ports within a established port call sequence. Finally, we extend previous formulations adding a decision variable and penalty costs for cargo not transported allowing feasible solutions in cases where disruptions decrease network routing capacity below transport demands.

The remainder of this paper is structured as follows: Section 2 describes the methodology used by first proposing a classification scheme of network perturbations, differentiating between systemic and external. This section describes the cost-based assignment model that forms the core of the perturbation analysis framework. Section 3 provides a case-study focusing on the Southeast Asia to Europe trade where the model is applied in two scenarios of port disruption: seismic hazards and political conflicts. Lastly, section 4 presents conclusions and outlines future work.

2 Methodology

2.1 Classification scheme for liner shipping network perturbations

We define "network perturbation" as any change, positive or negative, to the existing state of main components of liner shipping networks. These include ports (nodes), routes operated by container liner services (links), vessels size (capacity), and transport demands (origin-destination pairs). Whether a perturbation is positive or negative often depends on the point of view of each stake holder. For example, the 1995 Port of Kobe disruption caused by an earthquake diverted local cargo to the ports of Osaka, Nagoya and Yokohama and transhipment cargo to the ports of Busan and Kaohsiung improving their cargo volumes and business. Though the port of Kobe recovered and the local cargo returned, significant transhipment volumes never returned (Lam, 2012). Positive or negative perturbations impacts are not isolated to port disruptions. For example, the improvement of existing infrastructure such as the Panama Canal expansion scheduled for completion in 2016 will relax vessel deployment upper bound constraints through this waterway. Potential impacts include transshipment cargo shifting in the Caribbean area from ports without capacity to receive post-panamax vessels to those with adequate infrastructure to accommodate such vessels (Rodrigue and Ashar, 2015).

In order to identify in which scenarios a container routing model can provide a contribution to the analysis of network perturbations, we proposed a classification scheme which differentiates between systemic and external perturbations. This differentiation allows to identify sources of disruptions which, from a modelling stand-point, dictate the main parameters of the network that will be modified.

Previous studies have focused on the study of maritime supply chains risk with a focus on port disruptions (e.g. Lam, 2012; Loh and Van Thai, 2014; Mansouri et al., 2010; Qi, 2015). However, this initial non-exhaustive taxonomy is, to the best of our knowledge, the first attempt to classify perturbations that impact additional liner shipping network components beyond ports as focal point such as route capacity and factors influencing origins and destinations of containerised cargo. Our proposed classification adapts macroeconomic, operational and competitive factors discussed by Rodrigue (2010) to include perturbations derived from the liner shipping industry while additional environmental and human risk factors are used to capture exogenous perturbations.

Figure 2.1 presents and hierarchical representation of the proposed classification with examples of liner network perturbations. Systemic perturbations refer to changes that are intrinsic to the liner shipping industry. These are mainly driven by macroeconomic factors that impact supply and demand of containerized trade; operational factors such regulatory restrictions and industry practices such as "cascade" effects of larger containerships; and competitive factors such as the development of new infrastructure (e.g. London Gateway port). External perturbations refer to changes driven by exogenous factors to the liner shipping industry. These include environmental changes such as the potential use of arctic shipping routes and natural disasters such as earthquakes; and human risk factors such as port labour strikes, piracy and political conflicts.

Some of the perturbations shown in Figure 2.1 can be categorised under more than one of the proposed factors due to existing underlying relationships. For example, though "vessel cascade" is an operational measure driven by the increased use of economies of scale, the use of larger containerships is also the result of increased demand volumes (macroeconomic factor) and ocean carriers' strategy to reduce their transportation costs (competitive factor).

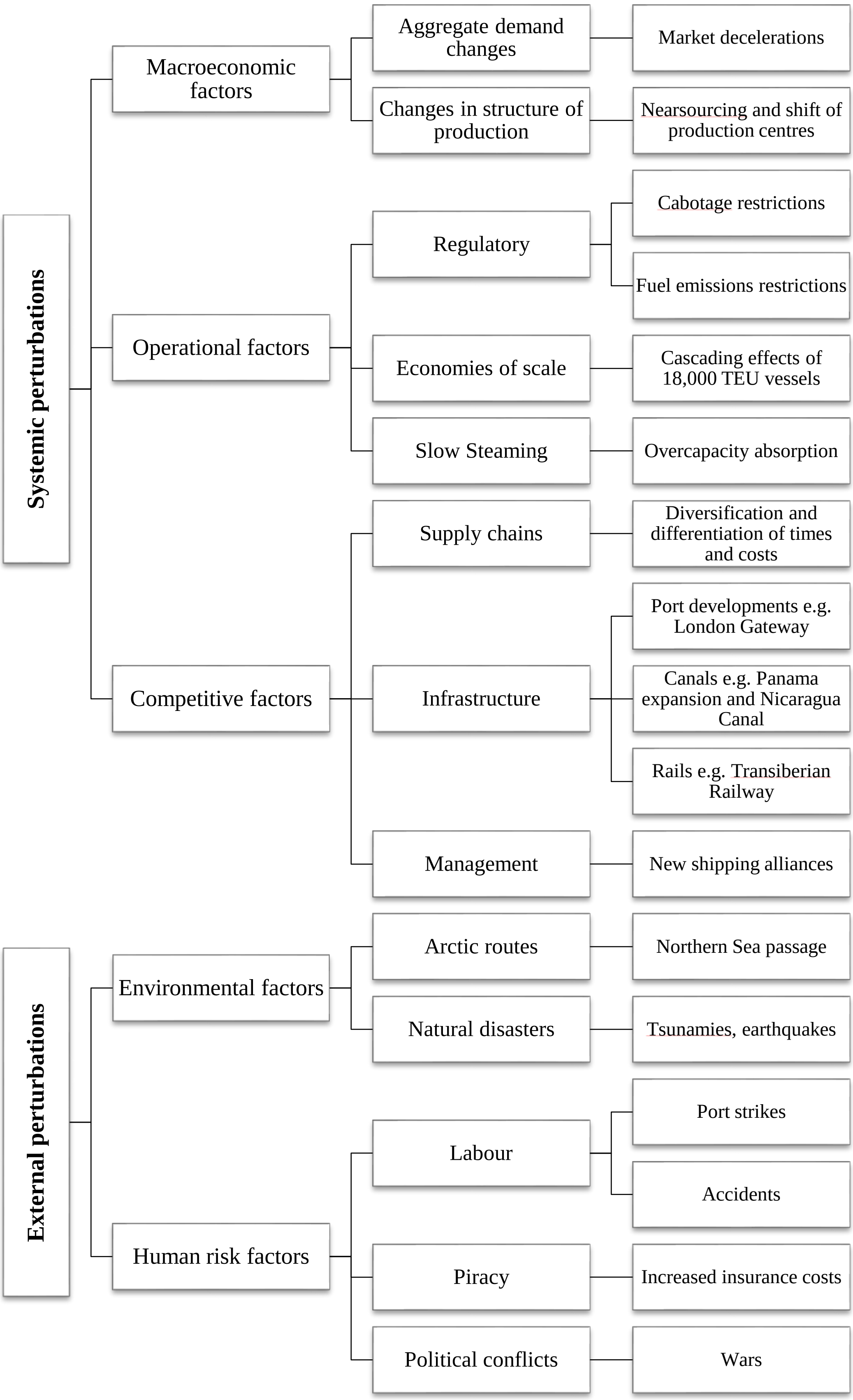

Figure 2.1: Classification scheme for liner shipping network perturbations.

Perturbation scenarios evaluated in this study focus on two cases of port disruptions caused by seismic hazards and political conflicts assuming that in both cases the pertubartions are inevitable. The scenarios were selected in collaboration with the Cambridge Centre for Risk Studies[1] due to their relevance to Southeast Asia as a major production of containerised goods and illustrate potential disruptive effects of environmental and human risk factors (external perturbations) on regional transshipment hubs and trade partner regions such as Europe. The port disruption cases stand to affect the examined port network in different ways including being the root cause for marine accidents, the characteristics of which are illustrated sections 3.1 and 3.2 for the earthquake and political conflict scenario respectively.

Port disruptions cases were also selected because they are a common cause of network perturbations and the necessary data for modelling their impact (e.g. recovery time and effects on terminal operability) is often publicly available in historical records. Root-causes for port disruptions such as an earthquake or a tsunami can also offset existing safety plans in port operations leading to greater number of accidents. Previous works have discussed the impact of port disruptions from risk sources other than natural disasters and political conflicts including labour strikes, equipment failure, human errors and terrorist attacks (Lam and Yip, 2012; Lewis et al., 2013; Mansouri et al., 2010). Table 2.1 includes a list of various examples of port disruptions that occurred between January 2012 and January 2014 (Qi, 2015) in order to illustrate the vulnerability of the liner shipping industry to these events. For comprehensive reviews of port-centric disruptions affecting maritime supply chains we refer to Lam (2012) and Loh and Van Thai (2014). Similarly, detailed reviews of sources of accidents and incidence in container shipping operations can be found in Fabiano et al. (2010).

[1] http://www.risk.jbs.cam.ac.uk/

Table 2.1: Examples of port disruptions in recent years. Source: Qi (2015).

Date	Event	Port	Consequences
Jan-2012	High winds	Felixstowe and South Hampton	Disruptions in services at the two largest container hubs in the UK.
Feb-2012	Shipping pilots' strike	Antwerp	MSC container services affected over 21 vessels.
Nov-2012	Hurricane	New York/New Jersey	Container terminal operations closed.
Mar-2013	40-day port labour strike	Hong Kong	Reduced dock capacity by 20%, vessels delayed by 2-4 days and some vessels skipping port calls at Hong Kong
Sep-2013	Failure of a quay crane's gearbox	Botany (DP World Terminal)	Sudden and unforeseen vessel slot cancelations.
Jan-2014	Snow storms	New York/New Jersey	Port closure multiple times during and after the storm resulting in 7-10 delays to deliveries.

2.2 Cost-based assignment model

As indicated in section 1, in order to assess the effects of port disruptions, the network model considered in this study consist of the following container network concepts based on earlier work carried by Bell et al. (2013).

- Routes: A scheduled sequence of port calls operated by a shipping line or alliance. Also known as liner service.
- Links: A physical connection of adjacent pair of port calls served by a route.
- Legs: A virtual transport task executed by a given route.
- Paths: A chain of transport tasks or 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.
- An exogenous origin-destination (O-D) matrix is used as demand input for the model. The rate at which containers are shipped does not vary with time.
- Containers are transported by ocean carriers operating fixed liner service routes between ports. Liner services have fixed port call frequency but the arrival at each port is uncoordinated

between ships of different services. Hence, container dwell time at each port is assumed to be the inverse of the sum of the service frequencies at each port.

- Route capacity constraints ensure that the flow of containers on each route does not exceed the capacity deployed by the ocean carrier.
- Combined inbound and outbound flow at each port cannot exceed port throughput capacity.

Our extension on the assignment model presented by Bell et al (2013) includes a penalty cost for each container not transported which allows feasible solutions for instances where the network transport capacity, either port throughput or liner service capacity, is not sufficient to satisfy the transport demand. This feature is desirable for a model capable of quantifying to what extent network perturbations hamper the network capability to re-route existing transport demand.

The penalty cost formulation requires an additional decision variable that dictates what cargo to route through the network from the given O-D matrix input. As such, penalty costs inputs for containers not transported must be higher than any routing costs alternatives to ensure that cargo flows are maximised when routing capacity is available.

Other costs considered in the model are: container handling cost, container rental cost and inventory cost. Ship operating costs are considered fixed and do not affect the routing decision. In this application, only flows of loaded containers are considered. The repositioning of empty containers is excluded. The model is then formulated as the following linear program (see Appendix for notation):

Objective

$$Min\,TRC = \left(\sum_{n\in N}\sum_{a\in A} CHC_n\, x^f_{a+}\right) + \left(\sum_{a\in A} x^f_{a+} c_a + w^f_{++}\right)(CR + DV) + \left(\sum_{r\in O}\sum_{s\in D}(D_{rs} - t^f_{rs})\right)(PC) \qquad (2.1)$$

Subject to

$$\sum_{a\in A_i^+} x^f_{as} - \sum_{a\in A_i^-} x^f_{as} = b^f_{is} \quad for\ all\ i \in I, s \in D \qquad (2.2)$$

$$x_{as}^{f} \leq w_{is}^{f} f_a \quad for\ all\ a \in A_i^-, i \neq s \in I, s \in D \tag{2.3}$$

$$k_i \geq \sum_{a \in A_i^-} x_{a+}^{f} + \sum_{a \in A_i^+} x_{a+}^{f} \quad for\ all\ i \in I \tag{2.4}$$

$$RC_n \geq \sum_{a \in A} x_{a+}^{f}\, \delta_{aln} \quad for\ all\ l \in L_n, n \in N \tag{2.5}$$

$$x_{as}^{f} \geq 0 \quad for\ all\ a \in A, s \in D \tag{2.6}$$

$$b_{is}^{f} \begin{cases} -t_{rs}^{f} & if\ i = r \in O \\ t_{+s}^{f} & if\ i = s \in D \\ 0 & otherwise \end{cases} \tag{2.7}$$

$$t_{rs}^{f} \leq TD_{rs} \quad for\ all\ r \in O, s \in D \tag{2.8}$$

Objective function (2.1) minimizes total routing cost *TRC* which includes container handling cost on each leg, container rental and inventory cost as a function of the transit time and dwell time at each port and a penalty cost for each container not transported from the original O-D flow demand. Constraint (2.2) enforces flow conservation. Constraint (2.3) sets the container port dwell time as the inverse of the combined service frequencies of the liner services calling at each port. Constraint (2.4) and (2.5) ensure that port throughput and route capacity are not exceeded. The non-negativity constraint is included in (2.6). In (2.7), origin and destination constraints are included where, for transhipment ports, the inbound flow should equal outbound flow. Constraint (2.8) sets the amount of cargo transported to be less or equal to the O-D flow demand.

Route capacity inputs for the model adapt a slot capacity analysis approach (Lam and Yap, 2011; Lam, 2011) but with a weekly time window instead of a annual basis. This approach is suitable for our analysis because it relies on publicly available slot capacity data of liner services which is accessible through most ocean carriers' websites. Alternative approaches based on port-to-port container throughput differentiated by liner services would require commercially sensible data which will be difficult or impossible to obtain (Lam, 2011).

We assume that ocean carriers determine the number of vessels to be deployed on each route *n* dividing the total voyage time (expressed in days) by the desired route frequency (e.g. weekly port calls). This assumption is derived from the common industry practice of having weekly port calls in competitive liner services. For example, if a complete port rotation takes 56 days, a shipping company will need to assign 8 vessels to achieve a weekly port call frequency. For liner services that operate on a weekly frequency, weekly route capacity RC_n in the model equals to the average containership nominal capacity deployed. Where this is not the case, route capacity across liner services with different port call frequencies can be standardised to the same time window multiplying the average containership nominal capacity by a desired capacity time window and the inverse of the service frequency as follows:

$$RC_n = \left(\frac{\sum_{p=1}^{V_n} NC_{pn}}{V_n}\right)\left(\frac{F}{f_n}\right) \tag{2.9}$$

Where

NC_{pn}	Nominal TEU capacity of vessel p deployed in route n
V_n	Total number of vessels deployed in route n
p	Index of vessels ranging from 1 to V_n
F	Standardised model input frequency in which the capacity will be expressed
f_n	Port call frequency of route n

It has to be noted that F is expressed as the actual number of days (or time window) for the service frequency in which the route capacities will be standardised. For example, if the route capacities in the model are standardised to a weekly time window then $F = \left(\frac{7\ days}{1\ week}\right)$. The service frequency f_n can be given in the input data or replaced by $\left(\frac{T_n}{V_n}\right)$ where T_n represents the total voyage time for the complete rotation.

3 Problem instance

The model proposed in section 2.2 is applied to representative combined network of five liner services shown in Figure 3.2 and Figure 3.1. The network was constructed based on existing liner services sourced from the Port Operations Research and Technology Centre (PORTeC) Delos Database[2] to assess the vulnerability of ports in Southeast Asia, namely Singapore, Port Kelang (Malaysia), Jakarta/Tanjung Priok and Belawan (Indonesia). Singapore, Port Klang and Belawan operate in close proximity to the Malacca Straights, which is regarded as one of most crucial maritime routes in the Southeast Asia-Europe trade lane. The Southeast Asia region and its trade to Europe was selected because of its high containerised trade flow and the region's susceptibility to impacts of earthquake and conflict scenarios presented in sections 3.1 and 3.2.

Liner service calls beyond this region were represented using two port group centroids, namely Southeast Asia and Europe. The Southeast Asian centroid collectively represents ports located in East Indonesia, East Indochinese Peninsula, Vietnam and Philippines. Given its location, Tanjung Perak (second largest port of Indonesia in terms of TEU throughput) 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 Le Havre, Felixstowe, Southampton, Antwerp, 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 transhipment ports.

[2] http://www3.imperial.ac.uk/portoperations/research/research%20platforms/delos

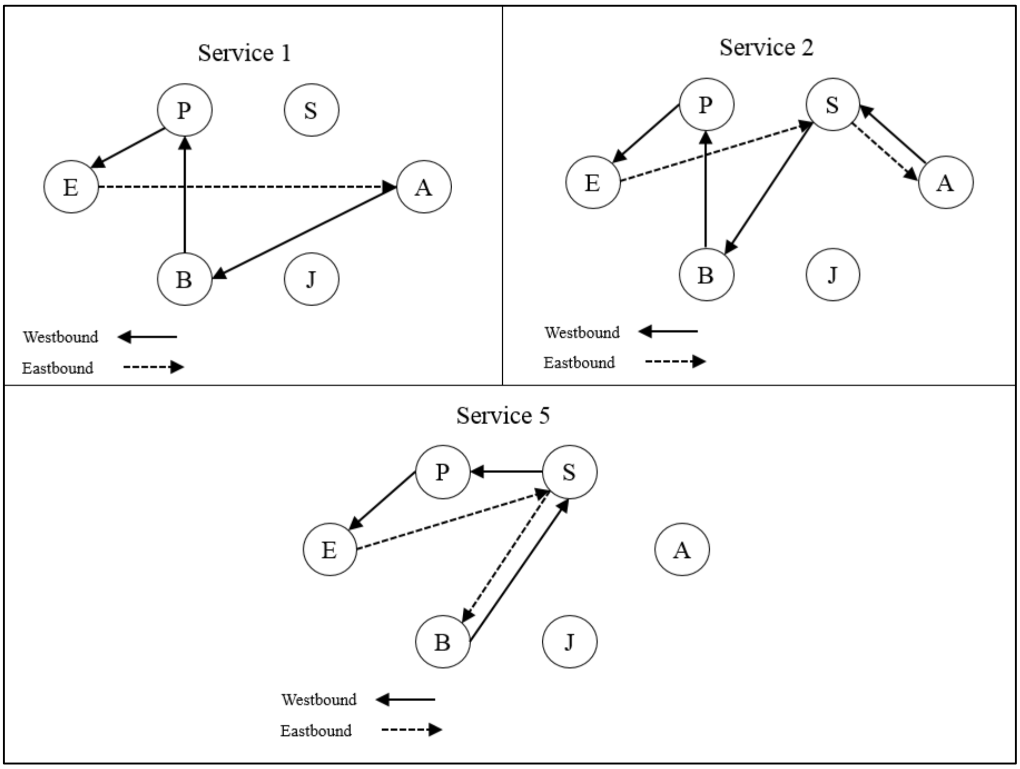

Figure 3.1: Asia-to-Europe liner services. Nodes: Southeast Asia centroid (A), Singapore (S), Port Klang (P), Jakarta (J), Belawan (B), Europe centroid (E).

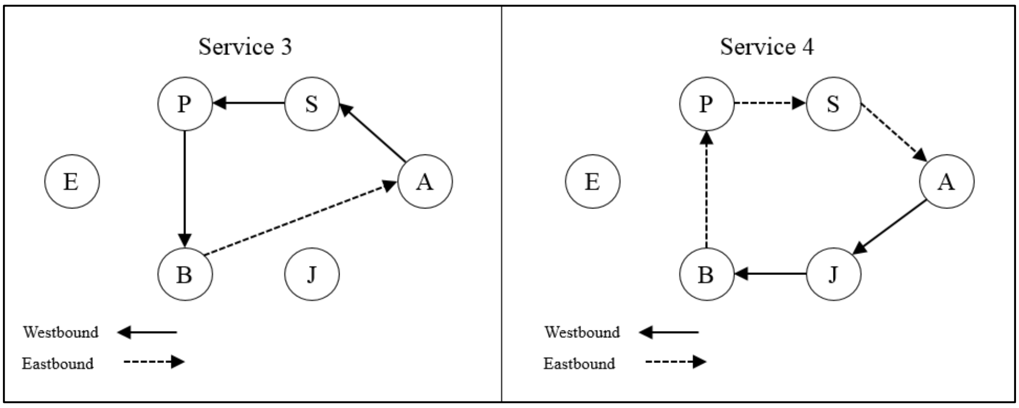

Figure 3.2: Intra-Asian liner services. Nodes: Southeast Asia centroid (A), Singapore (S), Port Klang (P), Jakarta (J), Belawan (B), Europe centroid (E).

As shown in Figure 3.1 and Figure 3.2, services 1, 2 and 5 correspond to weekly Southeast Asia-to-Europe liner services. Vessels in these services fall within the post-panamax range, with an average cargo carrying capacity of 8,000 TEU. Services 3 and 4 represent intra-regional services, offered weekly with an average ship size of 4,000 TEU. Vessels across all services in the model are assumed to operate at 20 knots. Since all liner services operate on a weekly basis, the maximum weekly route capacity on each leg equals to the maximum containership nominal capacity deployed on each liner service.

With the exception of Belawan, ports representing the core of the case study network are all positioned among the top 100 in the world in terms of yearly TEU throughput (Containerisation International, 2012). Port capacities used in this case study were estimated based on this port throughput data and the following formulation:

$$k_i = \frac{n_i}{N_i} K_i \tag{3.1}$$

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

Equation (3.1) is applied to reflect the weekly capacity allocated to the sub-network under investigation (data for each port is reported in Table 3.1). No throughput capacity constraints are applied to the Southeast Asia and Europe nodes given their status as port group centroids.

Table 3.1: Container handling capacity estimation at network ports.

Port	K_i **[TEU]**	N_i	n_i	k_i **[TEU]**
Singapore	513,000	288	7	14,500
Port Kelang	163,000	124	5	7,500
Jakarta	120,000	27	2	9,000
Belawan	15,500	8	4	7,500

For all scenarios presented in sections 3.1 and 3.2, 18,000 TEU are shipped from the Southeast Asia centroid to the European centroid. External factors that may influence supply and demand were not considered, therefore leading to the assumption that O-D demand volumes would not be affected by the disruptions. Container handling, rental and cargo depreciation costs used in the model are in accordance to the pricing structures used in previous studies by Bell et al. (2013, 2011). An average cargo value of USD 40,000 for loaded containers is used in this numerical example. Table 3.2 presents a summary of these values.

Table 3.2: Container handling, rental and depreciation costs.

Container handling costs	
Loading at origin and unloading at destination	400 USD/TEU
Loading at origin and unloading at transhipment port	350 USD/TEU
Loading at transhipment port and unloading at destination	350 USD/TEU
Loading and unloading at transhipment port	300 USD/TEU
Rental and depreciation costs	
Average value of cargo shipped per container	40,000 USD/TEU
Rental cost for full/empty container	4.5 USD/TEU/day
Rate of depreciation for a full container	20 USD/TEU/day

Penalty costs for containers not transported depend on factors such as type of containers (e.g. refrigerated or dry), the importance of the shipper to the ocean carrier and less quantifiable aspects such as loss of goodwill from the customer (Brouer et al., 2013). Due to the sensitivity of this information, previous studies that utilise these cost components are often not able to publish it. In absence of such data, we adopt Kjeldsen et al. (2011) approach to assign USD 1,000,000 as a penalty cost for each TEU not transported. It has to be noted that this high penalty cost is only included in the model to maximise the flow of containers routed when disruptions reduce network routing capacity below transport demand. As such, it cannot be used to compare re-routing costs when the penalty cost is incurred. For the latter cases, we replace the penalty cost with the assumption that ocean carriers assign sufficient transport capacity to the next available weekly services to transport any pending cargo but incurring a delay of 7 days. We then apply an opportunity cost of 4% per year (Notteboom, 2006) along with the cargo depreciation cost and container rental costs defined in Table 3.2 to estimate the delay costs.

3.1 Earthquake scenario

For the 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 United States Geological Survey Worldwide Seismic Design Maps (USGS, 2014a). The vulnerability of ports is measured using a Quality of Port Infrastructure rating, which measures business executives' perceptions of their country's port facilities. 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 (Power et al., 2013).

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 (Chang, 1996). USGS data indicate that the vulnerability of ports rating in Japan is 5.2. 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 (USGS, 2014a, 2014b). Using the conversion equations of Worden et al. (2012), this gives a Modified Mercalli Intensity[3] (MMI) scale of 7.7. Jakarta could therefore experience ground-shaking of a similar level to

[3] The Modified Mercalli Intensity (MMI) scale depicts shaking severity. Source: http://quake.abag.ca.gov/shaking/mmi/

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. Figure 3.4 provide a geographical representation of Southeast Asian ports and regional PGA values.

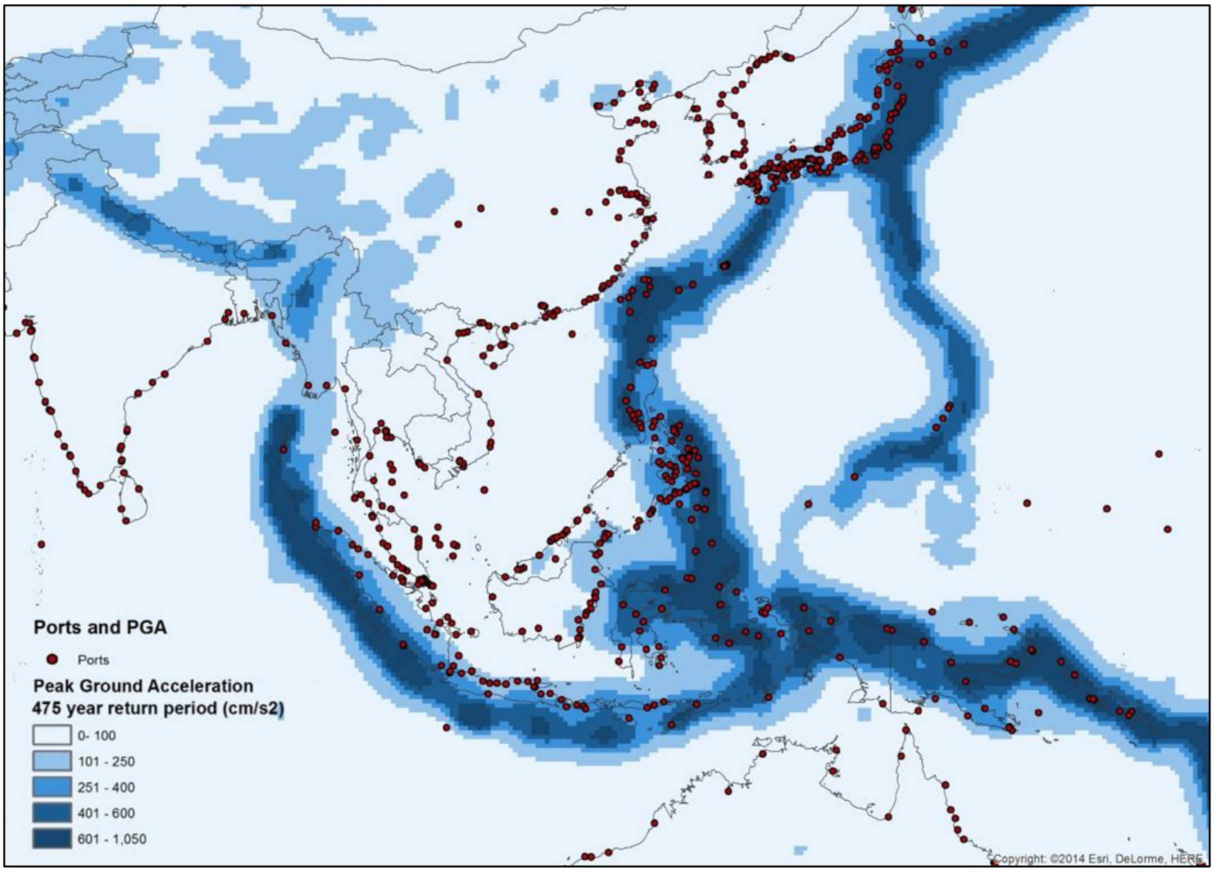

Figure 3.3: Earthquake hazard (PGA) - Southeast Asia.
Source: Cambridge Centre for Risk Studies

The impact of accidents resulting in loss of human life, injuries, damages to property and to the environment in the aftermath of an earthquake vary on a case-by-case basis depending on multiple factors such as magnitude of the earthquake, port infrastructure, stacking plan of containers, level of automation, etc. The unforeseen nature of any earthquake also increases the risk of accidents. For example terminal gantry crane or reach stacker operators maybe injured or killed if stacked containers fall near or on them due to the unexpected ground shacking. Similarly, potential of tsunami waves generated by the earthquake can capsize moored vessels or break their mooring during container/load discharge operations.

Caselli et al. (2014) list and classify observed risk factors that impacted port operations and surrounding areas in Iquique, Chile after the April 1, 2014 earthquake. These include structural damage to port infrastrucure such as the breakwater wall (building damage), blocking of access routes due to landslides (transportation facilities), shortage of water and electricity (lifeline facilities), loss of one of three available tugboats (transportation facilities), psychological impact due to large amounts of aftershocks (life difficulties), human suffering due to death or injured people (human suffering), damage to fishing boats and facilities (other facilities). Similarly, Kubo et al. (2005) review of impacts of tsunamis on moored ships and ports in Japan and Korea listing potential sources of accident and damage hazards. The latter include landing of the drifting material produced by the tsunami, fire or pollution caused by fuel in vehicles and vessels crashed, ship collisions during habour escape attempts, sand drift, waterway burying, and stranding and ceasing of logistics functions.

For modelling purposes, a suggested level of disruption is similar to that experienced in 1995 at the Port of Kobe. The potential sources accidents and damage mentioned above are considered in the aftermath of the Jakarta and Belawan earthquake scenarios and are captured in the following estimated recovery times: the port of Jakarta or the port of Belawan are estimated to be closed for container cargo for 2 months (equivalent to the 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).

3.2 War scenario

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.

The impact of accidents resulting in loss of human life, injuries, damages to property in a war scenario can be evaluated from historical evidence of merchant shipping in areas of political conflict. For example, Navias and Hooton (1996) present a detailed account of the impact of the Iran-Iraq Crisis of 1980-88 on merchant shipping in the Persian Gulf. The toll of this war were hundreds of merchant vessels attacked, more than 400 mariners killed, and economic losses worth millions of USD by owners, charterers and insurance companies (Navias and Hooton, 1996). Even though the main targets were oil tankers, about 40% of the vessels attacked were containerships, bulk carriers, tugs and others (Uhlig, 1997). An important aspect of the Iran-Iraq Crisis attacks were their effectiveness at disrupting exports and supply lines of the involved countries proving the vulnerability of neutral-flag merchant vessels operating in war or blockade zones. However, an often overlooked fact is the possibility of conflict escalation when such attacks on neutral-flag vessels provide context for international intervention of naval forces from countries not initially involved. For example, Uhlig (1997) describe how in the Iran-Iraq Crisis, the U.S. used its own registry flag to protect Kuwait's merchant fleet with U.S. naval forces.

For our war scenario, an initial naval blockade surrounding the Senkaku/Diaoyu Islands disrupts shipping routes through the East China Sea (Figure 3.4 – B1). The potential risks for loss of life, accidents, and economic damage and escalation are assumed to be similar to the Iraq-Iran Crisis. As the conflict escalates, the blockade zone increases to an area including Taiwan and the southern part of Kyushu and Shikoku islands (Figure 3.4 – B2). As other nations become involved in a naval standoff, the blockade zone expands further, encompassing access to China, Hong Kong, and Vietnam through the South China Sea (Figure 3.4 – B3). Additional threats to merchant vessels include the use naval mines to protect any exclusion or blockade zone, which present a risk of vessels straying into non designated or known waters. Environmental risks include hypothetical oil spills from damaged vessels. These risks are represented in our model as disrupted connectivity in the form of increased sailing times, reduced transport capacity and increased costs to and from the Asia centroid.

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 Southeast 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 due to the blockades. In spite of not being located in the conflict zone, container throughput at the port of Singapore and other regional transhipment hubs may be severely impacted also due to containers accumulated in the yards as cargo traffic to/from the conflict zone is blocked.

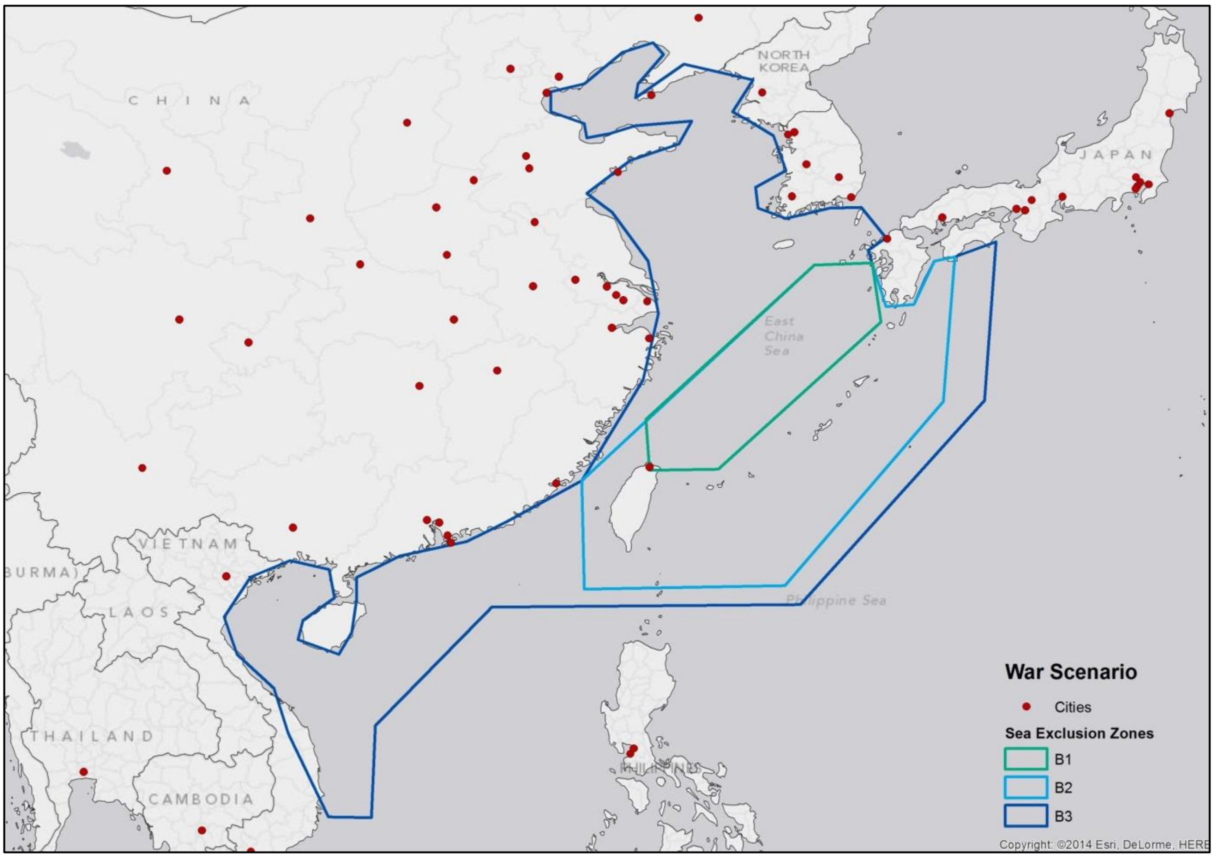

Figure 3.4: War scenario blockade regions.
Source: Cambridge Centre for Risk Studies

Table 3.3 summarizes four alternative outcomes of the earthquake and war scenarios are developed. As shown in the table, the consequences of these disruptive events 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. Transit times to and from disrupted ports are assumed to be increased by 300% immediately after the events and by 100% 2 months after. Resulting changes to route capacity in the scenarios evaluated are estimated using equation (2.9). Except for the war scenario, container handling capacity is reduced to 0% immediately after the events and to 40% 3 months after.

Table 3.3: Summary of scenarios and related parameters

ID	Scenario	Event time-frame	Capacity changes
0	Base scenario	None	all ports and routes working at standard operational level
1	Earthquake in Jakarta	a) Immediately after the event	0% port capacity in J +300% sailing time to/from J -16% capacity in Service 2 -46% capacity in Service 4
		b) 3 months after the event	40% port capacity in J +100% sailing time to/from J -3% capacity in Service 2 -12.5% capacity in Service 4
2	Earthquake in Belawan	a) Immediately after the event	0% port capacity in B +300% sailing time to/from B -17% capacity in Service 1 -70% capacity in Service 3 -39% capacity in Service 4 -18% capacity in Service 5
		b) 3 months after the event	40% port capacity +100% sailing time to/from B -5% capacity in Service 1 -46% capacity in Service 3 -7% capacity in Service 4 -7% capacity in Service 5
3	Earthquake involving Jakarta and Belawan simultaneously	a) Immediately after the event	0% port capacity in J and B +300% sailing time to/from J and B -17% capacity in Service 1 -16% capacity in Service 2 -70% capacity in Service 3 -56% capacity in Service 4 -18% capacity in Service 5
		b) 2 months after the event	40% port capacity in J and B +100% sailing time to/from J,B -5% capacity in Service 1 -3% capacity in Service 2 -46% capacity in Service 3 -22% capacity in Service 4 -7% capacity in Service 5
4	War affecting flows in Southeast Asia	a) Severe consequences	+300% sailing time to/from A -17% capacity in Service 1

ID	Scenario	Event time-frame	Capacity changes
			-16% capacity in Service 2
			-53% capacity in Service 3
			-30% capacity in Service 4
		b) Mild consequences	+100% sailing time to/from A
			-17% capacity in Service 1
			-16% capacity in Service 2
			-53% capacity in Service 3
			-30% capacity in Service 4

3.3 Application of the cost-based container assignment model

The cost-based container assignment model defined in section 2.2 was implemented IBM's OPL language and solved using the CPLEX optimisation engine to evaluate how each scenario stand to affect (or not) the routing of container in the constructed network. Resulting container flows and costs are reported in Table 3.4. In the base scenario, it can be seen that, under normal transport network conditions, the transport demand of 18,000 TEU from Southeast Asia to Europe can be normally satisfied by two services with direct connection to Europe (Services 1 and 2) and transhipment services connecting through in Port Klang (Service 3 connecting to Service 5). The total routing cost of this base scenario is USD 21.7 million.

A hypothetical earthquake in Jakarta (Scenario 1a) disrupts the network by increasing transit times in Services 2 and 4 which reduces route capacity as shipping companies do not have time to deploy additional vessels in order to compensate for the voyage time elongation immediately after the event. The increase of transhipment through Port Klang surpases its available port throughput capacity and the excess container flows are then re-routed through Singapore. The additional cost to route 18,000 TEU from Southeast Asia to Europe is USD 2.7 million (+12.5%) over the base scenario. Two months after the disruption (Scenario 1b), port capacity is improved to 40% and liner service capacity in services calling in Jakarta is significantly restored. Additional disruptions routing costs at this stage of the recovery are USD 1.0 million (+4.7%) over the base scenario. The improvement is the result of reduced transshipment flows through Port Klang.

Similarly, an earthquake in Belawan (Scenario 2a) resulting in complete disruption of its container terminal affects route capacity in services 1, 3, 4 and 5. The route capacity reductions increase the use of transshipment alternatives through Port Klang and Singapore which elevate routing costs by USD 3.0 million (+13.9%). Two months after the disruption (Scenario 2b), with port capacity restored to 40% and affected route capacity significantly restored, increased routing costs are reduced to USD 1.0 million (+4.7%) above the base scenario by replacing transshipment flows through Singapore with more direct shipments using services 1 and 2.

If Jakarta and Belawan are disrupted simultaneously by a major earthquake (Scenario 3a), all liner services in the network are impacted resulting in a reduction of outbound capacity at the Southeast Asia centroid to 16,319 TEU. This large-scale impact makes unfeasible to meet the weekly transport demand of 18,000 TEU through the network. The remaining 1,681 TEU incur a 7 day delay as described in section 3 resulting in a additional delay cost of USD 340,066 for the containers not routed in the first solution instance. The total routing cost increase is USD 6.3 million (+29.0%) over the base scenario.

Two months after the disruption (Scenario 3b), both ports are restored to 40% and liner service outbound capacity at the Asia centroid is restored to more than 20,000 TEU and the total outbound demand can be shipped in one solution instance. These improvements reduce additional routing costs to USD 2.1 million (+9.8%).

In scenario 4a, a blockade resulting from a potential political conflict increases sailing time to and from the Southeast Asia centroid by 300%. Such increase reduces available outbound weekly capacity and incresases more expensive transhipment alternatives through Singapore and Port Klang. The resulting cost increase of the blockade is USD 3.1 million (+14.6%). As the regional blockade is reduced (Scenario 4b), transit time to and from Southeast Asia is increases by 100% and transshipment is required only through Port Klang. Resulting cost increase is then reduced to USD 1.3 Million (+6.0%).

As summarized in Table 3.4, variations in total costs from the base scenario range from +4.7% in scenario 1b to +29.0% in scenario 3a. Across all liner services, service 3 is the most affected by the disruptions evaluated due to its greater percentage gains in transit times over regional voyages suggesting that intra-regional connectivity would be more susceptible to disruptions.

Table 3.4: Cost-based model scenario results

Scenario 0 – Total Cost: $ 21,725,800

Origin	Destination	Flow [TEUs]	Service n.
Asia	Europe	8000	1
Asia	Europe	8000	2
Asia	Port Klang	2000	3
Port Klang	Europe	2000	5

Scenario 1a - Total Cost: $ 24,439,538 (+12.5%)				Scenario 1b - Total Cost: $ 22,738,616 (+4.7%)			
Asia	Europe	8000	1	Asia	Europe	8000	1
Asia	Europe	6000	2	Asia	Europe	7754	2
Port Klang	Europe	625	2	Asia	Singapore	2246	3
Asia	Singapore	250	3	Singapore	Europe	2246	5
Asia	Port Klang	3750	3				
Singapore	Europe	250	5				
Port Klang	Europe	3125	5				
Scenario 2a – Total Cost: $ 24,738,643 (+13.9%)				**Scenario 2b – Total Cost: $ 22,768,763 (+4.8%)**			
Asia	Singapore	3220	1	Asia	Europe	7636	1
Asia	Europe	3412	1	Asia	Europe	8000	2
Asia	Europe	8000	2	Asia	Port Klang	2154	3
Asia	Port Klang	1217	3	Asia	Port Klang	210	4
Asia	Port Klang	2151	4	Port Klang	Europe	2364	5
Singapore	Europe	3220	5				
Port Klang	Europe	3368	5				
Scenario 3a – Total Cost: $ 28,034,207 (+29.0%)				**Scenario 3b – Total Cost: $ 23,857,285 (+9.8%)**			
Asia	Singapore	4085	1	Asia	Europe	7636	1
Asia	Europe	3011	1	Asia	Europe	7754	2
Port Klang	Europe	87	1	Asia	Port Klang	2154	3
Asia	Europe	6720	2	Asia	Port Klang	456	4
Port Klang	Europe	87	2	Port Klang	Europe	2610	5
Asia	Port Klang	2967	3				
Asia	Singapore	608	3				
Asia	Port Klang	1750	4				
Port Klang	Europe	18000	5				
Singapore	Europe	9386	5				
Scenario 4a – Total Cost: $ 24,894,877 (+14.6%)				**Scenario 4b – Total Cost: $ 23,028,490 (+6.0%)**			
Asia	Europe	6632	1	Asia	Europe	7412	1
Asia	Europe	6720	2	Asia	Europe	7754	2
Asia	Singapore	1900	3	Asia	Port Klang	2154	3
Asia	Port Klang	2748	4	Asia	Port Klang	680	4
Singapore	Europe	1900	5	Port Klang	Europe	2834	5
Port Klang	Europe	2748	5				

4 Conclusions and future work

The main contribution of this paper is the application of a cost-based container assignment methodology for assessing the vulnerability of a multi-port system against natural and man-made disruptions. Changes to route and port capacity parameters allow to capture potential effects to the network on the aftermath of port disruptions while a penalty cost extension to previous model formulations allows feasible solutions even when capacity is diminished below transport demands. The virtual network approach used in the model allows to skip disrupted ports within liner services. The latter is a common measure taken by ocean carriers to mitigate the financial impacts on their established services. The feasibility of solutions for instances of network routing capacities below transport demands and the ability to skip disrupted ports are desired capabilities of a suitable methodology for the analysis of container routing in disruptive scenarios.

Calibration and numerical applications of the model were carried translating historical data on previous events and hazard forecasts into operational functionality disruptions and recovery intervals for two cases of port disruptions: seismic hazard and political conflicts. For these disruption cases, the Southeast Asia to Europe corridor was investigated as case study trade lane due to its global strategic importance in terms of cargo volume and potential consequences from a chain effect of failures. Results suggested higher susceptibility of the intra-regional connectivity and demonstrated the applicability of the cost-based assignment model to improve the understanding of cargo re-routing and operational cost impacts in the scenarios evaluated. Changes in parameters such as sources of disruption, structure of network services, O-D flow pairs, functional impacts, recovery intervals and operational costs extend the applicability of this model to a wider range of port disruption cases discussed in the literature such as labour strikes, operational accidents, terrorist attacks, and port congestions providing a quantitative framework for their analysis.

Due to its exemplifying purpose, the network instance used in the scenarios presented make large use of secondary data, leaving room for further refinements in selection of data sources and calibration inputs. Such future data improvements are supported by the linear program approach used in the proposed formulation of this study which allows extensions of the model to wider more-realistic networks while still allowing the problem to be efficiently solvable with commercially available solvers. The cost minimisation formulation in the model may also be replaced in future applications by a profit maximisation or a cargo prioritisation approach to allow for cases where certain cargo must be routed first in a network incapable of transporting all O-D flows. Examples of such cases include humanitarian relief goods or high value cargoes prioritised over less valuable shipments.

A fully developed application of the container assignment model (e.g. including empty container repositioning and liner network design capabilities) could provide shipping lines and logistics providers with a tool for the evaluation of hazardous events, allowing them to estimate the operational and financial consequences of cargo flow redistributions. Accident analysis at container terminals that benefit from sudden surges in cargo from disrupted ports could also help improve the understanding and modelling of connected risks of port disruptions. Additional applications may help policy-makers in evaluating the robustness of networks and the associated strategic importance of container terminals, supporting decision making processes and orientating investments on port infrastructures.

Successful applications in a resilience context could then be extended to evaluate the effects of other relevant large-scale perturbations to the liner shipping industry such as new infrastructure developments or environmental-driven changes. For the latter purpose, this study has also proposed a classification scheme of maritime network perturbations in order to identify events beyond port disruptions that could alter relevant parameters in liner shipping operations where applications of the cost-based assignment model or similar methodologies can be used as decision support tools.

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Appendix: Model notation

Sets		**Subsets**		**Indices**	
A	Legs	A_i^+	Legs entering port i	a	for legs
O	Origin ports	A_i^-	Legs entering port i	i	for ports
D	Destination ports	A_n	Legs on route n	l	for links
I	All ports	A_n^t	Legs on route n	n	for routes
N	All routes	L_n	Links on route n	r	for origin ports
L	All links			s	for destination ports
T	Leg types			t	for leg types

Parameters

c_a	Sailing time on leg a, including loading and loading times at the ends
CHC_n	Container handling cost for route n
CR	Rental cost per unit time per container
TDF_{rs}	Total demand of full containers to be transported from origin *r* to destination *s*
DV	Depreciation per unit time per full container (inventory cost)
δ_{aln}	1 if leg a uses link l on route n, and 0 otherwise
f_a	Frequency of sailing on leg a
k_i	Maximum throughput capacity at port i
PC	Penalty cost for full containers not transported
RC_n	Capacity of route n

Decision variables

t_{rs}^f	Flow of full containers from origin *r* to destination *s*
x_{as}^f	Flow of full containers on leg a en route to destination s
w_{is}^f	Expected dwell time at port i for all full containers en route to destination s

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 (Bell et al., 2013): $x_{a+}^{f} = \sum_{s\in D} x_{as}^{f}$, $w_{++}^{f} = \sum_{i\in I} \sum_{s\in D} w_{is}^{f}$, $t_{+s}^{f} = \sum_{r\in O} t_{rs}^{f}$.