Transportation Research Part A 157 (2022) 1–23

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Enhancing resilience through port coalitions in maritime freight networks

Wenjie Li [a], Ali Asadabadi [b], Elise Miller-Hooks [a,*]

[a] Sid & Reva Department of Civil, Environmental and Infrastructure Engineering, George Mason University, Fairfax, VA 22030, USA
[b] Operation Research and Business Transformation, FedEx Express, Memphis, TN 38125, USA

ARTICLE INFO

Keywords:
Resilience
Maritime systems
EPEC
Shipping
Global supply chains
Port networks

ABSTRACT

Reliable port services are key to maritime freight transport system performance. These systems are vulnerable to disasters of anthropogenic or natural cause, which can significantly impact port capacity, handling times and overall system performance. To improve resilience of individual ports, strategies involving capacity sharing and protective cross-port investments through coalition formation are proposed. This collaborative port protection and investment approach to improve individual and system-level port resilience is formulated as an Equilibrium Problem with Equilibrium Constraints. That is, the program is bi-level with multiple players in the upper level and a common liner shipping problem in the lower level. Its solution is obtained at a Nash equilibrium wherein no port stakeholder can achieve better performance by unilaterally changing its investment plan. A Stackelberg equilibrium between upper and lower levels infers that best investment decisions are made given competition between ports and the market's response to improvements. The benefits of regional coalitions in this co-opetitive (competitive and collaborative) environment in terms of port and system resilience, port- and system-level demand fulfilment rates and return on investment are investigated from multiple perspectives, including the perspectives of shippers, port owners and the larger shipping network. With insights gained through study of the proposed coalition policies, this work aims to facilitate port authorities in making decisions on port capacity expansion, infrastructure investment and forming strategic partnerships. Shipping companies may also take into consideration the ability of a port to provide service under disruption events when choosing which ports to include in their service loops.

1. Introduction

Maritime networks and their components are critical to efficient global intermodal goods movements. Yet ports, sea links and other facilities in these systems are vulnerable to physical damage and disruption from diverse causes, including anthropogenic (e.g. malicious attack, cyber security breach, power-loss, construction/maintenance, political conflict, worker strikes), natural (e.g. hurricanes/cyclones, tsunamis, earthquake) or accidental (e.g. hazardous material incident, crash with berth, fuel spill) causes. Such events can impact port capacity, handling times and overall system performance. Constancy in these networks can significantly influence trade within worldwide markets and the wider global economy. Thus, the resilience of these critical transportation components to disruption is crucial to economies across the globe.

* Corresponding author.
E-mail address: miller@gmu.edu (E. Miller-Hooks).

https://doi.org/10.1016/j.tra.2022.01.015
Received 15 August 2020; Received in revised form 14 January 2022; Accepted 17 January 2022
Available online 24 January 2022
0965-8564/

Preventative and mitigative investments can be made to harden both physical and cyber infrastructure or to prepare for post-disaster recovery at individual ports. However, even if an individual port can invest to eliminate all risks, uninterrupted operations are not guaranteed, because the port is part of a larger maritime network. The performance of any port depends on the performance of other ports in the network, and a single poorly functioning port can severely degrade the performance of the entire system. To improve resilience of individual ports, strategies involving capacity sharing and protective cross-port investments through coalition formation are proposed. This collaborative port protection and investment problem is formulated as a bi-level program with multiple players in the upper level and a common liner shipping problem in the lower level, forming an Equilibrium Problem with Equilibrium Constraints (EPEC). EPECs are particularly well suited to problems in which multiple, competing stakeholders serve as leaders whose decisions jointly impact the reaction of a common follower (Gabriel et al., 2012). Its solution is obtained at a Nash equilibrium wherein no port stakeholder can achieve better performance by unilaterally changing its investment plan. A Stackelberg equilibrium between upper and lower levels infers that best investment decisions are made given competition between ports and the market's response to improvements.

Applying this EPEC conceptualization, this paper investigates the potential of coalition formation to reduce the impact of a disruptive event on goods movements and increase port and system-wide resilience in serving the global market. The benefits of regional coalitions in this co-opetitive (competitive and collaborative) environment in terms of port- and system-level resilience, demand fulfilment rates (DFR) and return on investment (ROI) are investigated from multiple perspectives, including the perspectives of shippers, port owners and the larger shipping network. This co-opetitive approach seeks the best payoff for the individual ports whether or not they are part of a coalition. Thus, a non-cooperative approach is employed. A cooperative approach could apply where maximum collective gains are sought for a particular coalition or one that includes all ports.

With insights gained through study of the proposed coalition policies, this work aims to facilitate port authorities in making decisions on port capacity expansion, infrastructure investment and forming strategic partnerships. Shipping companies may also take into consideration the ability of a port to provide service under disruption events when choosing which ports to include in their service loops.

This paper contributes to the literature through a modeling and solution framework based on concepts of EPECs for studying the potential gains in resilience from port coalitions, where ports can invest in protecting other ports within the coalition and coalition members can share capacity during disaster events. This framework makes it possible to assess proposed port- and network-based performance indicators of resilience, demand fulfillment and return on investment.

The next section, Section 2, reviews the relevant literature and asserts the paper's contributions. This is followed by problem formulation details and a diagonalization approach for its solution in Section 3. Section 4 provides details of numerical experiment with results and analysis, where the potential benefits of port coalitions are explored. Conclusions are provided in Section 5.

2. Literature review

The effects of disruption on port operations has been the focus of several studies over the past decade. Some works focus on the resilience of individual ports. Paul and Maloni (2010) simulated port shutdowns and other disruption scenarios with the aim of optimally selecting shipping routes given dynamically updated port conditions. The effects of human-made and natural disruptions on port capacity, and thereby port operations, for both outbound and inbound services was modeled by Omer et al. (2012). Nair et al. (2010), Omer et al. (2012), Shafieezadeh and Ivey Burden (2014), and Yang et al. (2015) proposed quantitative frameworks for evaluating port resilience as a function of capacity and satisfied demand under one or more scenarios. These works all consider the potential of protective and/or recovery strategies for enhancing a single seaport's resilience.

Other works have considered disruption impacts on larger port networks. Ordinary uncertainties and uncertainties arising from possible future disruption events at ports were simultaneously considered in several earlier works that develop real-time schedules for liner shipping services at ports (Wang and Meng, 2012a, 2012b; Li et al., 2016). Both may impact port handling times and cause delays. They also noted that variability at one port can even impact optimal schedules of other ports. Achurra-Gonzalez et al. (2019) modelled impacts of single disruptions in the maritime network due to earthquake, flooding and political conflict, and optimized container cargo routing under these circumstances to minimize total system-wide cost. Their paper quantified port and route capacity reduction, as well as handling time increases, due to each considered disaster event. Resilience of the larger port network is studied using graph theoretic concepts in (Angeloudis et al., 2013) and by comparing throughput before and after disruption (Achurra-Gonzalez et al., 2019; Peng et al., 2016; Omer et al., 2012).

In these prior works on port networks, it is assumed that protective investment decisions can be made centrally as if all ports are willing to fully cooperate for the good of the whole. Competition for business between ports is ignored in such centralized approaches. Moreover, the idea that ports from different owners or even countries will pool and share large capital investment funds is unrealistic. Agarwal and Ergun (2008) point out the lack of realism associated with centralized decision-making in the context of freight shipping by truck. Asadabadi and Miller-Hooks (2018) proposed a co-opetitive (competition plus collaboration) optimization scheme to replace centralized decision-making in protecting port networks through cross-port investment. In their framework, port stakeholders acting as players in a game simultaneously collaborate through cross-port investment to improve throughput in a disaster event while competing for business. Their work builds on a concept of a co-opetition that was introduced by Nalebuff et al. (1996) in the context of business management. They model several cross-port investment strategies through various games: unrestricted, wherein all ports can invest in any port; restricted, wherein ports only self-invest; and semi-restricted, wherein a subset of ports can invest in any port, while others will only self-invest. They extended their concept and methodology to compute the resilience or reliability of a port network under multiple potential possible hazard events in (Asadabadi and Miller-Hooks, 2020).

Few studies have considered collaboration in the context of maritime networks. Python and Wakeman (2016) noted the importance of information sharing in this competitive environment during disruptions for both the individual port and the larger supply chain. Although they did not consider coalitions, Asgari et al. (2013) discussed perfect competition and cooperation among hub ports and shipping companies. In their work, shipping companies act as leaders and two hub ports act as followers. The optimal solution is obtained at a Stackelberg equilibrium between the shipping companies and the two hub ports who play a Nash game. Guo et al. (2018) considered port cooperation or integration in a region with many nearby ports, and provide a mathematical model to set the maximum size of a port coalition with an aim of maximizing social welfare. Hoshino (2010) proposed a series of collaboration measures, including joint financing and facility investment, integration of information systems, joint promotion and sales activities, and transfer of empty containers for maintaining a balanced inventory at facilities in a coalition formed among neighboring ports. Finally, an optimal collaboration strategy is sought in the context of liner shipping through capacity exchange among service providers, such as liner shipping companies, in works by Panayides and Wiedmer (2011) and Zheng et al. (2015).

Agarwal and Ergun (2008) noted that individual players exploit synergies between multiple players by forming alliances. Liner shipping is performed over fixed-transit, ocean-based routes that generally follow fixed arrival schedules through a network of ports. Since the economic downturn of 2008, ocean carriers have joined just three or four shipping alliances. These alliances can improve efficiencies and enable companies to withstand periods of decreased demand. It also gives them bargaining power.

Capacity sharing as a collaboration strategy has been applied in diverse contexts, including air traffic flow management, supply chains, submarine command and control, and container liner shipping (e.g., Ball et al., 2000; Carlson, 2000; Chang et al., 2001; Sherali et al., 2003; Groothedde et al, 2005; Panayides and Wiedmer, 2011; Zheng et al., 2015; Ruan et al., 2018). Kuo et al. (2008) proposed three collaboration strategies for rail-based intermodal freight services among multiple carriers. Collaborative flight scheduling among military and commercial airline carriers is modelled, for example, by Godfrey et al. (2004) with a distributed optimization approach to serve military missions and balance commercial air carrier workloads.

Some works develop mechanisms for incentivizing collaboration, and provide evidence of capacity sharing benefits, especially in terms of stability enhancement. For example, in (Agarwal and Ergun, 2008), a game theoretic method and reverse optimization techniques for capacity exchange or purchase among players working within a carrier alliance are proposed that provide rewards to players in exchange for capacity, thus incentivizing alliance (coalition) membership. Agarwal and Özlem (2010) applied their capacity exchange mechanism to liner shipping, where carriers are motivated to form alliances and pursue an optimal collaborative strategy. Moghaddam and Nof (2014) proved mathematically that demand and capacity sharing among entities in general (for any unspecified application) outperforms previous non-collaborative models in terms of resource utilization and stability, both in competing and non-competing enterprises. Seok and Nof (2014) suggested that manufacturers collaborate through capacity sharing to maximize their production capacity utilization in the long-term. Capacity sharing was framed by Yu et al. (2015) as a cooperative game in which independent firms report information following a cost-allocation rule. Last, and of greater pertinence here due to its maritime application, Ruan et al. (2018) designed a 'hub-and-spoke' port service network by allowing capacity sharing among ports. They present a nonlinear, mixed integer model for determining which small or medium ports would benefit from joining the hub-and-spoke network and how much capacity to share. The model does not account for competition, however.

Building on this concept of capacity or resource sharing in a competitive environment, this paper investigates the potential of port coalition formation, where coalition members provide capacity to other members in the event of a major disruptive event, enabling a port to serve a significant portion of its customers along alternative routes. Like in (Asadabadi and Miller-Hooks, 2018), cross-port investments are allowed, but unlike in their work cross-port investments are limited to coalition members. Moreover, cross-port capacity sharing among members in post-disruption (or disaster) circumstances is explored as a potential mechanism to improve DFRs (served demand versus total demand) and as a means to enhance port services during disruption events. It is hypothesized that coalitions of this nature can provide a structure for jointly strategizing to improve port and maritime network resilience (in terms of post- versus pre-event throughput) and capture additional market share post-disaster by providing more reliable and dependable post-disruption services.

In the remainder of this paper, modeling techniques and alternative graph topologies are described that enable the use of the equilibrium-based approach given in (Asadabadi and Miller-Hooks, 2018) to explicitly incorporate formalized coalition strategies within an equilibrium-based mathematical conceptualization.

3. Problem conceptualization and solution

The problem of maximizing the resilience of individual ports through cross-port collaboration and coalition formation is modeled as an Equilibrium Problem with Equilibrium Constraints (EPEC). That is, the problem is multi-player with each player representing a specific port. Each player has its own bi-level optimization problem, where investment decisions are made at the top level, while disaster and investment impacts are modeled in a lower-level liner shipping problem. Investment decisions taken in the upper level are treated as inputs to the lower level and flows obtained from the lower level are inputs required for decisions at the upper level. Solution of the bilevel program is obtained at a Stackelberg equilibrium between the two levels. The bi-level problems of the individual ports must be considered and solved simultaneously. The solution across ports is obtained at a Nash equilibrium whereby no port can unilaterally change its investment strategy and fair better.

3.1. Single port problem with coalition

The collaborative port protection and investment problem studied herein is presented next, followed by a framework for its solution. The problem conceptualization builds directly on the EPEC formulation given in (Asadabadi and Miller-Hooks, 2018) with its liner shipping model from (Bell et al., 2013) embedded within the lower level. The bilevel formulation for a single port is presented. Seeking the simultaneous solution of the bilevel formulations of all individual ports as required in this competitive framework creates the EPEC, a solution method for which is described in the following subsection.

At the upper level, investment strategies, $x_{pp'}$, are determined given optimal flows, f_{od} and y_{ad}, from the lower-level program. The upper-level objective seeks to attract the maximum container traffic to use the port. For ports inside coalitions, constraints (2) and (3) restrict cross-port investments to occur only between coalition members. Coalition members are further prohibited in the model's constraints from making external investments in ports not participating in the coalition. Investment strategy variables are restricted to be non-negative by constraints (4). Any port not participating in the coalition is restricted from making external investments, which are modelled by constraints (5).

Bilevel formulation for single port *i*:

Port *i* inside coalition *C*			Port *i* inside non-coalition N		
Upper level			Upper level		
Maximize total container in- and outbound traffic	$Max\sum_{d\in D}\sum_{a\in A_i^+} y_{ad} + \sum_{d\in D} f_{id}$	(1)	Objective function (1)		
Subject to:			Subject to:		
Budget limitation	$\sum_{p\in P} x_{ip} \le b_i$	(2)	Constraints (2)		
No investment in ports outside coalition	$\sum_{p\in N} x_{ip} = 0 \forall i \in C$	(3)	No external investment	$\sum_{p\in P\setminus\{i\}} x_{ip} = 0 \forall i \in N$	(5)
Non-negative variables	$x_{ip} \ge 0 \quad \forall p \in P$	(4)	Constraints (4)		
Lower level					
Minimize total handling, depreciation, rental and penalty costs	$Min\sum_{r\in R}\sum_{a\in A_r}\left(CHC_r\sum_{d\in D} y_{ad}\right) + \sum_{o\in O}\sum_{d\in D}(TD_{od} - f_{od})PC + RDC\sum_{d\in D}\sum_{a\in A}\left(t_a - s_a\left(\sum_{p\in\{p^{a-},p^{a+}\}} g_p\left(\sum_{p'\in P\setminus\{p\}} x_{p'p} + qx_{pp}\right)\right) + \sum_{a\in A} 1/v_a\right)y_{ad}$	(6)			
Subject to:					
Flow conservation	$\sum_{a\in A_p^+} y_{ad} - \sum_{a\in A_p^-} y_{ad} = \begin{cases} -f_{od} & for \quad p = o \in O \\ \sum_{o\in O} f_{od} & for \quad p = d \in D \\ 0 & otherwise \end{cases} \quad \forall d \in D$	(7)			
Port capacity	$k_p + g_p\left(\sum_{p'\in P\setminus\{p\}} x_{p'p} + qx_{pp}\right) \ge \sum_{a\in A_p^+}\sum_{d\in D} y_{ad} + \sum_{a\in A_p^-}\sum_{d\in D} y_{ad} - \sum_{a\in L_p^+}\sum_{d\in D} y_{ad} \quad \forall p \in P$	(8)			
Route capacity	$RC_r + \sum_{p\in P_r} h_r\left(\sum_{p'\in P\setminus\{p\}} x_{p'p} + qx_{pp}\right) \ge \sum_{a\in A}\delta_{alr}\sum_{d\in D} y_{ad} \quad \forall l \in L, \ \forall r \in R$	(9)			
Origin- Destination (OD) flow limits	$0 \le f_{od} \le TD_{od} \quad \forall o \in O, \forall d \in D$	(10)			
Non-negativity	$y_{ad} \ge 0 \quad \forall a \in A, \forall d \in D$	(11)			

*Sets, parameters, and decision variables used herein are defined in Appendix A.

**This bi-level framework is adapted from Asadabadi and Miller-Hooks (2018), the lower-level of which was constructed on the liner-shipping formulations of Bell et al. (2013) and Achurra-Gonzalez et al. (2019).

Investments and more generally resilience-enhancing actions can increase overall port capacities, enhance leg traversal times across the system, and reduce the impact of disruptions by restoring port capacities post-disaster, or equivalently, preventing damage. Investment impacts on capacity are assumed to be similar for all routes or ports. Internal investments are assumed to have greater impact in capacity expansion and travel time reduction as investments made externally. These enhancements impact market response through the common liner shipping problem embedded at the lower level.

The lower-level problem is a cost-minimization container assignment problem, where containers are assigned to the maritime network constrained by route and port capacities. In liner shipping, routes are defined by a sequence of port calls. Each route consists of links that connect pairs of adjacent ports. Legs are subpaths. Containers are transported between OD pairs along these subpaths, allowing transshipment at hub ports. In the model, a leg is executed as a task, e.g., loading containers at one port and unloading containers at a second port. This definition follows from earlier works (Bell et al., 2013; Achurra-Gonzalez et al., 2019).

In the lower level, traffic flows that result from minimizing total handling, depreciation, rental and penalty costs via objective (6) are estimated. Investment decisions $x_{pp'}$ determined in the upper level provide improvements to leg traversal times through decreasing port handling times and increase capacity for handling TEUs (twenty-foot equivalent units). These effects are incorporated through parameters s_a, g_p, and h_r in the objective function and constraints. In objective function (6), s_a and g_p in the last term reduce leg traversal times from the original traversal times, $t_a, a \in A$.

Flow balance constraints at the ports are given in (7), and constraints (8) and (9) apply route and port capacity limitations. Specifically, g_p and h_r are incorporated within constraints (8) and (9) with the effect of expanding port and route capacities.

To allow capacity sharing among ports in coalitions, land links are introduced and treated as land legs. These legs are incorporated within routes and enlarge the maritime shipping network. Similar to the handling of marine-based routes, in constraints (9), land-link-based leg flows are limited to land-link-based route capacities. The land-based route capacities are set according to agreed-upon capacity sharing limits. Specifically, land-link-based inbound flows to a port are defined by L_p^+. These are added to the right-hand-side of constraints (8) to incorporate capacity-sharing characteristics when calculating in and outbound flows at the ports. For ports receiving capacity from another coalition member under a given disruption scenario, flows are shipped along land legs entering that port. Land flows will be deducted from in and outbound flows at the port based on the right-hand-side of constraints (8). This ensures that land-based leg flows are not counted against the port's capacity. This inbound flow term has no effect when a port shares its capacity with another port in its coalition. That is, for ports that contribute their capacity when in a coalition, related land-based leg flows are included only in the outbound flows of their throughput calculations. Those ports not participating in a coalition have no connection to land legs.

The nonnegativity of demand and leg flow variables is maintained through constraints (10) and (11), where flows also cannot exceed demand. Nomenclature employed in the formulation are defined in Appendix A.

To maintain the needed linearity of the lower-level problem to create an equivalent, single-level reformulation, the maritime network used in the common lower-level problem shared by all ports is topologically reconfigured to enable capacity sharing between ports within the same coalition.

It is presumed that carriers of containers, through solution of a shared liner shipping problem, will choose alternative routes to avoid an affected port in times of disruption when feasible. Fig. 1 illustrates the concept of capacity sharing proposed here wherein two ports that have formed a coalition back each other with a preset amount of their capacity. Capacity sharing creates a 'benefactor' that not only handles containers for its own clients, but also unloads containers previously routed to a 'beneficiary' through the predetermined level of shared capacity when required. Where possible to load containers to land-based travel modes that were originally destined for an outgoing ship, ports within the coalition can devise agreements for the sharing of equipment, such as chassis, to carry containers on-land. In this example, the ship will be rerouted to the benefactor from the beneficiary, unloaded, and containers will be transported by land to locations at the original destination port.

From the modeling perspective, capacity sharing warrants the introduction of land (or other local) links for on-land transport between collaborating ports to enable the diversion of container traffic. Table 1 illustrates service route changes that arise when two ports along a route form a coalition. Under the coalition agreement, Ports B and P are connected by in-sea voyages and a single land link. A land link connects each 'beneficiary' to its 'benefactor,' the capacity of which is set to the value of the agreed-upon shared capacity. Transport flow volumes along the land links, i.e., the usage of the shared capacity, between the 'beneficiary' and 'benefactor' are included in calculating the throughput of the 'benefactor,' which has its own capacity limitation less any capacity shared with a beneficiary. Leg and land flows are determined in the common liner shipping problem, which is expanded to include land links. With the inclusion of land links and proper settings, all ports, whether non-coalition ports, benefactors, or beneficiaries, can be treated similarly, using the bi-level formulation with small modifications on the expanded network representation as given in (Asadabadi and Miller-Hooks, 2018). However, capacities are handled differently for 'beneficiaries' than for other ports. As port capacity settings do not change, to maintain port capacity limits, land link flows are not counted against the beneficiary's capacity as modelled in constraints (8), but rather they are counted against the benefactor's capacity limits. In all cases, port capacities under any disruption scenario account for both disaster impacts and the protective effects of pre-event investment actions.

Similar to construction in Asadabadi and Miller-Hooks' work, the cross-port investment strategy modelled in the upper level is implemented as a semi-restricted game; however, those ports that are willing to invest in other ports will only do so in ports within their coalition. Moreover, ports in a coalition can not only invest in one another, but back each other by sharing a preset portion of their capacity with coalition members if a member port's capacity is reduced by a disruptive event. Ports outside the coalition are assumed to invest only in themselves and will not receive backup capacity from outside. Capacity sharing and, more generally, coalition formation was not considered in (Asadabadi and Miller-Hooks, 2018). The topological restructuring and formulation modifications described in this subsection address these aspects.

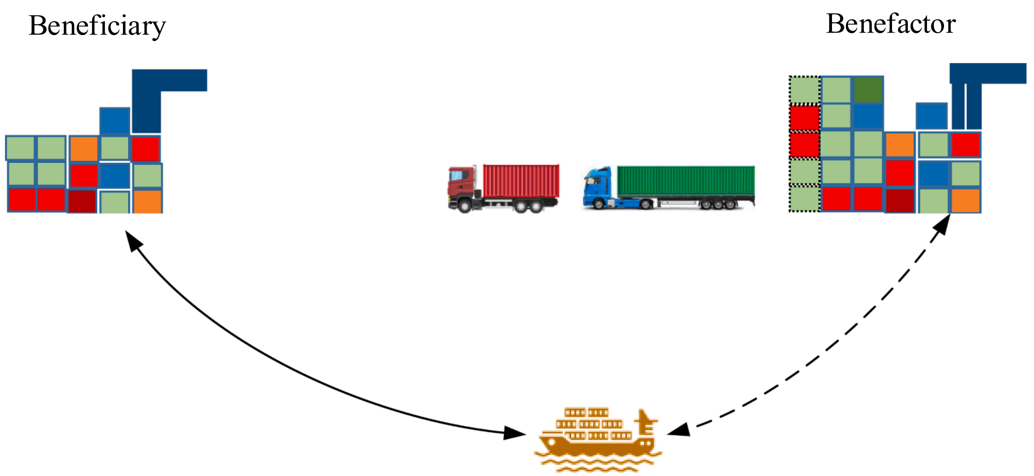


Fig. 1. Illustration of capacity sharing in coalitions where containers are rerouted from following the solid line to following the dashed line.

Table 1
Example of a service route before and after joining a coalition.

Service route	A→B→P→E→A
Service route with PB coalition	A→B→P→E→A

*Ports A (Southeast Asia centroid), B (Belawan), P (Port Klang), and E (Europe centroid).

3.2. Solution

By modifying the network topology instead of the lower-level program to incorporate coalition elements and, thus, maintaining a linear lower-level program, the Karush-Kuhn-Tucker (KKT) conditions of the lower-level problem can be shown to be necessary and sufficient, making it possible to reduce each individual port investment program to an equivalent, single-level Mathematical Program with Equilibrium Constraints (MPEC) through inclusion of the lower-level's KKT conditions at the upper level. Complementary slackness equations within the KKT conditions are linearized by a disjunctive constraints method of Fortuny-Amat and McCarl (1981), resulting in a single-level, linear, mixed-integer program (MIP) for each port.

To solve the resulting set of MIPs that together create the overarching EPEC as illustrated in Fig. 2, the diagonalization technique (reviewed in Gabriel et al., 2012) as used in (Asadabadi and Miller-Hooks, 2018) is also applied here. An overview of this approach follows that includes details needed for incorporating the inland links required for coalition modeling within the solution methodology.

In the diagonalization method, one MPEC (or its equivalent MIP) is solved by fixing investment values for all other ports, producing investment decisions for the subject port. Coalition-based, cross-port capacity-sharing modeling requires different constraint structures for ports inside (beneficiaries and benefactors) and outside a coalition. Because each MPEC is solved sequentially and independently, coalition-based cross-port and self-investment decisions are obtained through solution of the MPECs as specified for the port type. The KKT conditions common to all problems must be met for these upper-level investment decisions, inferring that the liner shipping flows are optimal for the upper-level decisions of all ports as currently set. Investment decisions for the subject port are updated before solving the next MPEC associated with the next port. When the MPECs associated with all ports are solved once, an iteration is complete. When all investment values obtained in two consecutive iterations converge, i.e. the value of their solutions differ by less than a given threshold ε, the procedure terminates. In this last iteration, flows obtained through the KKT conditions will likewise remain constant across port solutions. Fig. 3 illustrates the steps of the procedure and how intermediate solutions across iterations roll forward.

A Nash equilibrium is obtained upon termination of the diagonalization method, wherein no port can gain more throughput by unilaterally changing its investments. In general, the diagonalization method is not guaranteed to converge; however, equilibria solutions were obtained without difficulty for this case study. A multi-start approach can be applied if convergence is difficult to obtain from a particular starting point and to find alternate equilibria. While multiple starting points were tested here, only a single equilibrium was observed over all runs.

Solution efficiency of the diagonalization method is a function of the size of each MPEC and the number of iteration required to achieve convergence. The MIP for the multi-port investment problem with p ports, r service routes, a legs, l links, od OD pairs and d destinations, has $3od+2a \times d+l+p \times d+p^2$ continuous variables and $2od+a \times d+l+p$ binary variables associated with the disjunctive constraints. It also has $7od+4a \times d+3l+p \times d+p^2+2p$ constraints. Thus, generally, the problem size increases in the square of the number of ports. Practically, it was noted that the number of legs had a larger influence on run times. Also important is the setting of M in the disjunctive constraints. For this application, in most runs, the algorithm terminated within five iterations, requiring only seconds

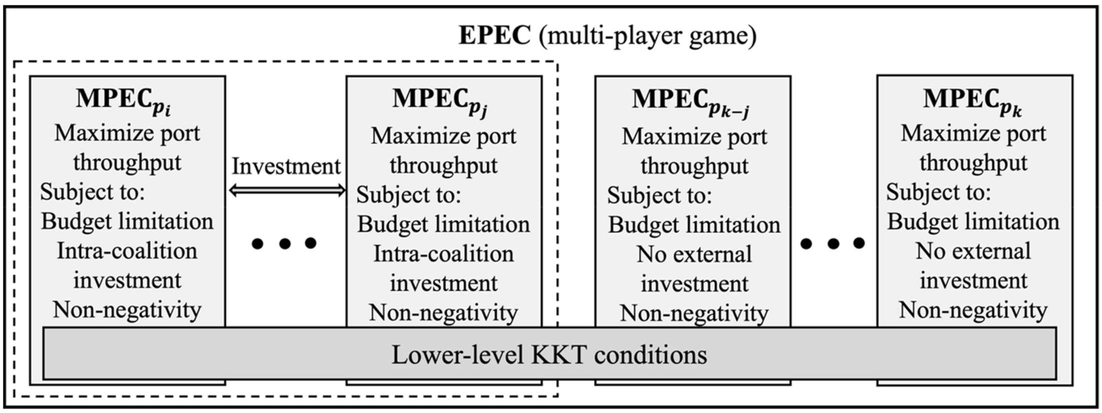


Fig. 2. Overview of EPEC formulation structure for partner ports p_i and p_j.

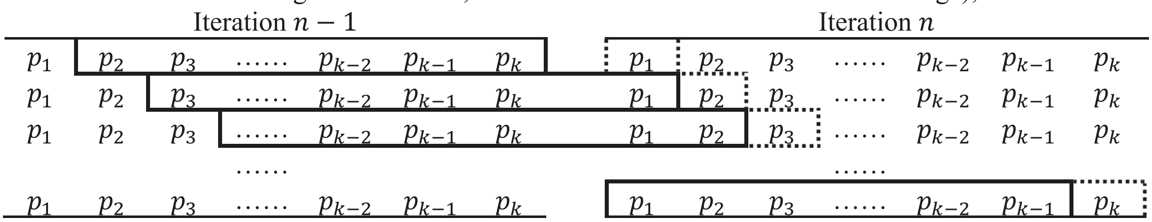
// Step 1: Initialization

Initialize iteration number $n = 1$;

Initialize investment decisions for all ports $x_{ip}^{n} = x_{ip}^{0}$.

// Step 2: Solving the MPECs

Solve the MPEC for each port with fixed x_{ip}^{n} for all $i \neq$ current port (lower-level flows as determined through the included, common KKT conditions are free to change);



The box with solid borders marks those ports whose solutions are temporally fixed in the associated iteration; the box with dashed borders marks the port for which a solution to its equivalent MIP (MPEC) is sought

// Step 3: Solution convergence check

$\left|x_{ip}^{n} - x_{ip}^{n-1}\right| < \varepsilon, \forall i \in P$

If the solutions satisfy convergence terms, an equilibrium solution is attained; otherwise, $n := n + 1$, go back to step 2.

Fig. 3. Diagonalization method in solving proposed EPEC.

to run. In the flooding scenario runs, it was typical to terminate only after 30 iterations, requiring one and one-half hours to run, and 60 iterations in the worst case.

3.3. *Performance indicators*

Benefits of capacity sharing and within-coalition investment, as well as their combination, are discussed from both system and port perspectives. Analysis of these benefits offers insights into the effectiveness of participating in a coalition for enhancing system resilience, DFR or ROI in attracting market share or increasing competitiveness.

Resilience is defined under a coalition through Equations (12) and (13) as the post-disruption throughput over pre-event throughput for both a single port (RES_p), and the port system (RES_s), respectively.

$$\text{RES}_p = \frac{ET_p}{T_p^0}, \forall p \in P, \tag{12}$$

$$\text{RES}_s = \frac{\sum_{p \in P} ET_p}{\sum_{p \in P} T_p^0}, \tag{13}$$

where ET_p represents expected throughput of port p over all tested scenarios, and T_p^0 represents throughput of port p in a benchmark scenario (replicating an undisrupted maritime network), respectively. These measures are agnostic to scale and normalize to pre-event performance.

Indicators of DFR for both single port (DFR_p) and system (DFR_s) perspectives are given by Equations (14) and (15), respectively. DFR is calculated in terms of served demand divided by total demand, and thus takes values between 0 and 1.

$$\text{DFR}_p = \frac{\text{SD}_p}{D_p}, \forall p \in P, \tag{14}$$

$$\text{DFR}_s = \frac{\text{SD}}{D_s}, \tag{15}$$

Additionally, ROI is defined and calculated as the increase of served demand (in TEUs) per unit investment ($), where served demand and investment cost are explored to test investment efficiency. Port (ROI_p) and system (ROI_s) are calculated in Equations (16) and (17), respectively.

$$\mathrm{ROI}_p = \frac{\mathrm{SD}_p - \mathrm{SD}_{p\_base}}{\mathrm{I}_p}, \forall p \in P, \tag{16}$$

$$\mathrm{ROI}_s = \frac{\mathrm{SD} - \mathrm{SD}_{base}}{\sum_{p \in P} \mathrm{I}_p}, \tag{17}$$

where I_p represents the investment made in port p. Single port and system demand are defined as D_p and D_s. SD_{base}, SD_{p_base}, SD, and SD_p give the total served demand in a base case (only disruption, no coalition) or other coalition strategy for system and port perspectives, respectively.

4. Illustrative example

Numerical experiments were designed and conducted to investigate the potential role of coalitions among ports in coping with disaster (here, earthquake, flooding, tsunami, and hurricane scenarios) in the context of world-wide, port-maritime-cargo shipping networks. The experimental design and results of runs are given next.

4.1. Experimental design

The experiments were conducted on a six-node maritime network consisting of two nodes each representing multiple ports in Europe and Asia, and four East Asian ports, specifically the ports of Singapore, Port Klang, Jakarta, and Belawan presented in (Achurra-Gonzalez et al., 2019). When good operating conditions exist within this maritime network, five routes provide transport services across these areas.

Disaster events, or other causes of significant disruption, can negatively influence the operations of ports, increasing handling times and reducing the number of processed containers. These events can also affect the time needed at sea. Here, such disaster impacts on the maritime network are replicated through capacity reduction taken at ports and along the shipping routes, both of which constrain demand fulfillment and lead to longer processing and traversal times. In the earthquake scenario, ports in Jakarta and Belawan have reduced capability for handling either inbound or outbound containers. Handling times in these two disrupted ports are tripled accordingly. All other portions of the network are presumed to be unaffected. Port Klang's throughput handling times increase (two-fold) in the flooding scenario as a consequence of reduced capacity (at 10% of its ordinary capacity), thus, impacting port throughput and arrivals to downstream ports. Also in the runs, for every \$1,000 of investment, approximately 500 TEUs (g_p, $p \in \mathrm{P}$, and h_r, $r \in R$) are protected from a disaster event, and traversal times along the maritime legs and land links improve by 0.15 time units per 1,000

Table 2
Model inputs and parameters in three tested scenarios.

Port, p	Budget (units of capacity), b_p	Port capacity (TEU), k_p				
		Benchmark scenario	Earthquake scenario	Flooding scenario	Tsunami scenario	Hurricane scenario
Singapore (S)	2900	14,500	14,500	14,500	0	14,500
Port Klang (P)	1500	7500	7500	750	7500	7500
Jakarta (J)	1500	9000	0	9000	9000	9000
Belawan (B)	1500	7500	0	7500	7500	7500
Asia (A)	6000	30,000	30,000	30,000	30,000	3000
Europe (E)	6000	30,000	30,000	30,000	30,000	30,000
Service routes	Routes, r	Route capacity (TEU), RC_r				
		Benchmark scenario	Earthquake scenario	Flooding scenario	Tsunami scenario	Hurricane scenario
1	A → B → P → E → A	8000	6640	5600	8000	7200
2	A → S → B → P → E → S → A	8000	6720	6400	4800	7200
3	A → S → P → B → A	4000	1200	3600	3600	2800
4	A → J → B → P → S → A	4000	1760	2800	3400	2800
5	S → P → E → S → B → S	8000	6560	7200	5200	8000
ID	Origin	Destination	OD demand (TEU), TD_{od}			
1	Asia (A)	Europe (E)	18,000			
2	Jakarta (J)	Europe (E)	2000			
3	Singapore (S)	Port Klang (P)	3000			
4	Belawan (B)	Port Klang (P)	2000			
Transporting cost	Unit cost					
Handling cost at ports, CHC_r	\$300/TEU					
Rental and depreciation cost, RDC	\$24.5/TEU/day					
Penalty cost, PC	\$1000/TEU					

TEUs ($s_a, a \in A$). Internal investments taken to reduce disaster impacts are assumed to have 1.3 times (q) the impact in capacity expansion and travel time reduction as investments made externally. Pre-disaster port handling times were randomly generated according to a uniform distribution between one and five days. The setting of s_a should be chosen to maintain positive port handling times.

Inputs and parameters required in the model listed in Table 2 include route configuration, port and route capacities, route frequencies, port budgets, OD demand, and handling, rental, depreciation and penalty costs, as well as changes in network attributes in response to four disaster scenarios: earthquake, tsunami, hurricane and flooding scenarios. These parameters, including those for the earthquake and flooding scenarios, follow identically the inputs given in (Asadabadi and Miller-Hooks, 2018), most of which replicate inputs provided in the original example from Achurra-Gonzalez et al. (2019), with some modification, as the lower-level liner shipping problem. Parameters assumed in the tsunami and hurricane scenarios created for this study are also presented in Table 2. Port-related parameters used in the model, including port capacities and budgets, can be obtained from publicly available reports, many of which are accessible on the ports' websites and are updated seasonally or annually. Li et al. (2021) provides details of available resources for obtaining key global port data elements.

Proposed coalition strategies constructed around within-coalition investments, and in some cases, capacity sharing, under disaster impacts were tested. Coalitions were formed around Ports P (Port Klang) and E (Europe). These ports are, respectively, most and least impacted by the disaster scenarios. In any scenario, no port cooperates in more than one coalition and at most one coalition exists.

Based on their relative geographical proximities, Port P-centered coalitions of (P and B), (P and S), and (P, B and S) were considered. In these three coalitions, within coalition cross-port investment and capacity sharing are supported among all members. While not necessarily the case in reality, it was assumed that land or alternative links connecting coalition members in these cases could be realistically implemented to enable the envisioned capacity-sharing strategies. Under each disaster scenario, it is presumed that the damaged port will be able to take advantage of a predetermined amount of capacity from port(s) in coalitions. Shared capacity values between ports operating within a coalition are set as 500 and 1000 TEUs for ports P and B, ports P and S, respectively, as shown in Table 3. No capacity sharing is undertaken when all ports inside a coalition are operating at full capacity.

Numerical experiments were designed to test efficiency and effectiveness of the proposed capacity sharing and within-coalition investment strategies. Base (control) runs include one run with no disruption and four runs in which a scenario related to each of the disaster categories is presumed to impact the maritime network, but where no capacity sharing or investments are made. 56 additional runs were completed and their results compared with a base run result to assess the value of different investment and/or capacity sharing strategies on maritime network performance under disruption. The 56 additional runs consist of 14 runs per disaster type. These 14 runs consist of two runs with restricted and unrestricted investment and no capacity sharing and 12 additional runs, 4 for each coalition (PB, PS, PSB). Any of these four runs include one run with investments among coalition members without capacity sharing, and three runs with a combination of capacity sharing and one of the following investment implementations: no investment, restricted to only self-investment (internal) or restricted to coalition members (coalition-based). Only one coalition is formed in any run and no scenario affects more than one port in the coalition. Capacity sharing strategies might be reconsidered in disaster events where two or more coalition members incur capacity-reducing damage. Detailed results of all 61 runs are provided in Appendix B.

In addition to these 61 runs, 60 runs were made to further test coalition strategies. Centered around Port E, five two-port coalitions, (E and B), (E and S), (E and J), (E and A), (E and P), and ten three-port coalitions, (E, B and S), (E, B, and J), (E, B, and A), (E, B and P), (E, S and J), (E, S, and A), (E, S, and P), (E, J, and A), (E, J and P), (E, A and P), were tested on the four disaster scenarios. In all of these combinations, only cross-port investments are tested, as the geographical location of Port E precludes the possibility of capacity sharing as envisioned herein.

4.2. *Results analysis*

The results of numerical experiments for the case study using quantities of individual-port and port-network resilience, DFR, and ROI are given in this section. These results are broken down by runs with only capacity sharing, only coalition-based cross-port investment, and both.

4.2.1. *Capacity sharing*

Maritime networks under disruption, and individual ports inside such networks, benefit from capacity sharing in serving more OD

Table 3
Capacity (in TEUs) shared among coalition members for each grouping.

Coalition	Port (from)	Port (to)		
		P	S	B
PB	P	0	0	500
	B	500	0	0
PS	P	0	1000	0
	S	1000	0	0
PSB	P	0	1000	500
	S	1000	0	1000
	B	500	1000	0

demand than without sharing as shown in Table 4. For example, in the flooding scenario, system-wide DFR increased from 0.77 to 0.83 (a nearly 8% improvement) due to capacity sharing among coalition members in PSB. System DFRs for the three coalitions under the three of four disruption scenarios are all higher than if no capacity sharing is permitted.

Individual ports also increased their DFRs under the four disruption scenarios when sharing capacity through joining a coalition. DFRs for ports operating independently remain unchanged in runs with no capacity sharing. There are long-term benefits for the benefactor as roles of beneficiary and benefactor can reverse as a function of the disaster realization. Thus, capacity sharing is an effective strategy for improving system-level and port-level DFR in a disrupted network. With the increase of DFRs from capacity sharing, both maritime networks and ports in coalitions are competitive in holding their market share. Note, however, that in the earthquake, tsunami, and hurricane scenarios, where no ports within the coalition are disrupted, no increase in DFR was noted, as there is no need to take advantage of the potential for capacity sharing.

While system resilience is improved for coalition PSB, Table 4 indicates that not all individual ports benefit from coalition-based capacity sharing. Although Port B joins all three coalitions (PB, PS and PSB) under different runs, this port's resilience increases only when joining coalition PSB. Likewise, the resilience of Port S increases from capacity sharing in coalition PSB, but not from joining coalition PS. The resilience of ports that do not join a coalition remains unchanged. This analysis of capacity sharing benefits provides information to support decisions on whether a port should join a particular partnership.

4.2.2. Investment

Disrupted maritime networks benefit from investments in and across ports with increased DFR, market share for many ports, and improved services for shippers. Thus, a coalition-based, cross-restricted investment strategy wherein ports do not share capacity is modeled for this purpose.

The results of the twelve relevant runs (Table 5) indicate that disrupted maritime networks benefit from cross-port investment in four of the twelve runs (specifically, coalitions PB and PSB under both earthquake and flooding scenarios) compared with restricted (internal-only) investment. In the remaining eight runs, ports choose to keep their investments internally. In the four runs where the ports invest in others in their coalition, total network-wide DFR increases. Comparing results of capacity-sharing-only and investment-only runs indicates that investing across ports for tested monetary and capacity levels is more effective than capacity sharing. In fact, in the best cases for each, the relative benefits (served OD demand) of within-coalition, cross-port restricted investment is nearly double that of the impact of capacity sharing in these runs. Additional runs can be conducted to determine a capacity-sharing level that is commensurate with the investment level or a reduced investment that give comparable results to capacity made available for sharing.

Further benefits of cross-coalition investment were noted in terms of ROI and DFR of cross-port investment as compared with restricted (within port) investment. Specially, all ports in coalitions fulfilled more demand through cross-port investment than through

Table 4
Maritime network DFR and resilience with only coalition-based capacity sharing.

Demand fulfillment rate							
Coalition	System	Port					
		A	E	P	S	B	J
No Disruption	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Earthquake							
No coalition	0.77	0.91	0.82	**0.60**	**1.00**	**0.00**	0.00
PB	0.79	0.91	0.82	**0.70**	1.00	**0.25**	0.00
PS	0.77	0.91	0.82	**0.60**	**1.00**	0.00	0.00
PSB	0.83	0.91	0.82	**0.90**	**1.00**	**0.75**	0.00
Flooding							
No coalition	0.77	0.91	0.92	**0.15**	**0.00**	**0.38**	1.00
PB	0.79	0.91	0.92	**0.25**	0.00	**0.63**	1.00
PS	0.81	0.91	0.92	**0.35**	**0.33**	0.38	1.00
PSB	0.83	0.91	0.92	**0.45**	**0.33**	**0.63**	1.00
Tsunami							
No coalition	0.80	0.89	0.90	**0.40**	**0.00**	**1.00**	1.00
PB	0.80	0.89	0.90	**0.40**	0.00	**1.00**	1.00
PS	0.84	0.89	0.90	**0.40**	**0.33**	1.00	1.00
PSB	0.87	0.89	0.90	**0.40**	**0.67**	**1.00**	1.00
Hurricane							
No coalition	0.40	0.17	0.25	**1.00**	**1.00**	**1.00**	1.00
PB	0.40	0.17	0.25	**1.00**	1.00	**1.00**	1.00
PS	0.40	0.17	0.25	**1.00**	**1.00**	1.00	1.00
PSB	0.40	0.17	0.25	**1.00**	**1.00**	**1.00**	1.00
Resilience							
Coalition group	System	Port					
		A	E	P	S	B	J
No coalition	0.586	0.57	0.58	0.55	0.65	0.64	0.60
PB	0.586	0.57	0.58	0.55	0.65	0.64	0.60
PS	0.586	0.57	0.58	0.55	0.65	0.64	0.60
PSB	0.592	0.57	0.58	0.55	**0.70**	**0.66**	0.60

Table 5
System and port performance by only coalition-based cross-port investment under four disruption scenarios.

Disruption	Coalition	Port	Demand fulfillment rate (DFR)		Return on investment (ROI)	
			Restricted investment	Coalition cross-port investment	Restricted investment	Coalition cross-port investment
Earthquake	PB	A	1.00	1.00		
		E	0.94	0.94		
		P	0.80	**0.85**	0.65	**0.43**
		S	1.00	1.00		
		B	0.50	**0.63**	0.66	**0.84**
		J	0.44	0.44	0.59	0.59
		System	0.92	**0.93**	1.30	**1.24**
	PS	A	1.00	1.00		
		E	0.94	0.94		
		P	0.80	0.80	0.65	0.65
		S	1.00	1.00		
		B	0.50	0.50	0.66	0.66
		J	0.44	0.44	0.59	0.59
		System	0.92	0.92	1.30	1.30
	PSB	A	1.00	1.00		
		E	0.94	0.94		
		P	0.80	**0.85**	0.65	**0.43**
		S	1.00	1.00		
		B	0.50	**0.63**	0.66	**0.84**
		J	0.44	0.44	0.59	0.59
		System	0.92	**0.93**	1.30	**1.24**
Flooding	PB	A	1.00	1.00		
		E	1.00	1.00		
		P	0.35	**0.40**	0.65	**0.84**
		S	0.00	0.00		
		B	0.86	**1.00**		
		J	1.00	1.00		
		System	0.87	**0.88**	3.13	**2.10**
	PS	A	1.00	1.00		
		E	1.00	1.00		
		P	0.35	0.35	0.65	0.65
		S	0.00	0.00		
		B	0.86	0.86		
		J	1.00	1.00		
		System	0.87	0.87	3.13	3.13
	PSB	A	1.00	1.00		
		E	1.00	1.00		
		P	0.35	**0.40**	0.65	**0.84**
		S	0.00	0.00		
		B	0.86	**1.00**		
		J	1.00	1.00		
		System	0.87	**0.88**	3.13	**2.10**
Tsunami	PB	A	1.00	1.00		
		E	1.00	1.00		
		P	0.77	0.77	0.65	0.65
		S	0.61	0.61	0.63	0.63
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.95	0.95	1.04	1.04
	PS	A	1.00	1.00		
		E	1.00	1.00		
		P	0.77	0.77	0.65	0.65
		S	0.61	0.61	0.63	0.63
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.95	0.95	1.04	1.04
	PSB	A	1.00	1.00		
		E	1.00	1.00		
		P	0.77	0.77	1.22	1.22
		S	0.61	0.61	0.63	0.63
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.95	0.95	1.04	1.04
Hurricane	PB	A	0.36	0.36	0.59	0.59
		E	0.43	0.43		
		P	1.00	1.00	2.32	2.32
		S	1.00	1.00		

(*continued on next page*)

Table 5 (*continued*)

Disruption	Coalition	Port	Demand fulfillment rate (DFR)		Return on investment (ROI)	
			Restricted investment	Coalition cross-port investment	Restricted investment	Coalition cross-port investment
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.54	0.54	0.94	0.94
	PS	A	0.36	0.36	0.59	0.59
		E	0.43	0.43		
		P	1.00	1.00	2.32	2.32
		S	1.00	1.00		
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.54	0.54	0.94	0.94
	PSB	A	0.36	0.36	0.59	0.59
		E	0.43	0.43		
		P	1.00	1.00	2.32	2.32
		S	1.00	1.00		
		B	1.00	1.00		
		J	1.00	1.00		
		System	0.54	0.54	0.94	0.94

restricted investment.

System-wide ROI (TEU/$) is calculated in Table 5 for each disruption scenario. In both earthquake and flooding scenarios, even though cross-port investment is allowed within coalition PS, ports chose to self-invest. However, Port P invests in Port B and Port B in P under runs with coalitions PB and PSB for earthquake and flooding scenarios, respectively.

Individual ports increase their ROI when receiving investment from coalition members, while ROI values decrease for ports that make investments in others. In the earthquake scenario, Port B increases its ROI through receiving investment from Port P. Although ROI for Port P decreases, Port P completes more unloading container tasks and fulfills more demand when investing in Port B. In the flooding scenario, Port P increases its ROI through receiving investment from Port B.

As indicated by the results in Table 5, DFRs at ports in a coalition, as well as the larger port network, increase as a result of cross-port investment. Under the earthquake scenario, DFRs at Ports P and B increased by 6.6% and 26.1%, respectively, as compared to self-investment alone. An improvement by 1% in port network performance in both earthquake and flooding disruption scenarios was obtained for the same circumstances. However, under the earthquake scenario, ROI decreased 33.9% for Port P and the system by allowing cross-port investments rather than restricting investments to self-investment. In summary, DFRs are higher through cross-port (coalition-based) investment compared with restricted investment. Meanwhile, throughput at Port P and the larger port network decreases from coalition-based, cross-port investment, leading to a decrease in system ROI. This is due to a decrease in transshipments served at Port P as a portion of Port P's capacity is required post-disaster by Port B.

These runs, thus, provide evidence that the performance of individual ports and the larger system in terms of ROI cannot be guaranteed by cross-port investment, but disrupted maritime networks and individual ports benefit from cross-port investment when joining coalitions in that more OD demand is fulfilled. Fulfilling greater demand infers that ports covered by a coalition have greater stability in holding market share when the coalition allows cross-port investment.

Table 6
Served OD demand (TEUs) by strategies under four disruption scenarios.

Collaboration	Only disruption	Capacity sharing	Restricted investment	Coalition cross-port investment	Capacity sharing & Coalition cross-port investment	No disruption
Earthquake						
PB	19,320	19,820	22,875	23,135	23,635	25,000
PS	19,320	19,320	22,875	22,875	22,875	25,000
PSB	19,320	20,820	22,875	23,135	23,879	25,000
Flooding						
PB	19,150	19,650	21,725	22,000	22,225	25,000
PS	19,150	20,150	21,725	21,725	22,725	25,000
PSB	19,150	20,650	21,725	22,000	23,225	25,000
Tsunami						
PB	20,000	20,000	23,836	23,836	23,826	25,000
PS	20,000	21,000	23,836	23,836	24,836	25,000
PSB	20,000	21,600	23,836	23,836	25,000	25,000
Hurricane						
PB	10,000	10,000	13,518	13,518	13,518	25,000
PS	10,000	10,000	13,518	13,518	13,518	25,000
PSB	10,000	10,000	13,518	13,518	13,518	25,000

Table 7
Port and system DFR and ROI with strategies under four disruption scenarios.

Disruption	Coalition	Port	Strategy							
			No strategy	Capacity sharing	Restricted investment		Coalition cross-port investment		Capacity sharing & coalition cross-port investment	
			DFR	DFR	ROI	DFR	ROI	DFR	ROI	DFR
Earthquake	PB	A	0.91	0.91		1.00		1.00		1.00
		E	0.82	0.82		0.94		0.94		0.94
		P	0.60	0.70	0.65	0.80	0.43	0.85	0.10	1.05
		S	1.00	1.00		1.00		1.00		1.00
		B	0.00	0.25	0.66	0.50	0.84	0.63	0.84	0.88
		J	0.00	0.00	0.59	0.44	0.59	0.44	0.59	0.44
		System	0.77	0.79	1.30	0.92	1.24	0.93	1.13	0.95
	PS	A	0.91	0.91		1.00		1.00		1.00
		E	0.82	0.82		0.94		0.94		0.94
		P	0.60	0.60	0.65	0.80	0.65	0.80	0.65	0.80
		S	1.00	1.00		1.00		1.00		1.00
		B	0.00	0.00	0.66	0.50	0.66	0.50	0.66	0.50
		J	0.00	0.00	0.59	0.44	0.59	0.44	0.59	0.44
		System	0.77	0.77	1.30	0.92	1.30	0.92	1.30	0.92
	PSB	A	0.91	0.91		1.00		1.00		1.00
		E	0.82	0.82		0.94		0.94		0.94
		P	0.60	0.90	0.65	0.80	0.43	0.85	0.65	1.00
		S	1.00	1.00		1.00		1.00		1.00
		B	0.00	0.75	0.66	0.50	0.84	0.63	0.66	1.00
		J	0.00	0.00	0.59	0.44	0.59	0.44	0.59	0.44
		System	0.77	0.83	1.30	0.92	1.24	0.93	2.05	0.96
Flooding	PB	A	0.91	0.91		1.00		1.00		1.00
		E	0.92	0.92		1.00		1.00		1.00
		P	0.15	0.25	0.65	0.35	0.84	0.40	0.65	0.45
		S	0.00	0.00		0.00		0.00		0.08
		B	0.38	0.63		0.86		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.77	0.79	3.13	0.87	2.10	0.88	2.45	0.89
	PS	A	0.91	0.91		1.00		1.00		1.00
		E	0.92	0.92		1.00		1.00		1.00
		P	0.15	0.35	0.65	0.35	0.65	0.35	0.65	0.55
		S	0.00	0.33		0.00		0.00		0.33
		B	0.38	0.38		0.86		0.86		0.86
		J	1.00	1.00		1.00		1.00		1.00
		System	0.77	0.81	3.13	0.87	3.13	0.87	3.13	0.91
	PSB	A	0.91	0.91		1.00		1.00		1.00
		E	0.92	0.92		1.00		1.00		1.00
		P	0.15	0.45	0.65	0.35	0.84	0.40	0.65	0.65
		S	0.00	0.33		0.00		0.00		0.41
		B	0.38	0.63		0.86		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.77	0.83	3.13	0.87	2.10	0.88	3.13	0.93
Tsunami	PB	A	0.89	0.89		1.00		1.00		1.00
		E	0.90	0.90		1.00		1.00		1.00
		P	0.40	0.40	0.65	0.77	0.65	0.77	0.65	0.77
		S	0.00	0.00	0.63	0.61	0.63	0.61	0.63	0.61
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.80	0.80	1.04	0.95	1.04	0.95	1.04	0.95
	PS	A	0.89	0.89		1.00		1.00		1.00
		E	0.90	0.90		1.00		1.00		1.00
		P	0.40	0.60	0.65	0.77	0.65	0.77	0.65	0.97
		S	0.00	0.33	0.63	0.61	0.63	0.61	0.63	0.95
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.80	0.84	1.04	0.95	1.04	0.95	1.04	0.99
	PSB	A	0.89	0.89		1.00		1.00		1.00
		E	0.90	0.90		1.00		1.00		1.00
		P	0.40	0.60	1.22	0.77	1.22	0.77	0.50	1.00
		S	0.00	0.67	0.63	0.61	0.63	0.61	0.67	1.00
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.80	0.86	1.04	0.95	1.04	0.95	1.44	1.00
Hurricane	PB	A	0.17	0.17	0.59	0.36	0.59	0.36	0.59	0.36

(*continued on next page*)

Table 7 (*continued*)

Disruption	Coalition	Port	Strategy							
			No strategy	Capacity sharing	Restricted investment		Coalition cross-port investment		Capacity sharing & coalition cross-port investment	
			DFR	DFR	ROI	DFR	ROI	DFR	ROI	DFR
		E	0.25	0.25		0.43		0.43		0.43
		P	1.00	1.00	2.32	1.00	2.32	1.00	2.32	1.00
		S	1.00	1.00		1.00		1.00		1.00
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.40	0.40	0.94	0.54	0.94	0.54	0.94	0.54
	PS	A	0.17	0.17	0.59	0.36	0.59	0.36	0.59	0.36
		E	0.25	0.25		0.43		0.43		0.43
		P	1.00	1.00	2.32	1.00	2.32	1.00	2.32	1.00
		S	1.00	1.00		1.00		1.00		1.00
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.40	0.40	0.94	0.54	0.94	0.54	0.94	0.54
	PSB	A	0.17	0.17	0.59	0.36	0.59	0.36	0.59	0.36
		E	0.25	0.25		0.43		0.43		0.43
		P	1.00	1.00	2.32	1.00	2.32	1.00	2.32	1.00
		S	1.00	1.00		1.00		1.00		1.00
		B	1.00	1.00		1.00		1.00		1.00
		J	1.00	1.00		1.00		1.00		1.00
		System	0.40	0.40	0.94	0.54	0.94	0.54	0.94	0.54

4.2.3. *Combination of capacity sharing and investment*

In runs allowing both investment and capacity sharing among coalition members, the effects in increasing served OD demand are nearly additive. In the earthquake scenario, OD demand served through coalitions PB and PS with combined capacity sharing and cross-port investment strategies equals the total increased served OD demand from coalition-based cross-port investment alone and capacity sharing alone. Similar additivity is also observed under coalition PSB for the flooding scenario, coalitions PB and PS for the tsunami scenario, and all coalitions for the hurricane scenario. In other cases, such additive improvements are not achieved.

Table 6 shows that for four disruption scenarios, investments outperform the capacity-sharing strategy. Further, combining strategies outperforms either of them alone. In four disruption scenarios, such additivity is not obtained for four of twelve runs (PSB in the earthquake and tsunami scenarios, PB and PSB in the flooding scenario); however, the required investment in these four cases is lower than results in only coalition-based, cross-port investment runs. Simultaneously, system ROIs for these four runs with combined capacity sharing and coalition-based investment are higher than only coalition-based investment.

ROI, DFR and resilience values are compared across the three coalitions under the four disruption scenarios, run results for which are given in Tables 7 and 8. All three system-level measures improve through combining coalition-based investment and capacity sharing strategies over allowing either alone. Specifically, individual ports in coalitions increase their ROIs and DFRs in all related runs through the combined strategy as compared to coalition-based cross-port investment alone.

For individual ports, resilience improvements from a combined strategy are more mixed. For example, the Port B, which participates in coalitions PB and PSB, has lowest resilience when joining in the coalition PSB with both coalition-based capacity sharing and cross-port investment strategies. OD demand originating from Port B and destined for Port P cannot be completely fulfilled because of disruptions at Port P. Thus, while Port B serves more transshipment containers, in its role as a destination port, it loads more containers to fulfill its OD demand tasks through aiding Port P (with both capacity and investment). With coalition PB, resilience increased for one port alone: Port S. This increase appears to occur because Port S serves a route supported also by Port B. This provides evidence that the impacts (good or bad) of changes in operations at one port can affect the performance of another port that is connected by a common market. Regional coalitions always increase system resilience through mutual capacity sharing and cross-port investment. Thus, ports whose markets are connected can expect a more stable market share when joining a coalition.

It is also noted that ports in a coalition are able to hold and attract market share from ports outside their coalition. In Table 9, it can be seen that under the earthquake scenario, Port S loses transshipment flows to Port P when Ports P and B join the coalition, and regains its transshipment flows when joining coalition PSB.

4.2.4. *Insights from expanded coalition study*

Although cross-port investment and capacity sharing are permitted among coalition members, individual port members may not always find these options to be advantageous. In fact, the experimental results show this to be the case in some disaster scenarios. For example, no external investments are made for the case with coalition PS under the four disruption scenarios. Larger coalitions were not always more beneficial than smaller coalitions. For example, the DFRs with coalition PSB under all disruption scenarios were no higher than with PS or PB coalitions in place when only cross-port investments were permitted. Likewise, the DFRs for coalition ESP for four disaster scenarios were no higher than for the smaller coalition PS.

Taking the perspective of a port that is damaged, it was generally noted that these ports gained from participation in a coalition, but

Table 8
Port and system resilience with strategies.

Coalition		System	Port					
			A	E	P	S	B	J
No coalition		0.586	0.57	0.58	0.55	0.65	0.64	0.60
PB	Only capacity sharing	0.586	0.57	0.58	0.55	0.65	**0.64**	0.60
	Only coalition cross-port investment	0.660	0.67	0.67	0.72	0.67	**0.48**	0.69
	Combination	0.657	0.67	0.67	0.70	**0.73**	**0.43**	0.69
PS	Only capacity sharing	0.586	0.57	0.58	0.55	0.65	0.64	0.60
	Only coalition cross-port investment	0.662	0.67	0.67	0.72	0.72	0.46	0.69
	Combination	0.662	0.67	0.67	0.72	0.72	0.46	0.69
PSB	Only capacity sharing	0.592	0.57	0.58	0.55	0.70	**0.66**	0.60
	Only coalition cross-port investment	0.660	0.67	0.67	0.72	0.67	**0.48**	0.69
	Combination	0.666	0.67	0.67	0.71	0.80	**0.45**	0.69

Table 9
Route flows for each OD pair.

Origin	Destination	Demand	Good condition		Earthquake scenario							
					Only disruption		Coalition PB		Coalition PS		Coalition PSB	
			Route	Flow	Route	Flow	Route	Flow	Route	Flow	Route	Flow
A	E	18,000	A → E	16,000	A → E	13,360	A → E	16,936	A → E	16,730	A → E	16,135
			A → S → E	750	A → S → E	710	A → P → E	1065	A → P → E	1270	A → S → E	757
			A → P → E	1250	A → P → E	2250					A → P → E	1108
J	E	2000	J → B → E	2000			J → P → E	879	J → P → E	879	J → P → E	879
S	P	3000	S → P	3000	S → P	3000	S → P	3000	S → P	3000	S → P	3000
B	P	2000	B → P	2000			B → P	1256	B → P	996	B → P	1000
											B → S → P	1000

it was not always the case. Similarly, ports that are not directly impacted by the disaster event were found to benefit. For example, Port E invested in external members when participating in coalitions EJ, EA, EBJ, EJP, ESJ, EAB, ESA, EAP, or EJA, consequently increasing its overall throughput.

Finally, the system performed best in terms of DFRs under three coalitions: EJ (or EBJ, ESJ, EJA, EJP containing EJ) for the earthquake scenario with damaged ports B and J, PSB for flooding (damaged port P) and tsunami (damaged port S) scenarios, and EA (or EAB, ESA, EJA, EAP containing EA) for the hurricane (damaged port A) scenario. In terms of system resilience, coalition EJA outperforms all other coalitions, including coalition PSB. This arises despite that coalition one or more of PSB's members are disrupted in three of the four disruption scenarios while Port E is never disrupted and Ports J and A are disrupted only under one scenario each. Moreover, the best performing coalitions did not always contain all damaged ports. Last, it was found that the more connected a port is within the port network, the greater the cross-port activity within the coalition.

5. Conclusions and future research

This paper hypothesizes and tests coalition strategies for improving port and maritime network resilience. The coalition strategies allow retention of market share post-disaster by enabling more dependable post-disruption services. This work, thus, provides insights for port authorities on the potential effectiveness of port capacity expansion, infrastructure investment and forming strategic partnerships. Shipping companies may also take into consideration the ability of a port to provide service under disruption events when choosing which ports to include in their service loops.

In results from numerical experiments on an example port network from the literature, proposed coalition strategies were found to be efficient and effective in improving the performance of the whole system and were especially effective for ports participating within a coalition in terms of resilience, DFR, and ROI. Ports, thus, participating in a coalition were noted to be more competitive and dependable in holding their market share. Although the resilience of individual ports, especially ports that invest in or share capacity with other ports, may decrease, system resilience improved as a result of investing within one another and backing each other up in the event of a major disruption or disaster. Moreover, coalitions were found to benefit both individual ports and improve system-wide performance under disruption.

In this paper, results were attained from tests on a global, but highly aggregated network with four origin–destination pairings, yet only six nodes. This restricts the findings to highly connected situations, where port coalition members are likely to be directly connected. Limited by the network size, only one coalition was tested in any given run. Maritime networks often involve more complex relationships. Such relationships will be studied in future research, including coalitions with more than one coalition. The additional costs from joining a coalition, such as coalition-participation fees, land transport costs, and added port handling costs from sharing capacity, and other terms of the coalition agreement, must be weighed against its potential benefits in determining whether it is wise for a port to join a particular coalition in practice. Such an analysis might also include potential long-term market share gains from increased port resilience. Further, incentivization mechanisms can be designed to support the formation of coalitions and monetary benefits can be evaluated. This work also considers the occurrence of only a single disaster scenario in each solution. Instead, a stochastic approach can be taken to create investment decisions and assess the benefits of coalitions in hedging against multiple possible future disaster events. This would enable trade-off analysis, where more than one coalition member could benefit under different future situations that are considered simultaneously. Long-term market share rebalancing due to improved reliability is expected based on findings in this work, but this aspect requires further investigation.

CRediT authorship contribution statement

Wenjie Li: Conceptualization, Methodology, Software, Validation, Data curation. **Ali Asadabadi:** Conceptualization, Methodology, Software. **Elise Miller-Hooks:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was partially funded by the National Science Foundation. This support is gratefully acknowledged but implies no endorsement of the findings.

Appendix A

Sets		Parameters	
A	Legs	t_a^0	Sailing time on leg a, $a \in A$
O	Origin ports	g_p	Capacity loss reduction due to disaster event per unit investment in port p, $p \in P$
D	Destination ports	h_r	Capacity loss reduction due to disaster event per unit investment in any port on route r,$r \in R$
P	All ports	s_a	Reduction in traversal time increase due to disaster event per unit investment in any port on leg a ,$a \in A$
C	Ports included in the coalition	q	Ratio of effectiveness of internal investment that is converted to external investment
N	Non-coalition ports	CHC_r	Container handling cost per container for a leg on route r, $r \in R$
R	All routes	RDC	Per container rental and depreciation cost (inventory cost) per unit time
L	All links	TD_{od}	Containers to be transported from origin o to destination d, $o \in O, d \in D$
A_p^+	Legs entering port p	δ_{alr}	1 if leg a uses link l on route r, 0 otherwise, $a \in A$, $l \in L$, $r \in R$
A_p^-	Legs leaving port p	v_a	Frequency of sailing on leg a, $a \in A$
A_r	Legs on route r	RC_r	Post-disaster capacity of route r, $r \in R$
L_r	Links on route r	k_p	Maximum throughput capacity at port p post-disaster, $p \in P$
P_r	Every port on route r	PC	Penalty cost for containers not transported
L_p^+	Land legs entering port p	b_p	Budget for port p, $p \in P$
Decision variables			
x_{ip}	Investment by port i in port p (decision variables in the upper level, and parameters in the lower level)		
f_{od}	Flow of containers from origin o to destination d		
y_{ad}	Flow of containers on leg a en route to destination d		

Notation table here is adapted from tables in Bell et al. (2013), Asadabadi and Miller-Hooks (2018), and Achurra-Gonzalez et al. (2019).

Appendix B. (This table can be provided on-line if preferred)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
0	No disruption, no strategy	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	3000	P	1250	5000	7500			
		4	2000	S	750	3000	4500			
				B	2000	2000	6000			
				J	0	2000	2000			
1	Earthquake, no strategy	1	16,320	A	0	16,320	16,320			
		2	0	E	0	16,320	16,320			
		3	3000	P	2250	3000	7500			
		4	0	S	710	3000	4420			

(continued on next page)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
				B	0	0	0			
				J	0	0	0			
2	Earthquake, Restricted investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	2149	3996	8294	1223		
		4	996	S	0	3000	3000			
				B	0	996	996	1500		
				J	0	879	879	1500		
3	Earthquake, unrestricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000		J	2485
		3	3000	P	2239	3996	8474	1500		
		4	996	S	692	3000	4384			
				B	0	996	996	1500		
				J	0	879	879	1500		
4	Earthquake, PB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	1944	4256	8144	992	B	508
		4	1256	S	0	3000	3000			
				B	0	1256	1256	1500		
				J	0	879	879	1500		
5	Earthquake, PS-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	2149	3996	8294	1223		
		4	996	S	0	3000	3000			
				B	0	996	996	1500		
				J	0	879	879	1500		
6	Earthquake, PSB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	1944	4256	8144	992	B	508
		4	1256	S	0	3000	3000			
				B	0	1256	1256	1500		
				J	0	879	879	1500		
7	Earthquake, PB-based capacity sharing	1	16,320	A	0	16,320	16,320			
		2	0	E	0	16,320	16,320			
		3	3000	P	2250	3500	7500			
		4	500	S	710	3000	4420			
				B	0	500	0			
				J	0	0	0			
8	Earthquake, PS-based capacity sharing	1	16,320	A	0	16,320	16,320			
		2	0	E	0	16,320	16,320			
		3	3000	P	2250	3000	7500			
		4	0	S	710	3000	4420			
				B	0	0	0			
				J	0	0	0			
9	Earthquake, PSB-based capacity sharing	1	16,320	A	0	16,320	16,320			
		2	0	E	0	16,320	16,320			
		3	3000	P	1750	4500	7500			
		4	1500	S	1710	3000	5420			
				B	0	1500	0			
				J	0	0	0			
10	Earthquake, PB-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	2149	4496	8294	1223		
		4	1496	S	0	3000	3000			
				B	0	1496	996	1500		
				J	0	879	879	1500		
11	Earthquake, PS-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	2149	3996	8294	1223		
		4	996	S	0	3000	3000			
				B	0	996	996	1500		
				J	0	879	879	1500		
12	Earthquake, PSB-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	1988	5000	8476	1500		
		4	2000	S	1757	3000	5514			
				B	0	2000	500	753		

(*continued on next page*)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
				J	0	879	879	1500		
13	Earthquake, PB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	1444	5256	7644	992	B	508
		4	1756	S	0	3000	3000			
				B	0	1756	1256	1500		
				J	0	879	879	1500		
14	Earthquake, PS-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	2149	3996	8294	1223		
		4	996	S	0	3000	3000			
				B	0	996	996	1500		
				J	0	879	879	1500		
15	Earthquake, PSB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	879	E	0	18,879	18,879			
		3	3000	P	1988	5000	8476	1500		
		4	2000	S	1757	3000	5514			
				B	0	2000	500	753		
				J	0	879	879	1500		
16	Flooding, no strategy	1	16,400	A	0	16,400	16,400			
		2	2000	E	0	18,400	18,400			
		3	0	P	0	750	750			
		4	750	S	3600	0	7200			
				B	2800	750	6350			
				J	0	2000	2000			
17	Flooding, Restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	0	P	4	1725	1733	1500		
		4	1725	S	4166	0	8332			
				B	2000	1725	5725			
				J	0	2000	2000			
18	Flooding, unrestricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	0	P	4	2000	2008	1500		
		4	2000	S	3649	0	7298			
				B	2000	2000	6000		P	500
				J	0	2000	2000			
19	Flooding, PB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	0	P	4	2000	2008	1500		
		4	2000	S	3649	0	7298			
				B	2000	2000	6000		P	500
				J	0	2000	2000			
20	Flooding, PS-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	0	P	4	1725	1733	1500		
		4	1725	S	4166	0	8332			
				B	2000	1725	5725			
				J	0	2000	2000			
21	Flooding, PSB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	0	P	4	2000	2008	1500		
		4	2000	S	3649	0	7298			
				B	2000	2000	6000		P	500
				J	0	2000	2000			
22	Flooding, PB-based capacity sharing	1	16,400	A	0	16,400	16,400			
		2	2000	E	0	18,400	18,400			
		3	0	P	0	1250	750			
		4	1250	S	3600	0	7200			
				B	2800	1250	6350			
				J	0	2000	2000			
23	Flooding, PS-based capacity sharing	1	16,400	A	0	16,400	16,400			
		2	2000	E	0	18,400	18,400			
		3	1000	P	0	1750	750			
		4	750	S	3600	1000	7200			
				B	2800	750	6350			
				J	0	2000	2000			

(*continued on next page*)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
24	Flooding, PSB-based capacity sharing	1	16,400	A	0	16,400	16,400			
		2	2000	E	0	18,400	18,400			
		3	1000	P	0	2250	750			
		4	1250	S	3600	1000	7200			
				B	2800	1250	6350			
				J	0	2000	2000			
25	Flooding, PB-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	225	P	0	2225	1725	1500		
		4	2000	S	4166	225	8557			
				B	1500	2000	4500			
				J	0	2000	2000			
26	Flooding, PS-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1000	P	0	2725	1725	1500		
		4	1725	S	4166	1000	8332			
				B	2000	1725	5725			
				J	0	2000	2000			
27	Flooding, PSB-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1225	P	0	3225	1725	1500		
		4	2000	S	4166	1225	8557			
				B	2000	2000	5500			
				J	0	2000	2000			
28	Flooding, PB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	225	P	0	2225	1725	1500		
		4	2000	S	4166	225	8557			
				B	1500	2000	4500			
				J	0	2000	2000			
29	Flooding, PS-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1000	P	0	2725	1725	1500		
		4	1725	S	4166	1000	8332			
				B	2000	1725	5725			
				J	0	2000	2000			
30	Flooding, PSB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1225	P	0	3225	1725	1500		
		4	2000	S	4166	1225	8557			
				B	2000	2000	5500			
				J	0	2000	2000			
31	Tsunami, no strategy	1	16,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	0	P	2750	2000	7500			
		4	2000	S	0	0	0			
				B	2450	2000	6900			
				J	0	2000	2000			
32	Tsunami, Restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
33	Tsunami, unrestricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
34	Tsunami, PB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
35	Tsunami, PS-based cross-port investment	1	18,000	A	0	18,000	18,000			

(*continued on next page*)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
36	Tsunami, PSB-based cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
37	Tsunami, PB-based capacity sharing	1	16,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	0	P	2750	2000	7500			
		4	2000	S	0	0	0			
				B	2450	2000	6900			
				J	0	2000	2000			
38	Tsunami, PS-based capacity sharing	1	16,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	1000	P	2750	3000	7500			
		4	2000	S	0	1000	0			
				B	2450	2000	6900			
				J	0	2000	2000			
39	Tsunami, PSB-based capacity sharing	1	16,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	1600	P	2750	3000	7500			
		4	2000	S	0	2000	0			
				B	3050	2000	7500			
				J	0	2000	2000			
40	Tsunami, PB-based capacity sharing & restricted investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
41	Tsunami, PS-based capacity sharing & restricted investment	1	18,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	2836	P	2320	4836	8476	1500		
		4	2000	S	0	2836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
42	Tsunami, PSB-based capacity sharing & restricted investment	1	18,000	A	0	16,000	16,000			
		2	2000	E	0	18,000	18,000			
		3	3000	P	2000	5000	8000	892		
		4	2000	S	0	3000	1000	1456		
				B	2000	2000	5000			
				J	0	2000	2000			
43	Tsunami, PB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	1836	P	2320	3836	8476	1500		
		4	2000	S	0	1836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
44	Tsunami, PS-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	2836	P	2320	4836	8476	1500		
		4	2000	S	0	2836	1836	2900		
				B	1339	2000	4678			
				J	0	2000	2000			
45	Tsunami, PSB-based capacity sharing & cross-port investment	1	18,000	A	0	18,000	18,000			
		2	2000	E	0	20,000	20,000			
		3	3000	P	2000	5000	8000	1000		
		4	2000	S	0	3000	1000	1500		
				B	2000	2000	5000			
				J	0	2000	2000			
46	Hurricane, no strategy	1	3000	A	0	3000	3000			
		2	2000	E	0	5000	5000			

(*continued on next page*)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
		3	3000	P	0	5000	5000			
		4	2000	S	0	3000	3000			
				B	2000	2000	6000			
				J	0	2000	2000			
47	Hurricane, Restricted investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
48	Hurricane, unrestricted investment	1	9224	A	0	9224	9224	6000		
		2	2000	E	0	11,224	11,224		A	6000
		3	3000	P	0	3175	3175	1500		
		4	2000	S	0	1175	1175			
				B	2000	2000	6000			
				J	0	2000	2000			
49	Hurricane, PB-based cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
50	Hurricane, PS-based cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
51	Hurricane, PSB-based cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
52	Hurricane, PB-based capacity sharing	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
53	Hurricane, PS-based capacity sharing	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
54	Hurricane, PSB-based capacity sharing	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
55	Hurricane, PB-based capacity sharing & restricted investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
56	Hurricane, PS-based capacity sharing & restricted investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
57	Hurricane, PSB-based capacity sharing & restricted investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		

(*continued on next page*)

(*continued*)

Run	Strategy and scenario	OD	Flow	Port	Port throughput			Investment		
					Transshipment	Land-sea	Total	Internal	To port	External
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
58	Hurricane, PB-based capacity sharing & cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
59	Hurricane, PS-based capacity sharing & cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			
60	Hurricane, PSB-based capacity sharing & cross-port investment	1	6518	A	0	6518	6518	6000		
		2	2000	E	0	8518	8518			
		3	3000	P	1738	5000	8476	1500		
		4	2000	S	0	3000	3000			
				B	263	2000	2526			
				J	0	2000	2000			

References

Asadabadi, A., Miller-Hooks, E., 2020. Maritime port network resiliency and reliability through co-opetition. Transport. Res. Part E: Logist. Transport. Rev. 137, 101916.

Achurra-Gonzalez, P.E., Novati, M., Foulser-Piggott, R., Graham, D.J., Bowman, G., Bell, M.G.H., Angeloudis, P., 2019. Modelling the impact of liner shipping network perturbations on container cargo routing: Southeast Asia to Europe application. Accid. Anal. Prev. 123, 399–410.

Asadabadi, A., Miller-Hooks, E., 2018. Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach. Transport. Res. Part B: Methodol. 108, 281–298.

Asgari, N., Farahani, R.Z., Goh, M., 2013. Network design approach for hub ports-shipping companies competition and cooperation. Transport. Res. Part A: Policy Practice. 48, 1–18.

Agarwal, R., Özlem, E., 2010. Network design and allocation mechanisms for carrier alliances in liner shipping. Oper. Res. 58 (6), 1726–1742.

Agarwal, R., Ergun, Ö., 2008. Mechanism design for a multicommodity flow game in service network alliances. Oper. Res. Lett. 36 (5), 520–524.

Angeloudis, P., Bichou, K., Bell, M., 2013. Security and reliability of the liner container-shipping network: analysis of robustness using a complex network framework. In: Chap.6 in *Risk Management in* Port Operations, Logistics and Supply Chain Security. Informa Law from Routledge, pp. 129–140.

Bell, M.G.H., Liu, X., Rioult, J., Angeloudis, P., 2013. A cost-based maritime container assignment model. Transport. Res. Part B: Methodol. 58, 58–70.

Ball, M., Hoffman, R., Knorr, D., Wetherly, J., 2000. Assessing the Benefits of Collaborative Decision Making in Air Traffic Management Process. Presented at 3rd USA/Europe Air Traffic Management R & D Seminar, Naples, Italy.

Chang, K., Howard, K., Oiesen, R., Shisler, L., Tanino, M., Wambsganss, M.C., 2001. Enhancements to the FAA Ground Delay Program under Collaborative Decision Making. Interfaces. 31 (1), 57–76.

Carlson, P.M., 2000. Exploiting the Opportunities of Collaborative Decision Making: a Model and Efficient Solution Algorithm for Airline Use. Transport. Sci. 34 (4), 381–393.

Fortuny-Amat, J., McCarl, B., 1981. A representation and economic interpretation of a two-level programming problem. J. Oper. Res. Soc. 32 (9), 783–792.

Guo, L., Yang, D., Yang, Z., 2018. Port integration method in multi-port regions (MPRs) based on the maximal social welfare of the external transport system. Transport. Res. Part A: Policy Practice. 110, 243–257.

Gabriel, S., Conejo, A., Fuller, J., Hobbs, B., Ruiz, C., 2012. Complementarity Modeling in Energy Markets. Springer Science & Business Media.

Groothedde, B., Ruijgrok, C., Tavasszy, L., 2005. Towards Collaborative Intermodal Hub Networks: A Case Study in the Fast Moving Consumer Goods Market. Transport. Res. Part E: Logist. Transport. Rev. 41 (6), 567–583.

Godfrey, G.A., Hellings, C., Knutsen, A., 2004. A multi-agent framework for collaborative airlift planning using commercial air assets. Mathe. Comput. Model. 39 (6-8), 885–896.

Hoshino, H., 2010. Competition and collaboration among container ports. Asian J. Shipping Logist. 26 (1), 31–47.

Kuo, A., Miller-Hooks, E., Zhang, K., Mahmassani, H., 2008. Train Slot Cooperation in Multicarrier, International Rail-BasedIntermodal Freight Transport. Transport. Res. Rec. 2043 (1), 31–40.

Li, C., Qi, X., Song, D., 2016. Real-time schedule recovery in liner shipping service with regular uncertainties and disruption events. Transport. Res. Part B: Methodol. 93, 762–788.

Li, W., Pundt, R., Miller-Hooks, E., 2021. An updatable and comprehensive global cargo maritime network and strategic seaborne cargo routing model for global containerized and bulk vessel flow estimation. Maritime Transport Res. 2, 100038.

Moghaddam, M., Nof, S.Y., 2014. Combined demand and capacity sharing with best matching decisions in enterprise collaboration. Int. J. Prod. Econ. 148, 93–109.

Nair, R., Avetisyan, H., Miller-Hooks, E., 2010. Resilience framework for ports and other intermodal components. Transport. Res. Rec.: J. Transport. Res. Board. 2166 (1), 54–65.

Nalebuff, B., Brandenburger, A., Maulana, A., 1996. Co-opetition. Harper Collins Business, London.

Omer, M., Mostashari, A., Nilchiani, R., Mansouri, M.o., 2012. A framework for assessing resiliency of maritime transportation systems. Maritime Policy Manage. 39 (7), 685–703.

Paul, J., Maloni, M., 2010. Modeling the effects of port disasters. Maritime Econ. Logist. 12 (2), 127–146.

Panayides, P., Wiedmer, R., 2011. Strategic alliances in container liner shipping. Res. Transport. Econ. 32 (1), 25–38.

Peng, Y., Wang, W., Guo, Z., Song, X., Zhang, Q.i., 2016. A stochastic seaport network retrofit management problem considering shipping routing design. Ocean Coastal Manage. 119, 169–176.

Python, G., Wakeman, T., 2016. Collaboration of port members for supply chain resilience. Ports 2016, 371–380.
Ruan, X., Feng, X., Pang, K., 2018. Development of port service network in OBOR via capacity sharing: an idea from Zhejiang province in China. Maritime Policy Manage. 45 (1), 105–124.
Shafieezadeh, A., Ivey Burden, L., 2014. Scenario-based resilience assessment framework for critical infrastructure systems: Case study for seismic resilience of seaports. Reliability Eng. Syst. Safeway. 132, 207–219.
Seok, H., Nof, S.Y., 2014. Collaborative capacity sharing among manufacturers on the same supply network horizontal layer for sustainable and balanced returns. Int. J. Prod. Res. 52 (6), 1622–1643.
Wang, S., Meng, Q., 2012a. Liner ship route schedule design with sea contingency time and port time uncertainty. Transport. Res. Part B: Methodol. 46 (5), 615–633.
Wang, S., Meng, Q., 2012b. Robust schedule design for liner shipping services. Transport. Res. Part E: Logist. Transport. Rev. 48 (6), 1093–1106.
Sherali, H.D., Staats, R.W., Trani, A.A., 2003. An Airspace Planning and Collaborative Decision-Making Model: Part I. Probabilistic Conflicts, Workload, and Equity Considerations. Transport. Sci. 37 (4), 434–456.
Yu, Y., Benjaafar, S., Gerchak, Y., 2015. Capacity sharing and cost allocation among independent firms with congestion. Prod. Oper. Manage. 24 (8), 1285–1310.
Yang, Z., Ng, A., Lee, P., Wang, T., Rodrigues, V., Pettit, S., Harris, I., 2015. Modelling risk based cost analysis of port adaptation measures to climate change. Paper presented at Soochow University Conference.
Zheng, J., Gao, Z., Yang, D., Sun, Z., 2015. Network design and capacity exchange for liner alliances with fixed and variable container demands. Transport. Sci. 49 (4), 886–899.