RESEARCH REPORT

VESSEL SCHEDULE DESIGN AND CONTAINER DIVERSION PROBLEM

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ABSRACT
This report proposes a methodology and a mathematical model for liner shipping companies to make sustainable decisions in case of port disruptions. It is assumed that the liner shipping company is able to skip a port of call, where disruption occurred, and divert containers to alternative ports of call, taking into account their excess port handling and inland transport capacities and costs, associated with service of the diverted demand. The objective of mathematical model minimizes the additional route service costs due to port disruptions. Numerical experiments are conducted for Pacific Atlantic 1 shipping route, served by NYK liner shipping company. Results showcase that the suggested methodology can yield substantial cost savings.

INTRODUCTION

Port disruptions negatively affect liner shipping operations and result in substantial vessel handling and cargo delivery delays. The Journal of Commerce (*1*) indicated that container volumes in the Port of Los Angeles decreased by 22.7% in January 2015 and by 10.2% in February 2015 due to long congestion periods and labor issues. The United States (U.S.) West Coast laden traffic declined by 12% in the first three months of 2015. Certain vessels were diverted from the U.S. West Coast to East and Gulf Coast ports. The Federal Maritime Commission reported that 2014 was the most active year for the U.S. cargo diversion (*2*).

Some experts underline that port congestion can be caused not only by peak-season volumes, but also by inability of container terminal operators to efficiently handle increasing quantities of large size vessels. According to the Journal of Commerce (*3*), around 50% of Post-Panamax vessels faced more than 12 hour delays at North and South American ports in July 2014. On the other hand, World Shipping Council (*4*) highlights that size of vessels is not the only factor, causing port congestion. Factors, affecting the port performance, include: labor productivity issues (e.g., strikes in the Port of Los Angeles); inefficiency of transportation infrastructure, connected to the marine terminal (roadway and rail); disruptions at marine terminals; lack of storage capacity; unexpected surges in container volumes (e.g., diversion of cargo from the U.S. West Coast to the East Coast in 2015); hours of operation; weather conditions; reliability of vessel schedules, etc.

Furthermore, the U.S. West Coast and Asia have potential earthquake hazard that may cause a complete port closure, and after re-opening the port may still not be able to operate at full capacity for some time. For example, reconstruction of Kobe Port facilities (Japan) after earthquake in 1995 was completed in March 1997 (*5*). Taking into account increasing volumes of containerized trade and increasing port concentration, liner shipping companies intend to improve efficiency of their operations in order to handle the growing demand and develop strategies that will alleviate negative externalities, which may be caused by port congestion and port disruptions.

This report proposes a methodology for liner shipping companies to make sustainable and timely decisions in case of port disruptions. According to the proposed methodology, the liner shipping company is able to skip the port of call, where the disruption occurred, and divert containers to alternative ports of call, taking into account their excess port handling and inland transport capacities and costs, associated with service of the diverted demand. The remainder of the paper is organized as follows. The next section presents an up-to-date review of studies, modeling port handling uncertainty and port disruptions in liner shipping. The third section provides the problem description, while the fourth section presents a mixed integer mathematical model for the problem. The fifth section describes numerical experiments, conducted to showcase applicability of the proposed methodology, while the last section outlines conclusions and future research directions.

LITERATURE REVIEW

Taking into account increasing seaborne trade volumes, liner shipping operations receive an increasing attention from the research community. For a detailed overview of liner shipping literature we refer to Meng et al. (*6*). Decisions that have to be made by a liner shipping company can be divided into three groups: a) strategic (long-term), b) tactical (medium-term), and c) operational (short-term). Long-term decisions include vessel fleet size and mix, alliance strategy, and network design, while medium-term decisions focus on service frequency determination, fleet deployment, sailing speed optimization, and construction of the vessel schedule. At the operational level the liner shipping company has to decide on cargo booking, cargo routing, vessel rescheduling and potential reject of cargo. All decision problems receive an increasing attention from the research community. The literature review presented herein is focused on studies, modeling port handling time uncertainty and port disruptions in liner shipping.

Chuang et al. (*7*) developed a fuzzy Evolutionary Algorithm to solve the containership routing problem, taking into account uncertainty in demand, vessel sailing speeds, and port handling times. The objective aimed to maximize the total profit, estimated as difference between the total revenue and the total route expenses. The route cost included voyage costs and port handling costs. A fuzzy logic based on the triangular distributions was applied for modeling uncertainty in demand, vessel sailing speeds, and port handling times. Numerical experiments demonstrated efficiency of the proposed methodology and the solution approach. Qi and Song (*8*) studied the vessel schedule design problem, considering the impact of port time uncertainty. The objective aimed to minimize the total expected fuel consumption and penalties due to vessel delays. Simulation-based stochastic approximation methods were employed to solve the problem. The port times were assumed to follow the uniform distribution. Six scenarios with different levels of port time uncertainty were considered. Computational examples indicated that increasing uncertainty in port times caused greater fuel consumption for a given route.

Wang and Meng (*9*) presented a liner shipping route schedule model, capturing uncertainty in sailing and port times. The objective of a mixed integer non-linear program minimized the total transportation cost, including weekly vessel operating cost and bunker cost. Port time contingency was modeled using the uniform distribution, while uncertain sailing time was estimated based on realization of a port time and an additional parameter, denoting hedge against contingency (proportional to the length of a voyage leg). The original program was reformulated as a linear problem and solved using CPLEX. A computational example was provided for the Asia-Europe-Oceania shipping network. It was found that sailing and port time contingency could require deployment of more vessels on a given route. Lower speeds were suggested for scenarios with high fuel costs. Wang and Meng (*10*) studied a liner shipping route scheduling problem, taking into account possible uncertainties in port waiting times (due to congestion) and container handling times. The objective of a mixed integer non-linear program minimized the total transportation cost, including three components: 1) weekly vessel operating cost, 2) bunker cost, 3) late handling cost. Uncertainties in port waiting and handling times were modeled using the truncated normal distributions. The original problem was linearized and solved using CPLEX. Sample average approximation (SAA) was used to estimate the expected values for stochastic port waiting and handling times. Numerical experiments were conducted for the Asia-America-Europe liner shipping route. It was found that a liner shipping company could improve robustness of its schedule by adding more vessels.

Yao et al. (*11*) developed a bunker fuel management strategy for liner shipping companies. The objective of a mixed integer non-linear model minimized the total bunker consumption cost and revenue loss due to weight of the bunker fuel. The authors presented empirical models, defining relationship between fuel consumption and sailing speed for different types of vessels. Port time was assumed to be known for each vessel. Various ports offered different fuel prices and discounts (depending on the volume of purchased fuel). The original model was linearized using a piecewise approximation method and solved using CPLEX. Numerical experiments were provided for the Asia-Europe-Express and the Atlantic-Pacific-Express service routes. It was found that port time windows increased the bunker related costs as compared to the case, when port time windows were relaxed. Furthermore, skipping certain minor feeder ports might decrease the total bunker related costs. Brouer et al. (*12*) studied a Vessel Schedule Recovery Problem (VSRP), taking into account disruptions that might occur in liner shipping. The problem was formulated as a mixed integer linear program. The following disruptive scenarios were modeled: a) vessel delays due to weather conditions, b) a port closure, c) a berth prioritization, when two vessels arrive simultaneously at the port and are scheduled at the same berth, and d) an expected port congestion. The following countermeasures were suggested to mitigate effects from the uncertainty: a) port omitting, b) increasing vessel speed, c) swap ports of call, and d) accept vessel delays. Generated problem instances were solved using CPLEX. It was found that the suggested methodology could yield up to 58% if the total cost savings.

PROBLEM DESCRIPTION

In this study we consider a liner shipping route with $I = \{1, \ldots, n\}$ ports of call (see Figure 1A). Each port is assumed to be visited once a week, and the sequence of visited ports (i.e., port rotation) is already known. The latter decision is made by a liner shipping company at the strategic level. The link between ports *i* and *i+1* is called leg *i*. If a given port of call is visited more than once during the voyage, an additional node is added to the graph to account for the second visit to the same port. For example, in liner shipping route, presented in Figure 2A, a total of 4 ports are served. Ports 1 and 2 are visited twice; hence, two additional nodes 1’ and 2’ are introduced to the graph, and the total number of ports to be visited will be $|I| = 4 + 2 = 6$ (see Figure 2B).

Weekly demand in TEUs at each port is known. The arrival time and the container handling rate at each port of call and the vessel sailing speed between subsequent ports are already established by the liner shipping company at the tactical level. We refer to Meng et al. (*6*) for a discussion on the vessel routing and scheduling problem in liner shipping at the strategic, tactical and operational levels.

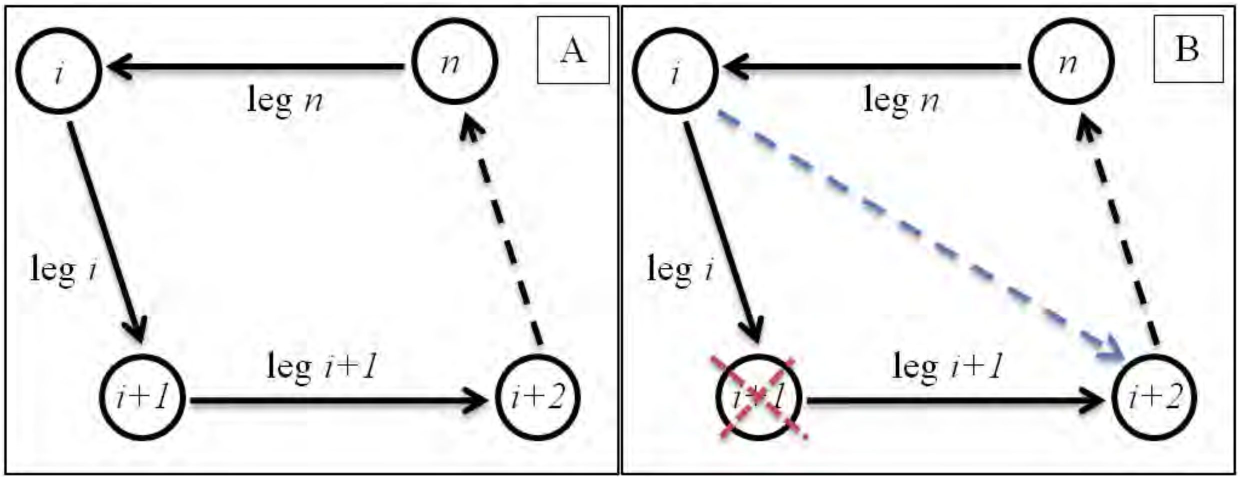

FIGURE 1 Illustration of a Shipping Route: A-Before Disruption, B-After Disruption.

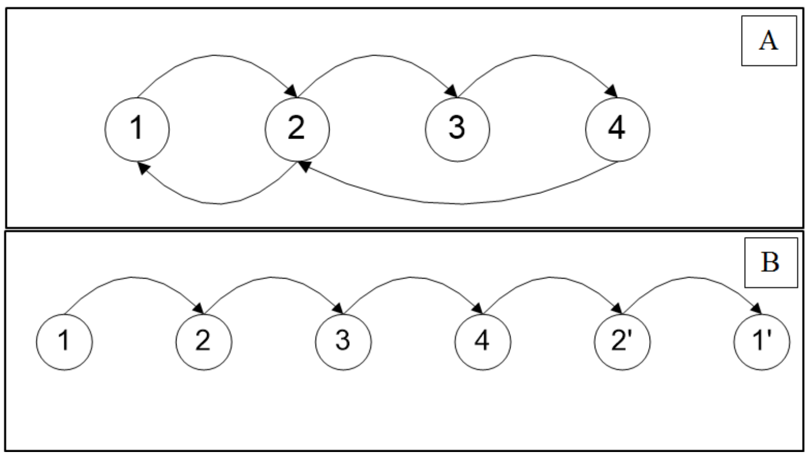

FIGURE 2 Visit of the Same Ports during the Voyage.

Vessel Service at Ports

It is assumed that the liner shipping company is able to skip a given port of call in case of a disruptive event (see Figure 1B). The disruption occurs after a given vessel leaves the port of origin. This assumption is crucial, since changes to the port rotation once the vessel leaves the port of origin are highly unlikely. If a port is skipped, the sequence of consecutive ports in the port rotation remains unchanged, and the liner shipping company has to divert containers, originally intended for discharge at the skipped port, to alternative port(s) belonging to the same port rotation. It is assumed that the liner shipping company can negotiate with (a subset of) marine container terminal operators on excess handling capacity, where containers may be potentially diverted. A candidate port for container diversion will be constrained on two major factors: 1) port location (e.g., cargo from the Port of Los Angeles can be diverted to the Port of Savannah, but cannot be diverted to the Port of Shanghai), and 2) adequate port handling and intermodal capacities.

The decision on where to divert cargo is based on the cost minimization. The liner shipping company will be charged an additional cost per TEU at any port, selected for cargo diversion. The liner shipping company is also expected to pay a penalty for skipping the disrupted port. This penalty compensates the terminal operator for the unmet demand (i.e., exports that will not be loaded on a vessel because of skipping the port), reserved port handling equipment and storage space, and reserved inland transport capacity. Depending on the contractual agreement between the terminal operator and the liner shipping company (including the relationship between the two, e.g. dedicated vs. multi-user terminal) this penalty may be omitted or imposed on the annual basis (i.e., not for a single skip). The skipped port may be visited on the return voyage to pick up export containers. If this decision is not supported, export containers can be loaded on the next vessel, calling the port, or on a vessel from alliance partner(s), and an additional cost will be paid to the latter to compensate for the additional demand (*12*). Furthermore, the liner shipping company has to account for the additional service time costs at each port, where cargo is diverted (incurred due to the additional diverted demand). The additional service time cost includes: 1) the cost of delays at the port, where the cargo will be diverted, and 2) the cost of inland transportation delay. The additional service time cost is assumed to be linearly increasing with the number of TEUs diverted at each port.

If the liner shipping company chooses not to skip port i and endure the delay, a penalty cost is applied from delayed arrivals at the subsequent ports of call. These costs may stem from request of service outside an agreed time window, additional dwell time of export containers, import containers not delivered on time, etc. The objective of the model presented herein is to account for all these different costs/delays and optimally decide on cargo diversion/port rotation.

Inland Service

Once containers are unloaded at each port, inland transport operators (i.e., trucking companies and/or rail companies) are responsible for delivering the cargo to the inland destinations. It is assumed that the liner shipping company can negotiate with certain inland operators on excess capacity at each port, where the cargo will be diverted. The liner shipping company will be charged an additional cost for inland transport of the diverted cargo. It is assumed that diversion can only take place, if both excess port handling and inland transport capacities are sufficient. As it is highly unlikely that one port/inland transport system can handle all of the diverted demand, the model assumes that cargo can be diverted to multiple ports.

Decisions

The problem, considered in this study, can be classified as an operational level problem and will be referred to as the vessel schedule design and container diversion problem ***VSDCDP.*** In this problem the liner shipping company has two choices: a) do not skip the port with disruptions, or b) skip the port with disruptions and divert demand to other ports in the port rotation. The goal of the proposed mathematical model is to determine if the disrupted port will be skipped and how the cargo, originally intended for discharge at that port, will be distributed among the remaining ports in the port rotation. The objective is to minimize the total additional route service cost due to port disruptions and/or cargo diversion. The main contribution of this research is that diversion decisions are made by considering both the ability of the ports and the inland transport network to handle the diverted cargo.

MODEL FORMULATION

In this section we present the basic notations used throughout the paper, followed by the mixed integer mathematical model for the vessel schedule design and container diversion problem **VSDCDP**. Additional notations will be defined as needed.

Nomenclature

Sets

$I = \{1, \dots, n\}$	set of ports to be visited

Decision variables

$x_i\ \forall i \in I$	=1 if port i is skipped (=0 otherwise)
$y_{ij}\ \forall i, j \in I, i \neq j$	=1 if containers are diverted from port i to candidate port j (=0 otherwise)
$z_j\ \forall j \in I$	=1 if containers are diverted to candidate port j (=0 otherwise)

Auxiliary variables

$NCD_{ij}\ \forall i, j \in I, i \neq j$	number of containers diverted from port i to candidate port j (TEUs)
$LD_i\ \forall i \in I$	hours of late departure from port i (hrs.)
$HAS_j\ \forall j \in I$	hours of additional service time due to handling the diverted demand at candidate port j (hrs.)

Parameters

$d_i\ \forall i \in I$	=1 if there is a disruption at port i (=0 otherwise)
$NC_i\ \forall i \in I$	container demand at port i (TEUs)
$c_j^p\ \forall j \in I$	excess handling capacity at candidate port j (TEUs)
$c_j^{in}\ \forall j \in I$	excess inland capacity at candidate port j (TEUs)
$TLD_i\ \forall i \in I$	total expected vessel delay at port i, caused by disruption (hrs.)
$a_j\ \forall i \in I$	cost of handling the diverted demand at port j (USD/TEU)
$b_{ij}\ \forall i, j \in I, i \neq j$	average cost per TEU of inland transport of the diverted demand from port i at candidate port j (USD/TEU)
$p_i^s\ \ \forall i \in I$	penalty for skipping port i (USD)
$p_i^l\ \ \forall i \in I$	late arrival penalty to subsequent ports, caused by disruption at port i (USD/hr.)
$\delta_j\ \forall j \in I$	delayed service coefficient at candidate port j (hrs./TEU)
$p_j^{as}\ \ \forall j \in I$	cost of additional service time at candidate port j due to handling the diverted demand (USD/hr.)

VSDCDP

The objective function (1) minimizes the additional route service cost due to port disruptions, which includes 4 components: 1) total penalty for skipping a port, 2) total port handling cost for the diverted demand, 3) total inland transport cost for the diverted demand, 4) total late departure penalty due to disruptions, and 5) total cost of additional service time at alternative ports of call due to handling the diverted demand.

$$\min[\sum_{i\in I} p_i^s x_i + \sum_{i\in I}\sum_{j\in I: j\neq i} NCD_{ij} a_j + \sum_{i\in I}\sum_{j\in I: j\neq i} NCD_{ij} b_{ij} + \sum_{i\in I} LD_i p_i^l + \sum_{j\in I: j\neq i} HAS_j p_j^{as}] \quad (1)$$

Subject to:

Constraints set (2) ensure that the vessel can skip port i only in case of a disruption.

$$x_i \leq d_i \ \forall i \in I \quad (2)$$

Constraints set (3) indicate that containers can be diverted from port i to j only if port i is skipped.

$$y_{ij} \leq x_i \ \forall i, j \in I, i \neq j \quad (3)$$

Constraints set (4) ensure that candidate port j is selected for diversion if containers are to be moved from one of the ports, where the disruption occurred.

$$z_j \leq \sum_{i\in I: i\neq j} y_{ij} \ \forall j \in I \quad (4)$$

Constraints set (5) indicate that the total number of diverted containers does not exceed the port handling capacity.

$$\sum_{i\in I: i\neq j} NCD_{ij} \leq c_j^p z_j \ \forall j \in I \quad (5)$$

Constraints set (6) ensure that the total number of diverted containers does not exceed the inland transport capacity.

$$\sum_{i\in I: i\neq j} NCD_{ij} \leq c_j^{in} z_j \ \forall j \in I \quad (6)$$

Constraints set (7) indicate that the number of diverted containers should be equal to the total number of containers that were not handled at port i because of a disruption.

$$\sum_{j\in J: j\neq i} NCD_{ij} = NC_i x_i \ \forall i \in I \quad (7)$$

Constraints set (8) ensure that if the cargo is to be diverted from port i to j, the number of containers should be greater than zero.

$$y_{ij} \leq NCD_{ij} \ \forall i, j \in I, i \neq j \quad (8)$$

Constraints set (9) compute hours of late departure from port i, caused by a disruption (if a vessel does not skip port i in case of a disruption).

$$LD_i = TLD_i d_i (1 - x_i) \ \forall i \in I \quad (9)$$

Constraints set (10) calculate hours of additional service time at port j due to handling the diverted demand.

$$HAS_j = \delta_j \sum_{i \in I: i \neq j} NCD_{ij} \ \forall j \in I \quad (10)$$

Constraints (11) – (13) define ranges of parameters and variables.

$$x_i, y_{ij}, z_j, d_i \in \{0,1\} \ \forall i, j \in I, i \neq j \quad (11)$$

$$NCD_{ij}, NC_i \in N \ \forall i, j \in I, i \neq j \quad (12)$$

$$LD_i, c_j^p, c_j^{in}, TLD_i, HAS_j, a_j, b_{ij}, p_i^s, p_i^l, p_j^{as}, \delta_j \in R^+ \ \forall i, j \in I, i \neq j \quad (13)$$

VSDCDP can be solved efficiently using CPLEX even for large size problem instances (see numerical experiments section for examples).

NUMERICAL EXPERIMENTS

This section provides computational examples to showcase how the developed mathematical model can be used for container diversion decision making by a liner shipping company in case of disruptive events.

Input Data Description

This study considers Pacific Atlantic 1 route (see Figure 2[1]), served by NYK liner shipping company. This route connects Asia, U.S. West Coast, Panama, and U.S. East Coast. The port rotation for Pacific Atlantic 1 route includes 21 ports of call:

1. Shanghai → 2. Busan → 3. Kobe → 4. Nagoya → 5. Tokyo → 6. Tacoma → 7. Vancouver → 8. Oakland → 9. Los Angeles → 10. Manzanillo → 11. Savannah → 12. Norfolk → 13. New York → 14. Halifax → 15. New York → 16. Norfolk → 17. Savannah → 18. Manzanillo → 19. Los Angeles → 20. Oakland → 21. Yokohama → 1. Shanghai

[1] https://www2.nykline.com/liner/service_network/pdf/pa1_pacific.pdf

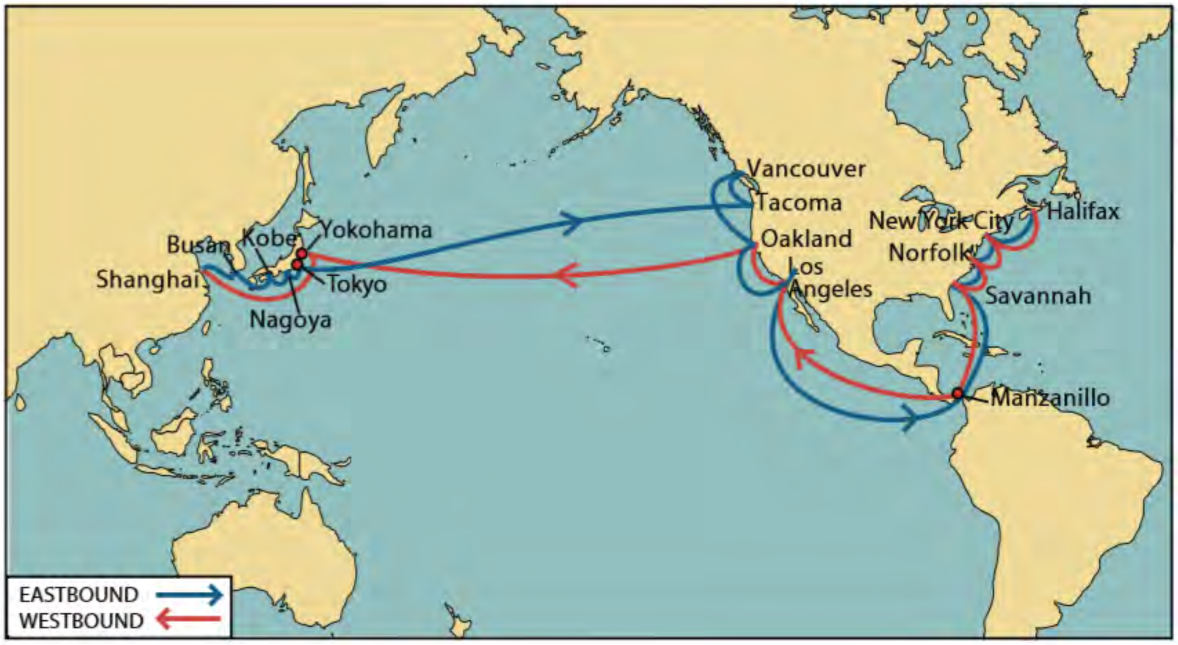

FIGURE 2 Pacific Atlantic 1.

Numerical data were generated using the available liner shipping literature and are presented in Table 1. Weekly demand NC_i at large ports was assigned as $U[500; 2{,}000]$ TEUs, where U denotes uniformly distributed pseudorandom numbers. Note that term "large port" was applied to those ports of call, if they were included in the list of top 20 world container ports based on their throughput (*13*). Weekly demand for smaller ports was generated as $U[200; 1{,}000]$ TEUs. Excess handling capacity c_j^p at each candidate port for container diversion was assigned as $c_j^p = U[200; 500]\ \forall j \in I$ (TEUs). Excess inland capacity at each candidate port for container diversion was generated as $c_j^{in} = U[200; 500]\ \forall j \in I$ (TEUs). The expected vessel delay at port i, caused by the disruption, was assumed to be $TLD_i = U[60; 100]\ \forall i \in I$ (hrs.). Based on the available literature (*14, 15*) and assuming a mix of vessel operations that include mooring, loading and discharge of containers, type of container (empty, loaded, size, reefer), re-stowing (on-board the vessel or via quay), the container handling cost was set equal to $a_j = U[400; 600]\ \forall j \in I$ USD/TEU. The average inland transport cost was assigned as $b_{ij} = U[1200; 1800]\ \forall i, j \in I, i \neq j$ USD/TEU (*16*). The penalty for skipping port i in case of disruption was assigned based on the container demand, average port handling costs ($\frac{400+600}{2} = 500$ USD), and average inland transport costs ($\frac{1{,}200+1{,}800}{2} = 1{,}500$ USD): $p_i^s = \gamma \times NC_i \times (500 + 1{,}500)$ USD, where $\gamma = 1.1$ is the inconvenience coefficient. The cost of late vessel arrival at port i was generated as $plh_i = U[5{,}000; 10{,}000]\ \forall i \in I$ USD/hr. (*17*). If a vessel waits for service at port i until the end of disruption, the late arrival penalty to subsequent ports of the given route was computed as follows: $p_i^l = \sum_{i=i+1}^{n}(plh_i)\ \forall i \in I$ (USD/hr.). The cost of additional service time at candidate port j due to handling the diverted demand was assigned as $p_j^{as} = U[5{,}000; 10{,}000]\ \forall j \in I$ (USD/hr.), while the delayed service coefficient was generated as $\delta_j =$

$U[0.01; 0.03]\ \forall j \in I$ (hrs./TEU). Different disruptive scenarios for the selected liner shipping route will be analyzed next using the developed mathematical model.

TABLE 1 Numerical Data

Container demand at large ports NC_i (TEUs)	$U[500; 2{,}000]$
Container demand at smaller ports NC_i (TEUs)	$U[200; 1{,}000]$
Excess port handling capacity c_j^p (TEUs)	$U[200; 500]$
Excess inland capacity c_j^{in} (TEUs)	$U[200; 500]$
Expected vessel delay due to disruption TLD_i (hrs.)	$U[60; 100]$
Cost of handling the diverted demand a_j (USD/TEU)	$U[400; 600]$
Cost of inland transport of the diverted demand b_{ij} (USD/TEU)	$U[1200; 1800]$
Port skipping inconvenience coefficient γ	1.1
Penalty for skipping port in case of disruption p_i^s (USD)	$\gamma \times NC_i \times (500 + 1500)$
Late vessel arrival penalty at port i (USD/hr.)	$U[5{,}000; 10{,}000]$
Late arrival penalty at subsequent ports due to disruption p_i^l (USD/hr.)	$\sum_{i=i+1}^{n}(plh_i)$
Cost of additional service time p_j^{as} (USD/hr.)	$U[5{,}000; 10{,}000]$
Delayed service coefficient δ_j (hrs./TEU)	$U[0.01; 0.03]$

Scenario Analysis

A total of 6 disruptive scenarios were considered. **VSDCDP** was solved for each one of the scenarios. The modeled scenarios and results are discussed next and presented in Table 2. Table 2 provides the following information: 1) scenario number; 2) disruption features; 3) decisions, suggested by **VSDCDP**, 4) disruption costs DC (i.e., **VSDCDP** objective), and 5) savings from the decisions SD - how much the liner shipping company will save from making decisions, suggested by **VSDCDP**, vs. the opposite decisions (e.g., skipping the port and diverting containers vs. not skipping the port and waiting until the end of disruption).

Scenario-1: Disruption at the Port of Los Angeles. There is a disruption at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs. **VSDCDP** suggests skipping the Port of Los Angeles and diverting the container demand of 800 TEUs from the Port of Los Angeles to the Port of Savannah (300 TEUs) and to the Port of Norfolk (500 TEUs).

Scenario-2: Disruption at the Port of Los Angeles, limited port handling capacity at the Port of Savannah. There is a disruption at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs. The excess handling capacity at the Port of Savannah is limited to 200 TEUs. **VSDCDP** suggests skipping the Port of Los Angeles and diverting the container demand of 800 TEUs from the Port of Los Angeles to the Port of Savannah (200 TEUs), the Port of Norfolk (500 TEUs), and the Port of Halifax (100 TEUs).

Scenario-3: Disruption at the Port of Los Angeles, limited port handling capacity at the Port of Savannah, limited inland transport capacity at the Port of Norfolk. There is a disruption at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs. The excess handling capacity at the Port of Savannah is limited to 200 TEUs. The excess inland transport capacity at the Port of Norfolk is limited to 200 TEUs. **VSDCDP** suggests skipping the Port of Los Angeles and diverting the container demand of 800 TEUs from the Port of Los Angeles to the Port of Savannah (200 TEUs), the Port of Norfolk (200 TEUs), and the Port of Halifax (400 TEUs).

Scenario-4: Disruptions at the Port of Los Angeles and the Port of Savannah. There are two disruptions at the given service route. One of disruptions occurred at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs., and the other disruption occurred at the Port of Savannah with expected duration of $TLD_{11} = 90$ hrs. **VSDCDP** suggests skipping the Port of Los Angeles and the Port of Savannah. The container demand of 800 TEUs should be diverted from the Port of Los Angeles to the Port of Norfolk (500 TEUs) and the Port of Halifax (300 TEUs). The container demand of 400 TEUs should be diverted from the Port of Savannah to the Port of New York (400 TEUs).

Scenario-5: Disruptions at the Port of Los Angeles and the Port of Savannah, limited port handling capacity at the Port of Norfolk. There are two disruptions at the given service route. One of disruptions occurred at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs., and the other disruption occurred at the Port of Savannah with expected duration of $TLD_{11} = 90$ hrs. The excess handling capacity at the Port of Norfolk is limited to 400 TEUs. **VSDCDP** suggests skipping the Port of Los Angeles and the Port of Savannah. The container demand of 800 TEUs should be diverted from the Port of Los Angeles to the Port of Norfolk (400 TEUs) and the Port of Halifax (400 TEUs). The container demand of 400 TEUs should be diverted from the Port of Savannah to the Port of New York (400 TEUs).

TABLE 2 Scenario Analysis Results

Scenario	Disruption Features	Decisions	DC, 10^6 USD	SD, %
1	Disruption at the Port of Los Angeles	Skip the Port of Los Angeles; Divert containers to the Port of Savannah (300 TEUs) and the Port of Norfolk (500 TEUs)	3.18	65.1
2	Disruption at the Port of Los Angeles, limited port handling capacity at the Port of Savannah	Skip the Port of Los Angeles; Divert containers to the Port of Savannah (200 TEUs), the Port of Norfolk (500 TEUs), and the Port of Halifax (100 TEUs)	3.22	64.6
3	Disruption at the Port of Los Angeles, limited port handling capacity at the Port of Savannah, limited inland transport capacity at the Port of Norfolk	Skip the Port of Los Angeles; Divert containers to the Port of Savannah (200 TEUs), the Port of Norfolk (200 TEUs), and the Port of Halifax (400 TEUs)	3.35	63.2
4	Disruptions at the Port of Los Angeles and the Port of Savannah	Skip the Port of Los Angeles and the Port of Savannah; Divert containers to the Port of Norfolk (500 TEUs), the Port of Halifax (300 TEUs), and the Port of New York (400 TEUs)	5.54	65.1
5	Disruptions at the Port of Los Angeles and the Port of	Skip the Port of Los Angeles and the Port of Savannah; Divert containers	5.58	64.8

	Savannah, limited port handling capacity at the Port of Norfolk	to the Port of Norfolk (400 TEUs), the Port of Halifax (400 TEUs), and the Port of New York (400 TEUs)		
6	Disruptions at the Port of Los Angeles and the Port of Savannah, limited port handling capacity at the Port of Norfolk, limited inland transport capacity at the Port of Halifax	Skip the Port of Los Angeles and the Port of Savannah; Divert containers to the Port of Norfolk (400 TEUs), the Port of Halifax (300 TEUs), and the Port of New York (500 TEUs)	5.60	64.7

Scenario-6: Disruptions at the Port of Los Angeles and the Port of Savannah, limited port handling capacity at the Port of Norfolk, limited inland transport capacity at the Port of Halifax. There are two disruptions at the given service route. One of disruptions occurred at the Port of Los Angeles with expected duration of $TLD_9 = 100$ hrs., and the other disruption occurred at the Port of Savannah with expected duration of $TLD_{11} = 90$ hrs. The excess handling capacity at the Port of Norfolk is limited to 400 TEUs. The excess inland transport capacity at the Port of Halifax is limited to 300 TEUs. **VSDCDP** suggests skipping the Port of Los Angeles and the Port of Savannah. The container demand of 800 TEUs should be diverted from the Port of Los Angeles to the Port of Norfolk (400 TEUs), the Port of New York (100 TEUs), and the Port of Halifax (300 TEUs). The container demand of 400 TEUs should be diverted from the Port of Savannah to the Port of New York (400 TEUs).

The total savings that can be achieved from the proposed methodology are presented in Figure 3 for each one of the considered scenarios. Results demonstrate that the liner shipping company will be able to significantly reduce additional route service costs due to port disruptions from skipping the disrupted ports and diverting the container demand to alternative port(s) of call. The total cost savings averaged on 8.1 million USD over the considered scenarios.

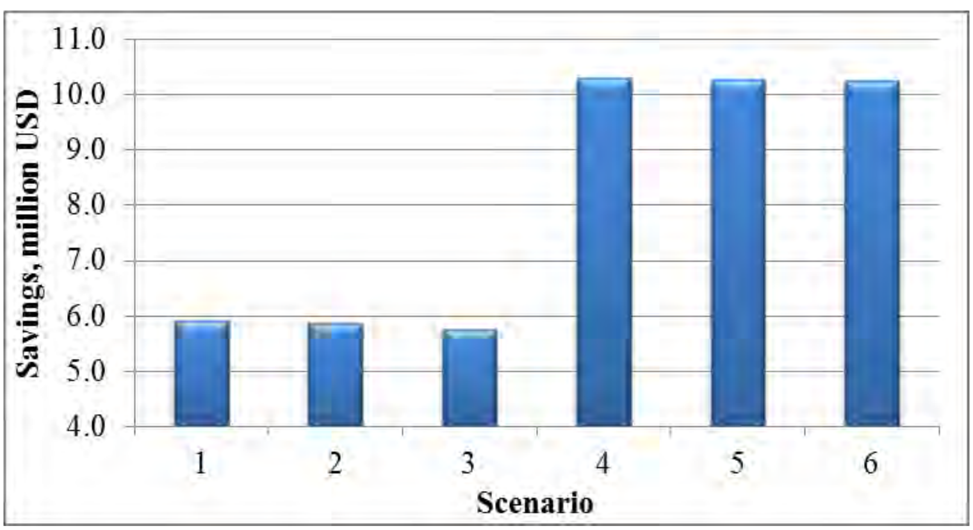

FIGURE 3 Savings from the Suggested Policy.

CONCLUSIONS

Port disruptions substantially affect reliability of liner shipping services and in turn may result in delayed delivery of goods to customers. This report proposes a new methodology, according to which the liner shipping company will be able to skip a disrupted port and divert container demand to alternative port(s) of call, taking into account excess port handling and inland transport capacities at candidate ports for container diversion and additional fees for serving the diverted demand. The objective of the developed mixed integer mathematical model aimed to minimize the additional route service costs due to disruptions. Numerical experiments were performed for Pacific Atlantic 1 route, served by NYK liner shipping company. Scenario analysis results indicated that the liner shipping company could save on average 8.1 million USD from implementation of the proposed methodology. The scope of future research includes the following: 1) consider nature of the disruption (e.g., man-made vs. natural, short-term vs. long-term disruptions), 2) account for possible changes in the vessel schedule due to disruptions (e.g., change in the vessel speed between subsequent ports of call), 3) apply the developed mathematical model to different liner shipping routes, 4) consider behavior of multiple liner shipping companies in case of a disruption at the given port of call, and 5) partial diversion, when the portion of cargo is diverted in case of a disruption at the given port to one of the preceding ports, while the other portion will be handled at the disrupted port towards the end of a disruption (so the liner shipping company will not need to pay a penalty for completely skipping the disrupted port of call).

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