USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 161PUY2.2

Intermodal Infrastructure Investment Decisions and Linkage to Economic Competitiveness

By

Irina V. Benedyk
Lyles School of Civil Engineering
Purdue University
Email: birina@purdue.edu

and

Srinivas Peeta, Ph.D.
Lyles School of Civil Engineering
Purdue University
Email: peeta@purdue.edu

and

Hong Zheng
NEXTRANS Center
Purdue University
Email: hong112@gmail.com

and

Yuntao Guo
Lyles School of Civil Engineering
Purdue University
Email: guo187@purdue.edu

and

Ananth V. Iyer
Krannert School of Management
Purdue University
Email: aiyer@purdue.edu

DISCLAIMER

Funding for this research was provided by the NEXTRANS Center, Purdue University under Grant No. DTRT12-G-UTC05 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

USDOT Region V Regional University Transportation Center Final Report

TECHNICAL SUMMARY

NEXTRANS Project No. 161PUY2.2 Final Report, 3rd April 2017

Title

Intermodal Infrastructure Investment Decisions and Linkage to Economic Competitiveness

Introduction

This study proposes a mixed integer dynamic capacitated intermodal facility location model that incorporates downside risk management to facilitate the strategic intermodal facility investment decision-making process under uncertainty in commodity flow. A uncoordinated and/or myopic strategic intermodal facility investment planning approach may lead to inadequate or wasteful intermodal facility investment. To address limitations of such an approach, this study proposes a holistic system level approach for strategic intermodal facility investment planning. The proposed approach incorporates systematic and coordinated decision-making for strategic intermodal facility investment planning. The proposed methodology provides national-level policymakers with tools to develop policy and regulatory decisions. It also enables local and regional stakeholders to make coordinated, more informed investment decisions that maximize their investment potential.

The IFLMD can also be used to address several real-world issues in the design of the strategic intermodal facility investment plan, including: uncertainty in commodity flow due to different estimates of future international trade, changes in commodity flow distribution due to congestion, system-level congestion reduction, the impact of emerging infrastructure development on commodity flow distribution within the region of interest, and the impact of empty container repositioning cost on commodity flow distribution. The downside risk is incorporated in the proposed model to hedge the investment risk associated with commodity flow uncertainty due to different estimates of future international trade and different emerging infrastructure projects. Downside risk analysis is used to identify different intermodal facility investment plans that are consistent with different risk tolerance levels of system level strategic intermodal facility investment decision-makers or policy-makers. The obtained intermodal facility investment plans illustrate trade-offs between two objectives: minimizing expected system costs and reducing downside risk. To perform the downside risk analysis, different allowed system level downside risk values are considered.

Findings

Results for different allowed system level downside risk values are analyzed to rank intermodal projects based on the associated risk. This helps to categorize at national level intermodal projects into several groups: (i) intermodal projects with low risk (six terminal projects: Arizona, Florida, Georgia, New Jersey, Pennsylvania, and Texas; and three port projects: Charleston, Boston, and New Orleans), (ii) intermodal projects that are not optimal in any scenario regardless of allowed system level downside risk (port project in Wilmington, terminal projects in Connecticut, Illinois, Indiana, Massachusetts, Maine, Michigan, Nevada, New York and Virginia), (iii) intermodal projects that may or may not be included depending on the allowed system level downside risk (port projects in Jacksonville and Los Angeles / Long Beach, terminal project in Utah, and three terminal projects in California).

Recommendations

Insights from the numerical experiments suggest that investing in terminals is preferable when the allowed system level downside risk is low. When the allowed system level downside risk is on the higher side, port intermodal projects become more preferable. The results also show that with lower allowed system level downside risk, the expected system costs and cost variance increase due to more restrictive conditions imposed on commodity flow distribution as fewer investment plans are feasible. Further, the optimal intermodal facility investment plan can change significantly due to uncertainty in commodity flow and different risk perceptions of the system level strategic intermodal facility investment decision-makers.

At a more fundamental level, of significant importance to maritime and intermodal infrastructure decision-makers at the local level and policy makers at the regional or national levels, the proposed study illustrates that decisions on significant investments in new infrastructure or enhancements to existing infrastructure should be based on holistic system level evaluations that incorporate important interacting factors and developments that may geographically far removed. That is, isolated local-level evaluations and uncoordinated decisions (related to such investments) due to the potential for competition for freight transportation demand among the various proposed projects can significantly enhance the risk of underperformance relative to the forecast growth strategies while making such investments. This further suggests that there may be an important role for regional- or national-level policymakers in terms of conducting appropriate studies and coordinating strategies, or providing advisories, in conjunction with the local and regional stakeholders.

ACKNOWLEDGEMENT

The authors would like to thank the NEXTRANS Center, the USDOT Region V Regional University Transportation Center at Purdue University, for supporting this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER1. INTRODUCTION

Intermodal freight transportation is the movement of goods in the same loading unit or vehicle by successive modes of transportation without the handling of the goods themselves when changing modes (European conference of ministers of transport, 1993). It is considered as a competitive mode (Bontekoning et al., 2004) that can reduce transportation cost, mitigate congestion, and provide environmental benefits by shifting commodity flows to more environmentally friendly modes. For these reasons, starting from the early 1990s, intermodal transportation has become an important policy consideration for freight transportation in Europe (European conference of ministers of transport, 1993) and the U.S. (Bill summary & status 103rd Congress (1993 - 1994) H.R.1758). Intermodal facilities, including container ports and inland intermodal terminals, hereafter referred to as ports and terminals, respectively, serve as key components in intermodal transportation.

Globalization and economic development of various countries have led to changes in the international commodity flow network substantially in recent years, and continue to shape their evolution. Manufacturing has shifted over time from North America and Europe to Asia (especially East Asia) (Fransoo and Lee, 2013), and may shift to other regions depending on the unfolding conditions in the future. This can lead to significant changes in the international commodity flow network in the future, and contribute to the uncertainties in the commodity flows themselves. In addition, emerging infrastructure projects like the construction of a new port in Nova Scotia, Canada (hereafter, referred to as the Nova Scotia Port), and Panama Canal expansion can further increase the uncertainty in commodity flow, and consequently increase the uncertainty in freight transportation demand for intermodal facilities.

To accommodate future freight transportation demand, terminal operators, port authorities, state legislatures, policy-makers and other stakeholders often develop strategic intermodal facility (port or terminal) investment plans independently without considering the intermodal facility investment made in other regions (e.g. Florida's Strategic Intermodal System Strategic Plan, 2010). These uncoordinated and/or myopic approaches may lead to inadequate or wasteful investment due to under- or over-estimation of the future freight transportation demand. Hence, a strategic intermodal facility investment plan should be designed using a holistic system level approach that accounts for the impact of the intermodal facility investment made in some regions on the commodity flows and freight transportation demand in other regions. The strategic investment planning should address four important aspects, including: (i) hedge the risk of investment due to freight transportation demand uncertainty induced by the global trade changes in a long-term horizon; (ii) accommodate future freight transportation demand for different scenarios; (iii) reduce port congestion in future; and (iv) consider the impacts of emerging infrastructure development projects in other regions on freight transportation demand. The need for a holistic approach is also consistent with national transportation goals highlighted in the MAP-21 Act and the draft of the National Freight Strategic Plan, which state that it is critical for state and local agencies to participate in multijurisdictional collaboration to coordinate strategic freight planning decision-making process and investments in intermodal facilities.

To hedge the investment risk associated with commodity flow uncertainty from the system level perspective, risk management should be incorporated in the strategic intermodal facility investment decision-making process. In this study, we use the concept of downside risk to quantify the risk associated with uncertainty in commodity flow. Downside risk, which has been widely adopted in financial risk management, is defined here as the difference between the target revenue (predetermined by the facility decision-makers) and the achieved revenue of an intermodal facility, if and only if the achieved revenue is lower than the target revenue. The downside risk is equal to zero if the achieved revenue is equal to or higher than the target revenue. The system level downside risk is the summation of the downside risk for each intermodal facility within that system. The downside risk is chosen as a risk metric because previous studies have shown that decision-makers are more sensitive to possible losses than to possible gains (Tversky and Kahneman, 1992), and the downside risk can capture losses for each intermodal facility in the system. An allowed system level downside risk is a parameter determined by system level strategic intermodal facility investment decision-makers or policy-makers, and used to control the system level downside risk. A lower value for allowed system level downside risk implies that these decision-makers or policy-makers tolerate lesser risk. The use of allowed system level downside risk can help decision-makers evaluate different strategic intermodal facility investment plans with different downside risk tolerance levels. This would also enable the identification of investment plans that are consistent with the individual downside risk tolerance levels of the decision-makers for each intermodal facility within the system.

The objective of this study is to explore the impacts of uncertainty in commodity flow on strategic intermodal facility investment plans by incorporating downside risk analysis in the investment decision-making process. These intermodal facility investment plans can include improvements to existing intermodal facilities and construction of new intermodal facilities. These intermodal facility investment plans can include improvements to existing intermodal facilities and construction of new ones. Investment in ports and terminals is considered simultaneously in the model, as terminal development relies on port enhancement or building of new ports that may be geographically far removed, and vice versa (Benedyk et al., 2016). To enable this, we propose a mixed integer dynamic capacitated intermodal facility location model with downside risk (IFLMD) to determine a system level strategic intermodal facility investment plan that factors uncertainty in commodity flow. To characterize the uncertainty in commodity flow, a scenario-based solution approach is used. Each scenario captures the uncertainty in commodity flow in terms of volume and distribution based on an estimate of future international trade and a realization of emerging infrastructure projects. The downside risk is used to capture the impact of the risk associated with these uncertainties on the strategic intermodal facility investment decision-making process. To perform the downside risk analysis, different values of allowed system level downside risk are considered. The strategic intermodal facility investment plan associated with each allowed system level downside risk represents a trade-off between two objectives: minimization of expected system costs and risk reduction associated with the uncertainty in commodity flows. Numerical experiments are designed to demonstrate the potential applicability of the proposed model in assisting the strategic intermodal facility investment decision-making process, and analyze the impact of uncertainty in commodity flow on the optimal national-level strategic intermodal facility investment plan for the U.S. Eight different scenarios are considered in the numerical experiments, including with or without the Panama Canal expansion, and with and without the construction of the Nova Scotia Port, for two different estimates of future international trade.

The remainder of the paper is organized as follows. Chapter 2 reviews the literature and summarizes research gaps in the intermodal facilities investment planning domain. Chapter 3 presents the mathematical formulation of the proposed IFLMD. Chapter 4 analyses and discusses results of the numerical experiments. Chapter 5 concludes with a summary of insights, practical implications and future research directions.

CHAPTER 2. LITERATURE REVIEW

Previous studies related to multimodal freight transportation planning can be classified into three types based on the planning horizon: operational, tactical, and strategic planning (SteadieSeifi et al., 2014). Strategic planning relates to making longer term investment decisions, tactical planning involves shorter term plans for the optimal utilization of given infrastructure, and operational planning deals with real-time planning (SteadieSeifi et al., 2014). The proposed study focuses on strategic intermodal investment planning. Intermodal transportation is a type of multimodal transportation in which the commodity is transported in units without handling the commodity itself (Crainic and Kim, 2007).

Based on the literature review, this study identifies six research needs in modeling the strategic intermodal investment decision-making process: (i) factoring the impacts of port and terminal congestion on container flow distribution and mode choice (SteadieSeifi et al., 2014); (ii) considering transshipment costs as a factor for container flow distribution (SteadieSeifi et al., 2014); (iii) incorporating the empty container relocation costs (SteadieSeifi et al., 2014); (iv) identifying different sources of uncertainty; (v) integrating dynamic changes in freight transportation demand over a long time horizon; (vi) incorporates risk management into strategic intermodal facility investment decision-making process to hedge the risk associated with the uncertainty in commodity flow. None of the existing studies address all six of these research needs simultaneously.

Several studies have shown that intermodal facility congestion can affect commodity flow distribution due to increase in transportation costs caused by delays. To reduce the potential congestion, some studies (Sharif et al., 2011; Sharif and Huynh, 2012; Kaveshgar and Huynh, 2014; Kaveshgar and Huynh, 2015) proposed different operational planning methods, including increasing productivity improvement at truck gates, yard, and quay cranes. Sharif et al. (2011) used an agent-based approach to manage truck gate congestion. Sharif and Huynh (2012) compared the results of centralized and decentralized approaches for modeling yard crane scheduling, and conclude that the centralized approach outperforms the decentralized approach due to complete and accurate information on future truck arrivals. Kaveshgar and Huynh (2014) developed a genetic algorithm to manage quay crane scheduling to improve the quay crane productivity. Kaveshgar and Huynh (2015) proposed an integrated model that identifies the optimal operational plan for truck gates, yard, and quay cranes simultaneously. Fan et al. (2012) studied the impacts of port and terminal congestion on container flow distribution and mode choice using queuing theory. They calculated the average waiting times at different congestion levels. Piecewise linear approximations were used to model congestion costs; a similar method is used in our study. Although several studies address port and terminal congestion in operational planning, to the best of our knowledge there are none that focus on strategic intermodal facility investment planning by factoring congestion. Other studies (Correia et al., 2010; Meng and Wang, 2011) modeled transit hub capacity limits but did not consider the congestion effect. Some studies (Alumur, 2012a; Huynh and Fotuhi, 2013; Ishfaq and Sox, 2010; Karimi and Setak, 2014) only consider transshipment costs (the second need) without factoring congestion costs. For shippers, the costs of both transshipment and delay can significantly impact transportation decisions (the first and the second needs).

Previous studies do not combine the facility location and empty container repositioning (the third need) problems together in strategic planning. The need for factoring empty container repositioning arises when an imbalance exists between incoming and outgoing commodity flows. Moving and storing empty containers can increase transportation costs for freight carriers, thereby affecting container flow distribution. Hence, it is important to incorporate empty container repositioning costs into the modeling process.

Several recent studies adopt different approaches to capture the impact of freight transportation demand uncertainty (the fourth need) on the strategic intermodal facility investment plan (e.g. Contreras et al., 2011; Alumur et al., 2012; Benedyk et al., 2016). Contreras et al. (2011) adopted a probabilistic approach to capture uncertainty in freight transportation demand and transportation costs. However, some studies (Owen and Daskin, 1998; Zhai et al., 2012) found that the probabilistic approach can increase model complexity and often lacks closed-form solutions. Alumur et al. (2012) and Benedyk et al. (2016) adopted scenario-based approaches to capture uncertainty in freight transportation demand. The scenario-based approach helps decision-makers to design the optimal strategic intermodal facility investment plan that minimizes the expected system costs across all of the scenarios considered (Eppen et al., 1989), and evaluate the impact of a particular scenario on the strategic intermodal facility investment decision-making process. However, the outcomes of the scenario-based approach depend on the scenarios considered. To avoid suboptimal solution, all possible scenarios should be included in the analysis. However, the time needed to identify those scenarios and the computational effort to generate the optimal solution can be significant. In addition, the optimal investment strategy identified using the scenario-based approach may not minimize the probability of unfavourable outcomes in terms of system performance. This implies that the optimal investment strategy may have high costs in some scenarios, even if the expected system costs across all scenarios are minimized.

Few studies consider dynamic demand for intermodal facilities over long time horizons (the fifth need). Most studies assume static freight transportation demand and solve the model for a single time point. Failure to account for freight transportation demand changes over a long time horizon could lead to port congestion or low port utilization.

None of the previous studies incorporates risk management (the sixth need) into strategic intermodal facility investment decision-making process to hedge the risk associated with the uncertainty in commodity flow. Eppen et al. (1989) proposed a model that incorporates downside risk to aid in making capacity decisions under demand uncertainty for four General Motors assembly plants. The optimal solution represented a trade-off between profit maximization and the downside risk reduction. Gebteslassie et al. (2012) used downside risk analysis to design the hydrocarbon biorefinery supply chain under demand uncertainty. They design the optimal configuration of the supply chain that minimizes expected system costs and satisfies the demand. In the strategic investment decision-making process, where large amounts of investment are involved over a long time horizon, both the average values of different performance measures (e.g. profit, cost, and volume) and risk values in different scenarios are important. Hence, it is important to incorporate risk control tools into the strategic intermodal facility investment decision-making process.

Single allocation (e.g. Correia et al., 2010; Contreras et al., 2011; Alumur et al., 2012) and multiple allocation (e.g. Cambell, 2009; Huynh, 2013; Benedyk et al., 2016) models have been adopted in previous studies to formulate strategic investment models. In single allocation models, commodity flow for each origin-destination (O-D) pair is routed through a single port or terminal, while in multiple allocation models every origin (or destination) can send (or receive) commodity flows through more than one port or terminal. In the context of intermodal freight transportation, multiple allocation models can reflect the freight transportation network better compared to single allocation models, as each commodity flow can consist of cargo from different shippers with various preferences and requirements (Guo and Peeta, 2015; Guo et al., 2016).

Based on the assumptions made in terms of terminals, ports and/or routes capacities, previous studies can be classified into capacitated (e.g. Correia et al., 2010; Meng and Wang, 2011; Benedyk et al., 2016) and uncapacitated facility location models (e.g. Contreras et al., 2010; Ishfaq and Sox, 2010). Only capacitated facility location models can capture the impact of port and terminal congestion and intermodal facility development of other regions on commodity flow distribution. Several studies address congestion in operational or tactical planning. Fan et al. (2012) explored the impact of congestion on special competition for U.S. container ports. Camargo et al. (2009) and Elhedhi and Hu (2005) proposed nonlinear congestion models and solution algorithms to study the impacts of congestion on passenger flow distribution and system costs for the U.S. air passenger transportation. Although several studies address port and terminal congestion in operational and tactical planning, studies considering the impact of congestion on commodity flow distribution in modelling the strategic intermodal facility investment planning are sparse (Benedyk et al., 2016). Congesting costs can have significant impact on shippers' transportation decisions, and hence congestion costs must be incorporated in the strategic intermodal facility investment decision-making process.

The aforementioned studies related to strategic intermodal facility investment planning can be summarized in Table 1.

The proposed IFLMD seeks to address all of the aforementioned needs. The transshipment costs for different congestion levels are incorporated into the IFLMD using a piecewise linear approximation similar to Fan et al. (2012), to address the first and second research needs. Costs for empty container repositioning are incorporated in the objective function to address the third research need. The number of empty containers that need to be moved is estimated as the difference between the imported and exported commodity flows for each port. The proposed IFLM uses a scenario-based approach to address freight transportation demand uncertainties and model the capacity changes of intermodal facilities in other regions. To account for the need to integrate dynamic changes in demand, the model is solved for ten years. To hedge the risks associated with uncertainty in commodity flow, downside risk analysis (Eppen et al., 1989) is incorporated into the proposed IFLMD. By using the downside risk analysis, different strategic intermodal facility investment plans can be obtained for different risk tolerance levels of the system level decision-maker(s). A scenario-based solution approach is used in this study to characterize the uncertainty in commodity flow. The proposed IFLMD captures the impact of congestion in ports and terminals, transhipment costs, changes in capacities of intermodal facilities, economies of scale, and empty container repositioning costs on the commodity flow distribution and the strategic intermodal facility investment plan.

Table 1 Literature on the intermodal facility location problem at the strategic level

Literature	Transpo-rtation Costs	Uncapa-citated or capaci-tated	Multiple or single allocation	Uncer-tainty	Risk control	Modes
Alumur et al. (2012)	Fixed	U	S	Y		Air, truck
Campbell (2009)	Fixed	U	M			Truck
Contreras et al. (2011)	Variable	U	S	Y		Not specified
Contreras et al. (2010)	Fixed	U	S			Not specified
Correia et al. (2010)	Fixed	C	S			Not specified
Huynh (2013)	Fixed	U	M			Truck, rail
Ishfaq and Sox (2010)	Variable	U	S			Truck, rail, air
Ishfaq and Sox (2011)	Fixed	U	M			Truck, rail
Karimi and Setak (2014)	Fixed	U	M			Not specified
Lüer-Villagra and Marianov (2013)	Fixed	U	M			Truck
Meng and Wang (2011)	Fixed	C	M			Maritime, rail, truck
Benedyk et al. (2016)	Variable	C	M	Y		Maritime, rail, truck
Proposed study	Variable	C	M	Y	Y	Maritime, rail, truck

U – uncapacitated facility location model
C – capacitated facility location model

M – multiple allocation
S – single allocation
Y – included in the model

CHAPTER 3. MODEL FORMULATION

3.1 *Problem Description*

We propose a mixed integer dynamic capacitated model with multiple allocations that incorporates downside risk. It seeks to determine the optimal strategic intermodal facility investment plan in a region based on minimizing expected system costs under uncertainty in commodity flow. We consider distribution of intermodal commodity flows through the global transportation network. The following system costs are captured in the model: transportation costs, congestion costs, handling costs, empty container repositioning costs, and investment costs. Other factors that may be of interest to shippers (such as commodity characteristics, past experience with particular mode or route, etc.), and hence, can influence the mode and route choices, and impact commodity flow distribution (Huang et al., 2015), are not considered due to the non-availability of data. The commodity flow between each O-D pair is routed through transit nodes (such as terminals, ports and the Panama and Suez Canals) by using maritime and ground transportation (truck or rail mode) systems. In each commodity flow route, at least one port must be included so as to transfer from maritime to ground transportation. However, the model does not restrict the number of ports and terminals in commodity flow routes. The capacity for each mode of transportation for transit nodes is bounded.

The uncertainty in commodity flow is modelled by using a scenario-based solution approach. Each scenario characterizes commodity flow through the global transportation network under a particular estimate of future international trade and a certain combination of emerging infrastructure projects. We assume that there is a finite set of scenarios. To hedge the risks associated with uncertainty in commodity flow, downside risk is incorporated in the model to quantify these risks. To perform the downside risk analysis, we solve the model with different allowed system level downside risk values. This allows the identification of a set of intermodal facility investment plans that trade-off expected system costs minimization and investment risk reduction.

3.2 *Model Notation*

Let the international commodity flow network, shown in Figure 1, be represented by a set of nodes P connected by a set of links E. The region of interest is the region for which the strategic intermodal facility investment plan is to be implemented. Commodity flows can be categorized into incoming and outgoing commodity flows for the region of interest, referred to as import and export commodity flows, respectively. P consists of three mutually exclusive and collectively exhaustive subsets: terminate nodes outside the region of interest, terminate nodes inside the region of interest, and transit nodes. The set of terminate nodes outside the region of interest is denoted by A, and each node in this set is the origin for import commodity flows and destination for export commodity flows. The set of terminate nodes inside the region of interest is denoted by B, and each node in this set is the origin for export commodity flows and destination for import commodity flows. Transit nodes include terminals, ports and the Panama and Suez Canals, and their set is denoted by R. Terminals are located inside the region of interest, ports are located on the boundary of the region of interest, and the Panama and Suez Canals are located outside the region of interest. Hence, investment plans in terms of intermodal projects are only for the ports and terminals as they are located in the region of interest.

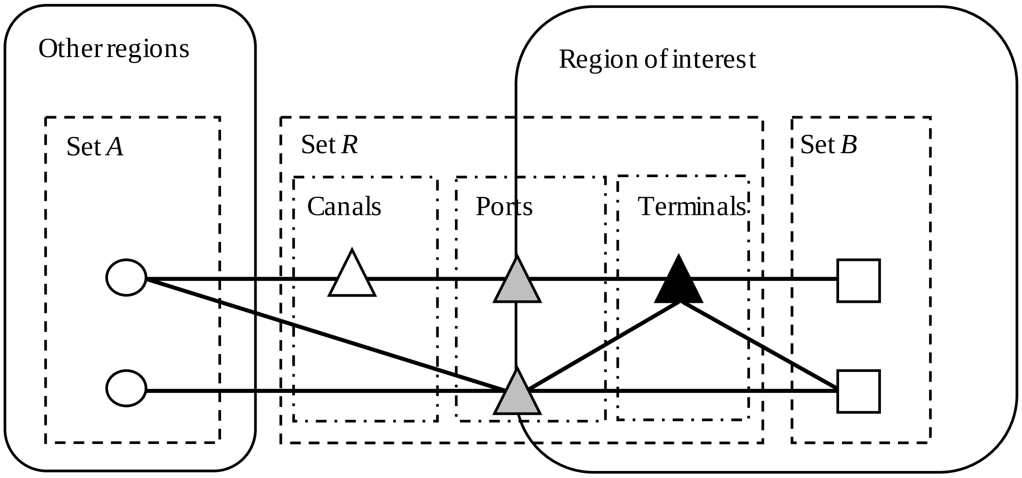

Figure 1 The conceptual network of international commodity flows

A link $(i, j) \in E$ represents transportation of commodity from node $i \in P$ to $j \in P$ by a specific mode, which could be either maritime or ground transportation. The ground transportation consists of rail and truck transportation. In the network, commodity flows between origins and destinations must pass through at least one port, while terminals and canals are optional. Commodity flows within and between other regions outside the region of interest are not considered in the network. Each transit node type of the set R is characterized by a specific type of transhipment operation. More specifically, ports allow intermodal transfer between the maritime and ground transportation (either rail or truck) modes. Terminals allow transhipment involving only the ground transportation modes. Canals allow only maritime transportation. Notations used in the IFLMD are summarized in Tables 2 and 3.

The proposed IFLMD selects the intermodal facility investment plan that minimizes the overall cost. Each intermodal facility investment plan includes a set of intermodal projects. Each intermodal project involves only one facility and either corresponds to improving an existing intermodal facility or constructing a new one. Intermodal project improvement of an existing facility can include capacity increase for one or several modes of transportation at that facility and/or the addition of a new mode of transportation at that facility. In addition, intermodal projects involving ports may involve enabling them to handle vessels of bigger size. Each intermodal facility $r' \in R'$ can have $|L_{r'}|$ intermodal projects, where $L_{r'}$ is the set of intermodal projects for that intermodal facility. Each intermodal project, denoted by φ, is associated with two vectors $h_t^{\varphi r' m}$ and $k_t^{\varphi r'}$. $h_t^{\varphi r' m}$ represents capacity improvement at existing intermodal facility or capacity of new intermodal facility. $k_t^{\varphi r'}$ specifies the investment cost needed for intermodal project φ.

Intermodal projects with different implementation start times within the time horizon of interest that entail the improvement of the same facility or the construction of the same new facility are viewed as different projects. In such cases, only at most one of these projects is selected as part of an investment plan. For an intermodal project, investment and capacity changes for existing modes of transportation or capacity for new modes enabled by the project are specified for each time period t. This enables modeling the temporal investment decisions and temporal capacity changes (capacity reduction during the construction period and capacity increase after completion of the construction) for that intermodal facility.

3.3 *Modelling Maritime Vessel Size and Transportation Costs due to Economies of Scale*

For maritime transportation, five vessel sizes are considered that have transportation costs associated with the sizes. Each maritime link is split into five arcs, where each arc represents the transportation involving a specific vessel size and the arc cost represents the corresponding transportation cost. Larger vessels have lower transportation costs due to economies of scale

(Cullinane and Khanna, 1998). Flows assigned to the arc represent flows transported by the vessel of that specific size. If a transit node cannot handle a specific vessel size, the corresponding arc capacity is set to zero.

Table 2 Sets, subscripts and superscripts used in the IFLMD

Notation	Description
A	Set of nodes that are located outside the region of interest and are origins for import commodity flows and destinations for export commodity flows;
α	Node in set A;
B	Set of nodes that are located inside the region of interest and are origins for export commodity flows and destinations for import commodity flows;
β	Node in set B;
R	Set of transit nodes (which include terminals, ports, and canals);
r	Node in set R;
$R' \subset R$	Subset of transit nodes that includes ports and terminals only;
r'	Node in set R';
$P = A \cup B \cup R$	Set of nodes;
i, j	Nodes in set P;
E	Set of links;
S	Set of possible scenarios of commodity flow based on different estimates of future international trade and different emerging infrastructure projects;
s	Scenario in set S;
M	Set of modes;
m	Mode in set M;
$M' \subseteq M$	Subset of maritime transportation modes, $M' \coloneqq \{m'_1, m'_2, m'_3, m'_4, m'_5\}$, consisting of five maritime modes that correspond to five vessel sizes in the increasing order of size;
m'	Maritime modes in set M';
$M" \subseteq M$	Subset of ground transportation modes, consisting of the rail and truck modes;
$m"$	Ground transportation mode in set $M"$;
T	Set of time periods of interest;
t	Time period in set T;
$L_{r'}$	Set of intermodal projects for intermodal facility $r' \in R'$;
φ	Intermodal projects in set $L_{r'}$;
Γ	Set of congestion levels, $\Gamma \coloneqq \{1,2,3\}$ represents three congestion levels in the increasing order of congestion;
τ	Congestion level in set Γ;

3.4 Modelling Congestion Costs

Increased volume at a particular transit node can result in congestion, and hence can cause extra costs for shippers associated with storage, demurrage cost for using containers, and delay costs. These costs are hereafter referred to as congestion costs. To capture the impact of congestion costs on commodity flow distribution, three congestion levels are introduced. Each link is split into three arcs that represent three congestion levels. At the first congestion level there is no congestion at the transit node and the basic handling costs specified by operators of the ports, terminals and canals are used. The first congestion level corresponds to an annual volume less than 3/5$^{\text{th}}$ of the capacity. At the second and third congestion levels, a transit node has congestion that involves congestion costs that must be paid by shippers. The second congestion level corresponds to an annual volume of between 3/5$^{\text{th}}$ and 4/5$^{\text{th}}$ of the transit node capacity. The third congestion level corresponds to an annual volume of more than 4/5$^{\text{th}}$ capacity. At the third congestion level, the transit node is highly congested.

Table 3 Parameters used in the IFLMD

Notation	Description
General parameters	
Θ_s	Probability of scenario $s \in S$;
Φ	Empty container repositioning cost per twenty-foot equivalent unit (TEU);
η	Interest rate;
w_{st}^{ij}	Demand from origin node i to destination node j in scenario s in time period t; where $i \in A$ and $j \in B$ for import commodity flows, and $i \in B$ and $j \in A$ for export commodity flows (U.S. Census Bureau, 2015);
u_{st}^{rm}	Capacity of transit node r for mode $m \in M$ in scenario s in time period t (American Association of Port Authorities, 2015);
Intermodal project parameters	
$h_t^{\varphi r'm}$	Capacity improvement at existing intermodal facility, or capacity of new intermodal facility r' of intermodal project φ for mode type m in time period t;
$k_t^{\varphi r'}$	Investment cost for intermodal project φ of intermodal facility r' in time period t;
Parameters related to downside risk analysis	
$\Psi_{r'}$	Target revenue for intermodal facility r';
ξ	Maximum allowed system level downside risk;
$\sigma \in [0,1]$	Parameter used to tighten the downside risk constraint;
Costs	
c_{mt}^{ij}	Transportation cost per TEU from node i to j through mode m in time period t (World Fright Rates, 2015);
$d_{rm\tau}$	Handling cost per TEU at transit node r for mode m at the congestion level $\tau \in \Gamma$.

3.5 Variables

Table 4 summarizes the variables used in the IFLMD. $x_{mst}^{\alpha ij}$ and $y_{mst}^{\beta ij}$ represent the import and for export commodity flow on link *(i,j)*, respectively. Indices α and β specify the origin node for each commodity flow, and are used to associate each $x_{mst}^{\alpha ij}$ and $y_{mst}^{\beta ij}$ with w_{st}^{ij}. Variables $x_{mst}^{\alpha ij}$ and $y_{mst}^{\beta ij}$ are split into $\delta_{mst\tau}^{\alpha ij}$ and $\zeta_{mst\tau}^{\beta ij}$, respectively, that denote the import and export commodity flows at different congestion levels τ. The sum of $\delta_{mst\tau}^{\alpha ij}$ and $\zeta_{mst\tau}^{\beta ij}$ at each congestion level is denoted by $\gamma_{rmst\tau}$.

Table 4 Variables used in the IFLMD

Notation	Description
$z_{r'}^{\varphi}$	1 if intermodal project φ is selected for intermodal facility r', 0 otherwise;
$x_{mst}^{\alpha ij}$	Import commodity flow from i to j with origin $\alpha \in A$ for mode m in scenario s and time period t;
$y_{mst}^{\beta ij}$	Export commodity flow from i to j with origin $\beta \in B$ for mode m in scenario s and time period t;
$\delta_{mst\tau}^{\alpha ij}$	Import commodity flow of $x_{mst}^{\alpha ij}$ at congestion level τ;
$\zeta_{mst\tau}^{\beta ij}$	Export commodity flow of $y_{mst}^{\beta ij}$ at congestion level τ;
$\gamma_{rmst\tau}$	Summation of import and export commodity flows at transit node $r \in R$ for mode m in scenario s and time period t at congestion level τ;
$\Delta_{r'st}^{+}, \Delta_{r'st}^{-}$	Imbalance variables representing surplus and deficit of empty containers at intermodal facility r' in scenario s and time period t;
$\Omega_{r's}$	Downside risk for transit node r' in scenario s;
$v_{st}^{r'm}$	Capacity for existing or new intermodal facility r' after implementation of the intermodal project, if any, for mode m in scenario s and time period t.

The binary variable $z_{r'}^{\varphi}$ represents the investment decision in the IFLMD, and takes a value 1 if intermodal project φ is selected for intermodal facility r', and 0 otherwise. Imbalance variables $\Delta_{r'st}^{+}$ and $\Delta_{r'st}^{-}$ represent the surplus and deficit of empty containers at intermodal facility r', respectively, and are used to capture the impact of the empty container repositioning costs on commodity flows distribution (discussed in detail in Section 3.6). The value of downside risk is denoted by variable $\Omega_{r's}$ (discussed in detail in Section 3.6). Implementation of an intermodal project will lead to either the capacity improvement at existing an intermodal facility or the construction of a new intermodal facility; the capacity of the intermodal facility after implementation of the intermodal project is denoted by $v_{st}^{r'm}$.

3.6 Intermodal Facility Location Model with Downside Risk Formulation

The objective function (Equation (1)) seeks to minimize the expected system costs while determining the strategic intermodal facility investment plan. The first term in Equation (1) represents the expected transportation cost of import commodity flows, and the second term represents the expected transportation cost of export commodity flows. The third term represents the expected handling and congestion cost at terminals, ports, and canals. The fourth term represents the investment cost for the chosen intermodal facility investment plan. The fifth term represents the cost for empty container repositioning.

The objective function is subject to constraints related to mass balance, non-negativity, capacity, maximum number of selected intermodal projects, imbalance, and downside risk.

Equations (2)-(7) ensure flow conservation at each node. Equations (2) and (3) address flow mass balance at origin nodes for import and export commodity flows, respectively. Equations (4) and (5) address flow mass balance at destination nodes for import and export commodity flows, respectively. Equations (6) and (7) address flow mass balance at transit nodes for import and export commodity flows, respectively. Equations (8) and (9) ensure non-negativity of decision variables $x_{mst}^{\alpha ij}$ and $y_{mst}^{\beta ij}$.

$$\begin{aligned} minimize \sum_{i\in P}\sum_{j\in P}\sum_{s\in S}\sum_{m\in M}\sum_{t\in T}\sum_{\alpha\in A} c_{mt}^{ij} x_{mst}^{\alpha ij}\Theta_s + \qquad (1) \\ \sum_{i\in P}\sum_{j\in P}\sum_{s\in S}\sum_{m\in M}\sum_{t\in T}\sum_{\beta\in B} c_{mt}^{ij} y_{mst}^{\beta ij}\Theta_s + \\ \sum_{\tau\in\{1,2,3\}}\sum_{r\in R}\sum_{s\in S}\sum_{t\in T}\sum_{m\in M} \gamma_{rmst\tau} d_{rm\tau}\Theta_s + \\ \sum_{r'\in R'}\sum_{\varphi\in L_{r'}}\sum_{t\in T} k_t^{\varphi r'} z_{r'}^{\varphi} + \\ \Phi \sum_{r'\in R'}\sum_{s\in S}\sum_{t\in T}(\Delta_{r'st}^{-} + \Delta_{r'st}^{+}) \end{aligned}$$

Commodity flow mass balance constraints:

- at origin nodes (for import and export):

$$\sum_{r\in R}\sum_{m\in M} x_{mst}^{\alpha ir} = \sum_{j\in B} w_{st}^{ij} \qquad \forall \alpha = i \in A, s \in S, t \in T \quad (2)$$

$$\sum_{r\in R}\sum_{m\in M} y_{mst}^{\beta jr} = \sum_{i\in A} w_{st}^{ij} \qquad \forall \beta = j \in B, s \in S, t \in T \tag{3}$$

- at destination nodes (for import and export):

$$\sum_{r\in R}\sum_{m\in M} x_{mst}^{\alpha rj} = w_{st}^{ij} \qquad \forall \alpha = i \in A, j \in B, s \in S, t \in T \tag{4}$$

$$\sum_{r\in R}\sum_{m\in M} y_{mst}^{\beta ri} = w_{st}^{ij} \qquad \forall \beta = j \in B, i \in A, s \in S, t \in T \tag{5}$$

- at transit nodes (for import and export):

$$\sum_{i\in A\cup R}\sum_{m\in M} x_{mst}^{\alpha ir} - \sum_{j\in R\cup B}\sum_{m\in M} x_{mst}^{\alpha rj} = 0 \qquad \forall \alpha \in A, r \in R, s \in S, t \in T \tag{6}$$

$$\sum_{i\in B\cup R}\sum_{m\in M} y_{mst}^{\beta ir} - \sum_{j\in R\cup A}\sum_{m\in M} y_{mst}^{\beta rj} = 0 \qquad \forall \beta \in B, r \in R, s \in S, t \in T \tag{7}$$

Non-negativity of decision variables (for import and export):

$$x_{mst}^{\alpha ij} \geq 0 \qquad \forall \alpha \in A, i, j \in P, m \in M, s \in S, t \in T \tag{8}$$

$$y_{mst}^{\beta ij} \geq 0 \qquad \forall \beta \in B, i, j \in P, m \in M, s \in S, t \in T \tag{9}$$

New capacity for intermodal facilities:

$$v_{st}^{r'm} = u_{st}^{r'm} + \sum_{\varphi \in L_{r'}} z_{r'}^{\varphi} \times h_t^{\varphi r'm} \qquad \forall r' \in R', m \in M, s \in S, t \in T \tag{10}$$

Definitional constraints involving commodity flows and the three congestion-related components:

$$x_{mst}^{\alpha ij} = \sum_{\tau} \delta_{mst\tau}^{\alpha ij} \qquad \forall \alpha \in A, i \in A \cup R, j \in R \cup B, m \in M, s \in S, t \in T \tag{11}$$

$$y_{mst}^{\beta ij} = \sum_{\tau} \zeta_{mst\tau}^{\beta ij} \qquad \forall \beta \in B, i \in R \cup B, j \in A \cup R, m \in M, s \in S, t \in T \tag{12}$$

Non-negativity of decision variables (for import and export):

$$\delta_{mst\tau}^{\alpha ij} \geq 0 \qquad \forall \alpha \in A, i \in A \cup R, j \in R \cup B, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \tag{13}$$

$$\zeta_{mst\tau}^{\beta ij} \geq 0 \qquad \forall \beta \in B, i \in R \cup B, j \in A \cup R, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \tag{14}$$

Volume of commodity flow at each congestion level:

$$\sum_{\alpha\in A}\sum_{i\in A\cup R} \delta_{mst\tau}^{\alpha ij} + \sum_{\beta\in B}\sum_{i\in A\cup R} \zeta_{mst\tau}^{\beta ij} = \gamma_{rmst\tau} \qquad \forall r \in R, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \tag{15}$$

Upper bounds for the three congestion levels for the maritime transportation mode for intermodal facilities:

$$\frac{3v_{st}^{r'm'_1}}{5} \geq \sum_{m'\in M'} \gamma_{r'm'st1} \geq 0 \qquad \forall r' \in R', s \in S, t \in T \tag{16}$$

$$\frac{v_{st}^{r'm'_1}}{5} \geq \sum_{m'\in M'} \gamma_{r'm'st2} \geq 0 \qquad \forall r' \in R', s \in S, t \in T \tag{17}$$

$$\frac{v_{st}^{r'm'_1}}{5} \geq \sum_{m'\in M'} \gamma_{r'm'st3} \geq 0 \qquad \forall r' \in R', s \in S, t \in T \tag{18}$$

Capacity constraints for maritime transportation mode for intermodal facilities:

$$\sum_{\tau\in\{1,2,3\}}\sum_{m'\in M'}\gamma_{r'm'st\tau} \le \upsilon_{st}^{r'm'_1} \qquad \forall r' \in R', s \in S, t \in T \qquad (19)$$

Upper bounds for the three congestion levels for the ground transportation modes for intermodal facilities:

$$\frac{3\upsilon_{st}^{r'm''}}{5} \ge \gamma_{r'm''st1} \ge 0 \qquad \forall r' \in R', m'' \in M'', s \in S, t \in T \qquad (20)$$

$$\frac{\upsilon_{st}^{r'm''}}{5} \ge \gamma_{r'm''st2} \ge 0 \qquad \forall r' \in R', m'' \in M'', s \in S, t \in T \qquad (21)$$

$$\frac{\upsilon_{st}^{r'm''}}{5} \ge \gamma_{r'm''st3} \ge 0 \qquad \forall r' \in R', m'' \in M'', s \in S, t \in T \qquad (22)$$

Capacity constraints for ground transportation modes for intermodal facilities:

$$\sum_{\tau\in\{1,2,3\}}\gamma_{r'm''st\tau} \le \upsilon_{st}^{r'm''} \qquad \forall r' \in R', m'' \in M'', s \in S, t \in T \qquad (23)$$

Upper bounds for the three congestion levels for canals:

$$\frac{3u_{st}^{rm'_1}}{5} \ge \sum_{m'\in M'}\gamma_{rm'st1} \ge 0 \qquad \forall r \in R\backslash R', s \in S, t \in T \qquad (24)$$

$$\frac{u_{st}^{rm'_1}}{5} \ge \sum_{m'\in M'}\gamma_{rm'st2} \ge 0 \qquad \forall r \in R\backslash R', s \in S, t \in T \qquad (25)$$

$$\frac{u_{st}^{rm'_1}}{5} \ge \sum_{m'\in M'}\gamma_{rm'st3} \ge 0 \qquad \forall r \in R\backslash R', s \in S, t \in T \qquad (26)$$

Capacity constraints for canals:

$$\sum_{\tau\in\{1,2,3\}}\sum_{m'\in M'}\gamma_{rm'st\tau} \le u_{st}^{rm'_1} \qquad \forall r \in R\backslash R', s \in S, t \in T \qquad (27)$$

Maximum number of selected intermodal projects:

$$\sum_{\varphi\in l_{r'}} z_{r'}^{\varphi} \le 1 \qquad \forall r' \in R' \qquad (28)$$

Domain constraint for binary variable:

$$z_{r'}^{\varphi} \in \{0,1\} \qquad \forall \varphi \in l_{r'}, r' \in R' \qquad (29)$$

Imbalance constraint:

$$\Delta_{r'st}^{+} - \Delta_{r'st}^{-} = \sum_{i\in A\cup R}\sum_{m\in M}\sum_{\alpha\in A} x_{mst}^{\alpha i r'} - \sum_{j\in B\cup R}\sum_{m\in M}\sum_{\beta\in B} y_{mst}^{\beta j r'} \qquad \forall r' \in R', s \in S, t \in T \qquad (30)$$

Non-negativity of decision variables:

$$\Delta_{r'st}^{+} \ge 0 \qquad \forall r' \in R', s \in S, t \in T \qquad (31)$$

$$\Delta_{r'st}^{-} \ge 0 \qquad \forall r' \in R', s \in S, t \in T \qquad (32)$$

Downside risk constraints:

$$\Omega_{r's} \ge \Psi_{r'} - \sum_{t\in T}\frac{\sum_{m\in M}\left(\sum_{\tau\in\{1,2,3\}} d_{r'm\tau}\gamma_{r'mst\tau}\right) - \sum_{\varphi\in L_{r'}} k_t^{\varphi r'} z_{r'}^{\varphi}}{(1+ir)^{t}} \qquad \forall r' \in R', s \in S \qquad (33)$$

$$\sum_{s\in S}\sum_{r'\in R'}\Theta_s\Omega_{r's} \le \sigma\xi \qquad (34)$$

Non-negativity of decision variables:

$$\Omega_{r's} \geq 0 \qquad \forall r' \in R', s \in S \qquad (35)$$

If an intermodal project is chosen, the capacity at the corresponding intermodal facility can change (capacity reduction during the construction period and capacity increase after completion of the construction). Equation (10) states that the intermodal facility capacity after implementation of the intermodal project is the sum of the initial capacity and the extra capacity ($h_t^{\varphi r'm}$). For a new intermodal facility, the initial capacity is zero.

Three congestion levels are used to reflect congestion costs. Commodity flows at a transit node are split into three components as the associated congestion levels have different handling costs. Equations (11) and (12) are definitional constraints, and state that the summation of the three congestion-related components should be equal to the corresponding commodity flows. Equations (13) and (14) ensure non-negative of decision variables $\delta_{mst\tau}^{\alpha ij}$ and $\zeta_{mst\tau}^{\beta ij}$.

The capacity of a transit node is shared by the import and export commodity flows. The import and export commodity flows going through a transit node at each congestion level are combined and denoted by variable $\gamma_{rmst\tau}$ in Equation (15).

Equations (16)-(18) specify the upper bounds for $\gamma_{r'm'st\tau}$ for the three congestion levels for the maritime transportation modes at intermodal facilities. Equation (19) ensures that the total commodity flow for the five maritime modes will not exceed the capacity of the intermodal facility.

Equations (20)-(22) specify the upper bounds for $\gamma_{r'm''st\tau}$ for the three congestion levels for the ground transportation modes at intermodal facilities. Equation (23) ensures that the total commodity flow for rail and truck modes will not exceed the rail and truck capacity of the intermodal facility, respectively.

Equations (24)-(26) specify the upper bounds for $\gamma_{rm'st\tau}$ for the three congestion levels for the canals. Equation (27) ensures that the total commodity flow for the five maritime modes will not exceed the capacity of a canal.

Equation (28) specifies that at most one intermodal project can be chosen at each intermodal facility. Equation (29) constrains $z_{r'}^{\varphi}$ to be a binary (0, 1) variable.

Equations (30)-(32) are introduced to determine the number of empty containers that require repositioning. Variables $\Delta_{r'st}^{+}$ and $\Delta_{r'st}^{-}$ are used to measure the surplus and deficit imbalance of empty containers for an intermodal facility, respectively. The right-hand side of the

Equation (30) computes the difference between the import and export commodity flows. A surplus of empty containers at an intermodal facility arises when the import commodity flow (and thus, numbers of imported containers) is more than the export commodity flow; a deficit arises when the import commodity flow is less than the export commodity flow. At an intermodal facility, for a scenario s in time period t, only either surplus or deficit can occur; hence, only one of the variables ($\Delta^{+}_{r'st}$ or $\Delta^{-}_{r'st}$) can be positive. It is possible that both these variables can be zero simultaneously if the import and export commodity flows are equal. To capture the impact of the empty container repositioning costs on commodity flow distribution, the variables $\Delta^{+}_{r'st}$ and $\Delta^{-}_{r'st}$ are incorporated in the objective function and multiplied by the empty container repositioning costs (Φ).

The model represented by Equations (1)-(32) is used for the scenario-based solution approach in the study numerical experiments. To enable the downside risk analysis, equations (33)-(35) are incorporated into the model.

In the IFLMD, downside risk is used to capture the investment risk due to uncertainty in commodity flow. To include downside risk, the facility decision-maker sets up a target revenue $\Psi_{r'}$ for each intermodal facility, and the maximum allowed system level downside risk ξ is determined by the system level strategic intermodal facility investment decision-makers (Eppen et al., 1989). In Equation (33), the non-negative variable $\Omega_{r's}$ measures the downside risk, which is a positive number if the intermodal facility r fails to meet the target revenue $\Psi_{r'}$ for scenario s. The expected downside risk across all considered scenarios is then compared with the allowed system level downside risk $\sigma \cdot \xi$ in Equation (34). Following Eppen et al. (1989), parameter σ is used to tighten Equation (34) so as to generate a set of intermodal facility investment plans representing trade-offs between expected system costs minimization and downside risk reduction. Equation (35) ensures the non-negativity of decision variables $\Omega_{r's}$.

CHAPTER 4. NUMERICAL EXPERIMENTS

The study experiments are designed to demonstrate the potential applicability of the proposed model in assisting the strategic intermodal facility investment decision-making process for the region of interest. In this study, the U.S. is selected as region of interest. The numerical experiments are used to determine the strategic intermodal facility investment plan under uncertainty in commodity flow for the U.S.

Table 5 illustrates the five maritime modes used to represent the five vessel types with different sizes. The use of bigger vessels reduces operational costs for maritime carriers and freight maritime rates for shippers (Felicio and Caldeirinha, 2013). The Suez Canal can accommodate all five vessel sizes considered, while the Panama Canal can handle only the first, second, and third (after expansion) vessel sizes.

Six candidate port intermodal projects and nineteen candidate terminal intermodal projects being planned between 2015 and 2023 are considered in the numerical experiments. These candidate intermodal projects are selected based on government reports and information from Internet searches. Note that the study experiments consider only capacity improvements and not new facilities. The candidate intermodal projects are summarized in Table 6.

Table 5 Container vessel sizes used in the model

Size	Size name	Volume	Maximum draft
1	Post Panamaxand smaller	Up to 6.000 TEU	43 ft/13 m
2	Post PanamaxPlus	6,000-12,500 TEU	48 ft/14.5 m
3	New Panamax	12,500-15,000 TEU	50 ft/15.2 m
4	Post New Panamax	15,000-18,000 TEU	51 ft/15.5 m
5	Triple E	> 18,000 TEU	51 ft/15.5 m

The network has 185 nodes, including 128 transit nodes (20 ports in the U.S., 5 ports in Canada, 3 ports in Mexico, 98 terminals), 49 terminate nodes inside the U.S., and 8 terminate nodes outside the U.S. Port and terminal locations are shown in Figure 2. Terminate nodes inside the U.S. represent the capitals of the 48 contiguous states and the District of Colombia.

Table 6 List of port and terminal projects

Project number	Port / Terminal	Project description	Capacity expansion
Port projects considered in all three experiments and in downside risk analyzes			
1	Boston	Depth increasing (from 40 ft/12.2 m till 48-50 ft/14.6-15.2 m); planned date of commencement is not defined.	3rd maritime mode will be allowed
2	Wilmington	Depth increasing (from 42 ft/12.8 m till >42 ft/12.8 m); planned date of commencement is not defined.	2nd maritime mode will be allowed
3	Charleston	Depth increasing (from 44 ft/13.7 m till >47 ft/14.3 m); planned date of commencement is not defined.	2nd maritime mode will be allowed
4	Jacksonville	Depth increasing (from 40 ft/12.2 m till >47 ft/14.3 m); planned date of commencement is not defined.	2nd maritime mode will be allowed
5	Los Angeles /Long Beach	Construction of a new port terminal; planned date of commencement is not defined.	Additional capacity of 1 million TEUs
6	New Orleans	Depth increasing (from 45 ft/13.7 m till 50 ft/15.2 m); planned date of commencement is not defined.	3rd maritime mode will be allowed
Terminal projects considered in the second and third experiments and in downside risk analyzes			
7	Illinois	Construction inland intermodal terminal; planned date of commencement is not defined.	Double capacity
8	Indiana		Double capacity
9	Michigan		Double capacity
10	Texas		Double capacity
11	Utah		Double capacity
Terminal projects considered only in the third experiment and in downside risk analyzes			
12	Arizona	Construction inland intermodal terminal; planned date of commencement is not defined.	Double capacity
13	California, Los Angeles		Double capacity
14	California, San Francisco		Double capacity
15	California, Santa Cruz		Double capacity
16	Connecticut		Double capacity
17	Florida		Double capacity
18	Georgia		Double capacity
19	Massachusetts		Double capacity
20	Maine		Double capacity
21	New Jersey		Double capacity
22	Nevada		Double capacity
23	New York		Double capacity
24	Philadelphia		Double capacity
25	Virginia		Double capacity

The world outside the U.S. is split into eight regions, where each region represents one economic and geographic region. These regions with terminate nodes outside the U.S are: Africa, Australia & Oceania, Europe, North America (excluding the U.S.), South & Central America, East & South East Asia, the Middle East, and South Asia.

Ports and terminals are aggregated by geographic area with the same first two digits of the U.S. postal ZIP code. For example, the ports of Long Beach and Los Angeles are combined because they are in the geographical area with the same first two digits of ZIP code. The largest terminal or port is used to represent the aggregated terminals or ports in an area.

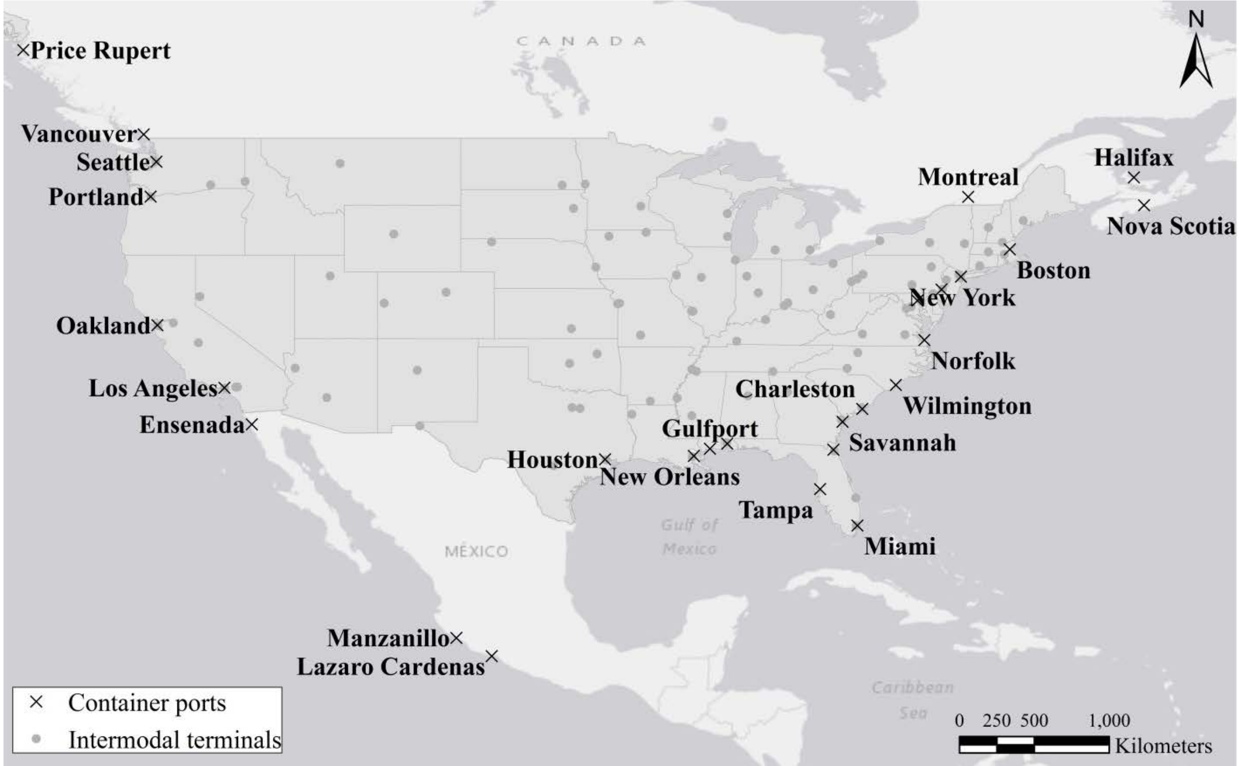

Figure 2 Port and terminal locations considered in the numerical experiments

Freight maritime transportation rates were obtained from the online service World Freight Rates. Port capacity information was collected from the official port websites and from American Association of Port Authorities (2015).

To account for uncertainty in commodity flow, two different estimates of future international trade were considered. The two estimates are considered as equally likely in the numerical experiments. The first estimate of future international trade represents forecasts from the World Trade Organization, and is hereafter referred to as WTO. The WTO reported a 3% commodity flow annual growth rate (World Trade Organization, 2015). The second estimate of future international trade is based on the forecast modelled by Oxford Economics, and is hereafter referred to as OE. It predicts a higher growth in both export and import commodity flows (HSBC Bank plc, 2015). OE provides predictions for U.S. trade annual growth rates ranging from 3% to 9% for different regions for three periods from 2015 to 2016, from 2017 to 2020, and from 2021 to 2030. Commodity flow data for the year 2014 was collected from the online service of the U.S. Census Bureau – U.S. Trade Online (2015). This resource provides the volumes of import and export containerized commodity flows from/to different world regions to/from different U.S. states. The commodity flow volumes for future years are determined using the commodity flow data for 2014 and the two estimates of future international trade. The difference between the two estimates of future international trade in ten years is 31.12% for import commodity flows and 28.43% for export commodity flows.

To demonstrate the impact of downside risk on the strategic intermodal facility investment decision-making process, the numerical experiments are split into two groups. In the first group, the IFLMD is solved without the downside risk constraints (that is, Equations (33)-(35) are excluded from the model). In the second group, the IFLMD is solved with the downside risk constraints. To perform the downside risk analysis, the model is solved for eight allowed system level downside risk values. In both groups of numerical experiments, the model is solved for eight scenarios simultaneously, with equal probability for each scenario. The scenarios are summarized in Table 7.

Based on Tyndall et al. (1990), a ten-year time horizon of interest is chosen. Tyndall et al. (1990) stated that a minimum of ten years should be used for strategic investment planning in transportation. The horizon is divided into five time periods, with each period representing every other year. Commodity flow data for every other year is used, i.e., 2015, 2017, 2019, 2021 and 2023. Commodity flow data for year 2014 is used to validate the proposed IFLMD, by solving it for only one time period and comparing the computed port volumes with the volumes reported by the American Association of Port Authorities in the year 2014. The difference between computed and reported volumes is less than 6% averaged across all ports. It indicates that the proposed IFLMD can adequately capture the commodity flow distribution in the real world. The difference can be attributed to some factors that may influence the shipper's mode and route choices, but are not included in the model (commodity characteristics, previous experience with particular port, terminal, mode, etc.).

Table 7 Description of scenarios used in numerical experiments

Scenario	S1	S2	S3	S4	S5	S6	S7	S8
Impact of Panama expansion	No	No	No	No	Yes	Yes	Yes	Yes
Impact of Nova Scotia	No	No	Yes	Yes	No	No	Yes	Yes
Estimates of future international trade	WTO	OE	WTO	OE	WTO	OE	WTO	OE
Scenario probability	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125

Optimization software IBM ILOG CPLEX 12.5 MILP solver is used to solve the IFLMD on one cluster node with four 2.3 GHz 12-Core AMD Opterom 6176, 192 GB RAM per node. The problem has 25 binary variables and 390.6 million continuous variables. It takes 8.2 hours to solve the model to an optimality gap of 5%.

CHAPTER 5. RESULTS AND INSIGHTS

5.1.Intermodal facility investment decision without Risk Management

To validate the proposed IFLMD, the model was solved for the year 2014, and the results for port volumes were compared with volumes reported by the Port Import Export Reporting Service in the year 2014. The difference in these volumes is less than 6% averaged across all ports, indicating that the proposed model can adequately capture the commodity flow distribution in the real-world as it considers the important factors (transportation costs and value of time). The difference can be attributed to other factors that may also impact shippers' mode and route choices, but are not considered here due to the non-availability of those data.

Intermodal facility investment decisions for the three experiments are shown in Table 9. Each experiment contains four different cases: (i) with the Panama Canal expansion, and the construction of the Nova Scotia Port; (ii) without the Panama Canal expansion, but with the construction of the Nova Scotia Port; (iii) with the Panama Canal expansion, but without the construction of the Nova Scotia Port; and (iv) without the Panama Canal expansion, or the construction of the Nova Scotia Port. The variation in results across the different cases indicate the significant impact of the Panama Canal expansion and the construction of the Nova Scotia Port on the intermodal investment decision-making process in the U.S. The variation in results in the three different experiments demonstrates the impact of changes in intermodal facility service level in some regions on the freight transportation demand in other regions in the intermodal investment decision-making process.

Three port projects, Boston, Charleston, and New Orleans, were chosen in all instances, indicating their importance. The decisions related to the Wilmington port project vary across the cases and experiments. For example, it was not chosen if the Nova Scotia Port is considered. This indicates that the Nova Scotia Port will compete with that of Wilmington by providing lower maritime transportation costs due to the usage of larger vessels. Figure 3 illustrates the impact of the construction of the Nova Scotia Port on the commodity flow through Wilmington in the OE commodity flow scenario. It shows that eight states (Delaware, Illinois, Maryland, Massachusetts, New Jersey, New York, West Virginia, and Virginia) shift their service port from Wilmington to other ports if the Nova Scotia Port is constructed. The commodity flow volume through Wilmington with the construction of the Nova Scotia Port is 55% lower than without it. Hence, Wilmington does not require capacity expansion if Nova Scotia Port is constructed.

The decision regarding Wilmington also depends on the set of terminal projects that are considered in the experiment. In the second experiment, Wilmington is selected in the case where the construction of the Nova Scotia Port is not considered, but the Panama Canal expansion is. This result indicates the impact of the Panama Canal expansion on the intermodal investment decision-making process. Increased Panama Canal capacity will allow additional commodity flow from East Asian ports to the east coast of the U.S. In the third experiment (25 candidate projects), Wilmington is not selected in any of the cases. Similarly, in the third experiment, the Jacksonville investment project is not selected in the cases where the construction of the Nova Scotia Port is considered.

There are two possible reasons. First, in the third experiment, unlike in the first and the second experiments, three terminal projects (Philadelphia, New Jersey and Georgia) were chosen. These three intermodal projects may decrease transportation costs through ports in New Jersey, Baltimore and Savannah. As a result, additional flow will be attracted to these ports. Coupled with the choice of the Nova Scotia Port, this will make improvements in Wilmington and Jacksonville less cost effective.

The second possible reason is the selection of a Los Angeles/Long Beach (LA/LB) port project in the third experiment in all cases. In the third experiment, three additional terminal projects in California exist, and all three of them are chosen for improvement. These improvements will attract additional flow to the west coast ports of the U.S. and decrease flow at the east coast ports, including Wilmington and Jacksonville. This result indicates that improvements in the LA/LB port are cost-efficient only if coupled with improvements in nearby terminals.

The Utah project is chosen in all cases in the second experiments, but not in the third. The commodity flows shift from Utah to Arizona in the third experiment. As the Arizona terminal project is considered only in the third experiment, the Utah terminal project is chosen in the second experiment. It suggests that investing in an Arizona terminal project may be more effective than investing in an Utah terminal project. It also indicates that Utah and Arizona terminal projects interact in the intermodal facilities investment decision-making process. This result indicates the importance of comprehensive analysis in the intermodal investment decision-making process at the national level. Limiting the case study to specific geographical regions without considering the impact of changes in intermodal facility service levels of some regions on the freight transportation demand in other regions, or considering a narrow set of the candidate projects can induce the inefficient allocation of investment resources. Figure 4 illustrates terminals that operate at full capacity level in the four cases and three experiments under one or both scenarios. Both terminals in Arizona are fully capacitated in both scenarios, while terminals in Utah are not.

As illustrated in Figure 4, many fully capacitated terminals for the WTO scenario are in close proximity to ports. These terminal improvements are necessary due to limited rail capacity at ports. Although improvements of these terminals save transportation costs significantly, increasing port capacities for rail could potentially lead to higher cost savings. This is because truck transportation costs from port to terminal would then be avoided. The improvements of terminals near ports and rail capacity of ports deserve further investigation for transportation in the U.S. For the OE scenario, additionally, the terminals in Idaho, Colorado, New Mexico, Texas and Wyoming also operate at full capacity levels due to higher volumes predicted by the OE scenario. It is noteworthy that there are no capacitated terminals in states in the East North Central, West North Central, and East South Central parts of the U.S. The results indicate that existing terminals will satisfy future freight transportation demand for that region in both scenarios, though utilization of these terminals varies from 85 to 99% for the OE scenario. Further analysis is required to identify the most critical terminals that need improvements to accommodate future demand.

The results also suggest that port projects in New Orleans, Charleston and Boston should receive high priority. Further, the results show that the LA/LB port project is selected for expansion, along with the projects of nearby terminals, to accommodate the increasing commodity flow in LA/LB. The model results show that the construction of the Nova Scotia Port and the Panama Canal expansion have significant impacts on the intermodal facility investment decision-making process related to the development or enhancement of U.S. ports on the east coast. The Panama Canal expansion would contribute positively to the economic efficiency of the port project in Wilmington. However, the construction of the new deep port in Nova Scotia would attract part of the commodity flows of the east coast U.S. ports, thereby contributing negatively to the economic efficiency of port projects in Wilmington and Jacksonville.

Table 8 Chosen port and terminal projects

Port/terminal	Case 1			Case 2			Case 3			Case 4		
Experiment	I	II	III	I	II	III	I	II	III	I	II	III
Boston	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Wilmington	Y	N	N	N	N	N	Y	Y	N	N	N	N
Charleston	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Jacksonville	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N
Los Angeles/Long Beach	N	Y	Y	N	N	Y	N	N	Y	N	N	Y
New Orleans	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Arizona	-	-	Y	-	-	Y	-	-	Y	-	-	Y
California, Los Angeles	-	-	Y	-	-	Y	-	-	Y	-	-	Y
California, San Francisco	-	-	Y	-	-	Y	-	-	Y	-	-	Y
California, Santa Cruz	-	-	Y	-	-	Y	-	-	Y	-	-	Y
Connecticut	-	-	N	-	-	N	-	-	N	-	-	N
Florida	-	-	N	-	-	N	-	-	Y	-	-	Y
Georgia	-	-	Y	-	-	Y	-	-	Y	-	-	Y
Illinois	-	N	N	-	N	N	-	N	N	-	N	N
Indiana	-	N	N	-	N	N	-	N	N	-	N	N
Massachusetts	-	-	N	-	-	N	-	-	N	-	-	Y
Maine	-	-	N	-	-	N	-	-	N	-	-	N
Michigan	-	N	N	-	N	N	-	N	N	-	N	N
New Jersey	-	-	Y	-	-	Y	-	-	Y	-	-	Y
Nevada	-	-	N	-	-	N	-	-	N	-	-	N
New York	-	-	N	-	-	N	-	-	N	-	-	N
Philadelphia	-	-	Y	-	-	Y	-	-	Y	-	-	Y
Texas	-	Y	Y	-	Y	Y	-	Y	Y	-	Y	Y
Utah	-	Y	N	-	Y	N	-	Y	N	-	Y	N
Virginia	-	-	N	-	-	N	-	-	N	-	-	N

Notes: 'Y' – project is selected, 'N' – project is not selected, '-'– project is not included in that experiment.

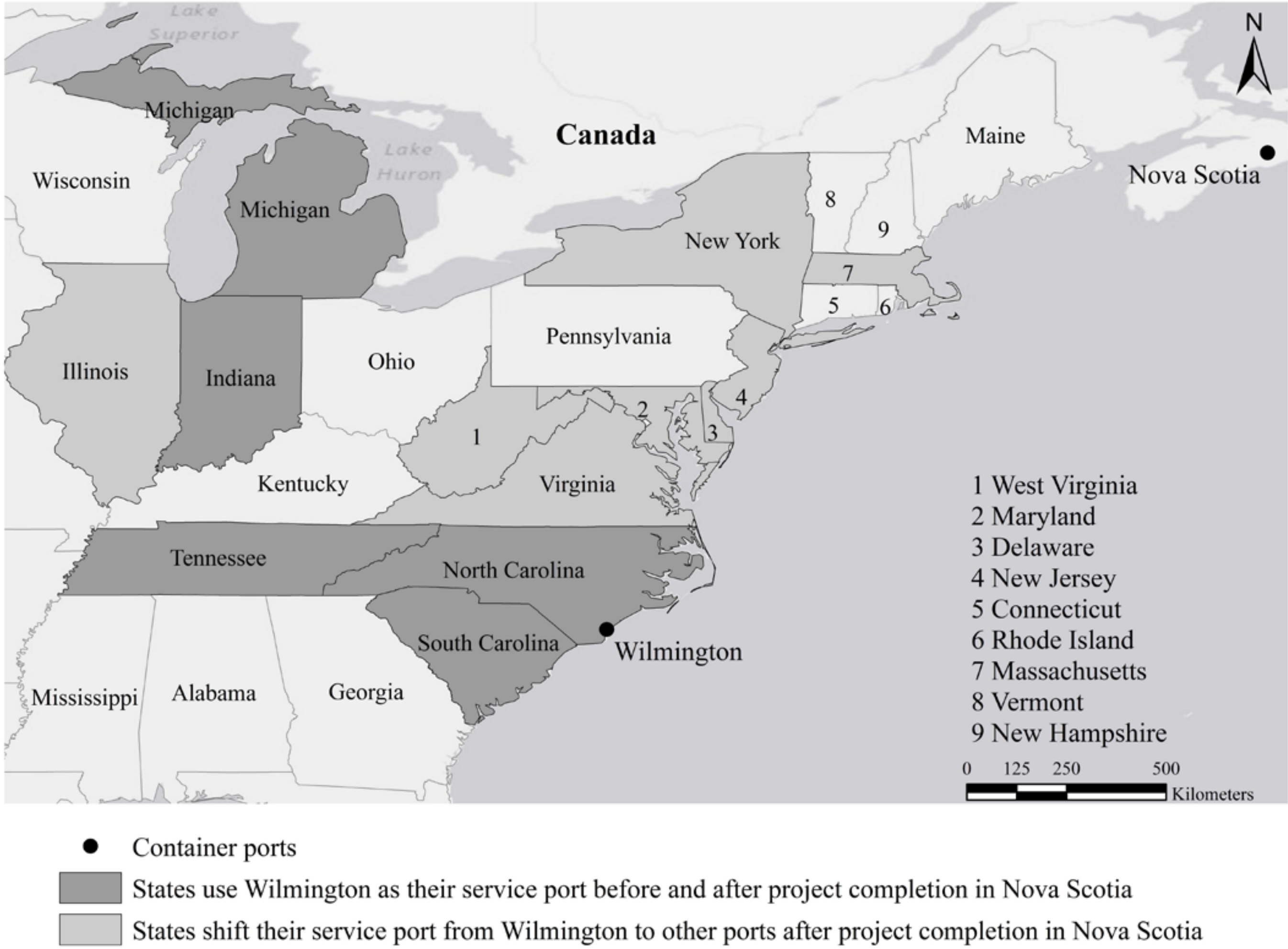

Figure 3 The impact of the construction of Nova Scotia Port on Wilmington

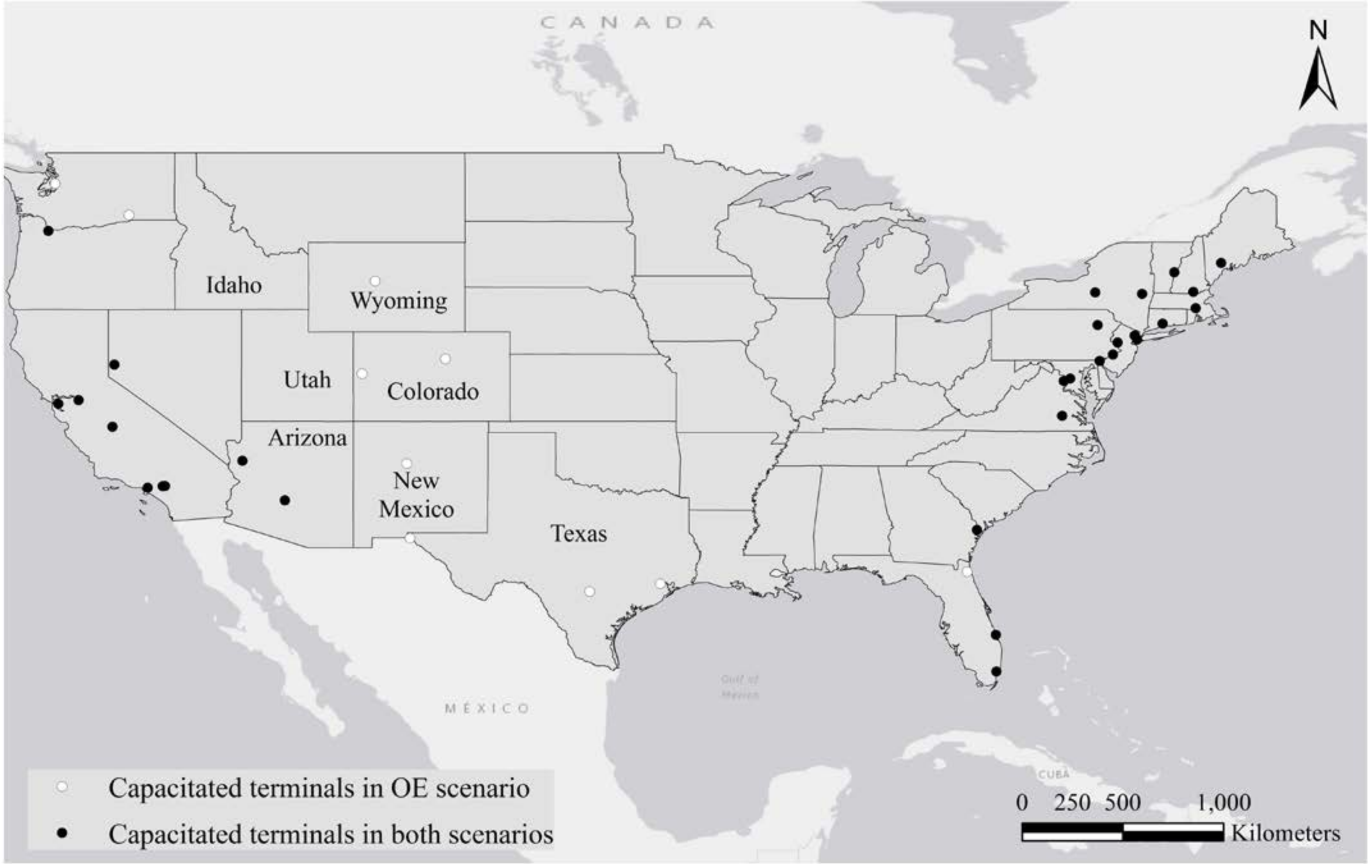

Figure 4 Capacitated terminals in all four cases and three experiments

5.2.Intermodal facility investment decision with Risk Management

To perform the downside risk analysis, the intermodal facilities are stated to operate with a target revenue that is the revenue obtained if the intermodal facility operates at 75% capacity. A failure to reach the target revenue implies downside risk. The downside risk is calculated for each intermodal facility for all of the considered scenarios. The sum of downside risks of all intermodal facilities is the system level downside risk (Equation (34)), which is bounded by the allowed system level downside risk $\sigma \cdot \xi$. By varying the value of σ from 0 to 1, the allowed system level downside risk is increased from 0 to 1.7 billion U.S. dollars. It enables the identification of different intermodal facility investment plans associated with the corresponding allowed system level downside risk values.

The model was solved for eight allowed system level downside risk values. Table 8 illustrates the intermodal facility investment plans selected by the model with and without downside risk. The IFLMD is infeasible if the allowed system level downside risk is less than 1.45 billion dollars ($\sigma < 0.85$). There are several ports and terminals in the system that operate at a very low or zero capacity. These ports and terminals generate downside risk and preclude feasibility if the allowed system level downside risk is less than 1.45 billion dollars. Hence, only results for $\sigma \geq 0.85$ are shown in Table 8 and discussed hereafter.

Three port intermodal projects (Charleston, Boston, and New Orleans) and six terminal intermodal projects (Arizona, Florida, Georgia, New Jersey, Pennsylvania, and Texas) are selected for improvement for all cases (with and without downside risk, and for all allowed system level downside risk values). It suggests that these nine intermodal projects entail high priority, as they are predicted by the model to have high commodity volume and low risk. Other ports and terminals that are considered for improvement will not operate at a high utilization level in some or all of the scenarios, and thus will generate some downside risk. Hence, the model must find specific combinations of intermodal projects to satisfy the downside risk constraints.

Table 9 Selected port and terminal intermodal projects

Port / terminal intermodal project	Without downside risk	With downside risk based on different values of $\boldsymbol{\sigma}$							
		0.85	0.87	0.88	0.90	0.91	0.93	0.94	1.00
Boston	Y	Y	Y	Y	Y	Y	Y	Y	Y
Wilmington	N	N	N	N	N	N	N	N	N
Charleston	Y	Y	Y	Y	Y	Y	Y	Y	Y
Jacksonville	Y	N	N	N	N	N	N	Y	Y
Los Angeles / Long Beach	Y	N	N	Y	Y	Y	Y	Y	Y
New Orleans	Y	Y	Y	Y	Y	Y	Y	Y	Y
Arizona	Y	Y	Y	Y	Y	Y	Y	Y	Y
California, Los Angeles	Y	N	N	Y	Y	Y	Y	Y	Y
California, San Francisco	Y	N	N	Y	Y	Y	Y	Y	Y
California, Santa Cruz	Y	N	N	Y	Y	Y	Y	Y	Y
Connecticut	N	N	N	N	N	N	N	N	N
Florida	Y	Y	Y	Y	Y	Y	Y	Y	Y
Georgia	Y	Y	Y	Y	Y	Y	Y	Y	Y
Illinois	N	N	N	N	N	N	N	N	N
Indiana	N	N	N	N	N	N	N	N	N
Massachusetts	N	N	N	N	N	N	N	N	N
Maine	N	N	N	N	N	N	N	N	N
Michigan	N	N	N	N	N	N	N	N	N
New Jersey	Y	Y	Y	Y	Y	Y	Y	Y	Y
Nevada	N	N	N	N	N	N	N	N	N
New York	N	N	N	N	N	N	N	N	N
Pennsylvania	Y	Y	Y	Y	Y	Y	Y	Y	Y
Texas	Y	Y	Y	Y	Y	Y	Y	Y	Y
Utah	N	Y	Y	N	N	N	N	N	N
Virginia	N	N	N	N	N	N	N	N	N

Note: ‘Y’ – intermodal project selected, ‘N’ – intermodal project not selected

The Utah intermodal project is part of the optimal intermodal facility investment plan under only low values of allowed system level downside risk, when other more economically efficient intermodal projects cannot be chosen due to the risk constraint. The Utah intermodal project is not selected when downside risk is not considered. Figure 5 and 6 illustrate the impact of different allowed system level downside risk values on commodity flow distribution through the terminal in Utah. As the allowed system level downside risk increases, the commodity flows volumes, number of ports, and number of states using the Utah terminal for transhipment commodity flows decreases.

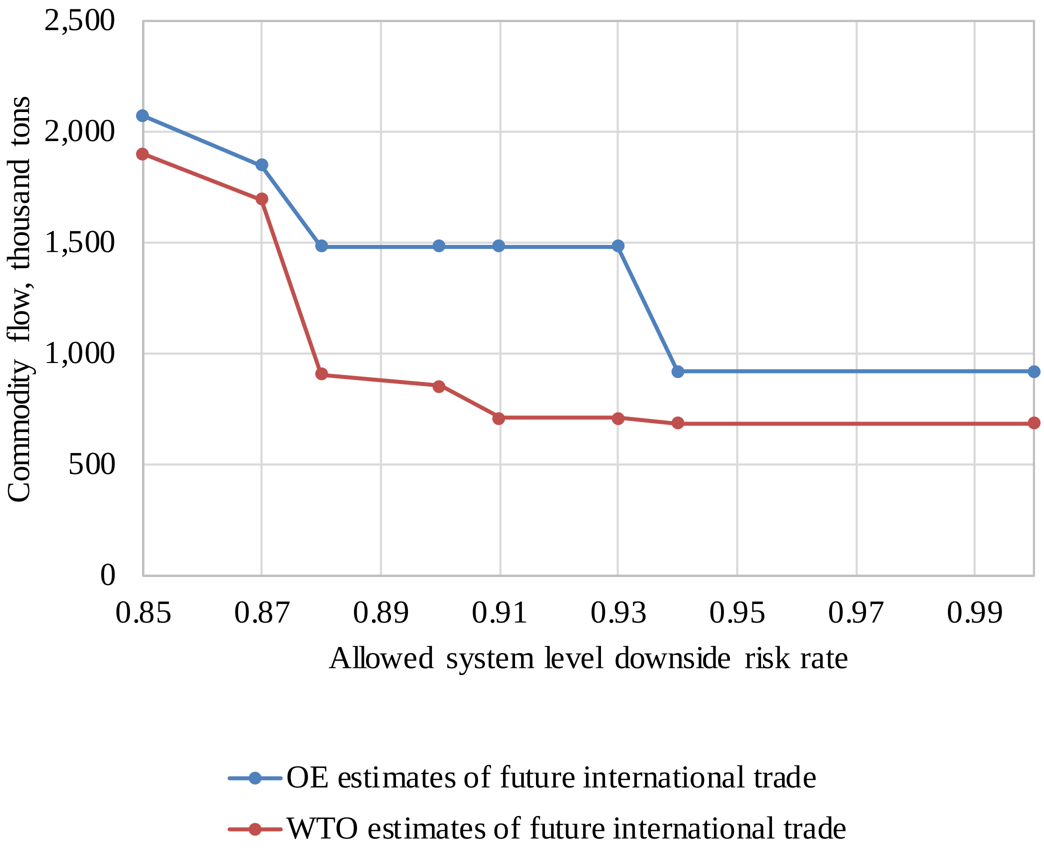

Figure 5 The commodity flow volume through terminal in Utah for different allowed system level downside risk values for $\boldsymbol{\sigma} \in [0.85,1.00]$

The results reveal that the west coast U.S. ports have lower utilization in scenarios where the Panama Canal expansion is considered. To reduce the risk associated with low utilization, the commodity flows from/to several states are routed by the model through Utah and those ports. These commodity flow requires more terminal capacity in that region due to lack of rail capacity in ports. These results suggest that under the low allowed system level downside risk, investing in terminals can be preferable to investing in ports as the former provide more flexibility for commodity flow distribution in terms of the ability to absorb commodity flows coming from different ports and states.

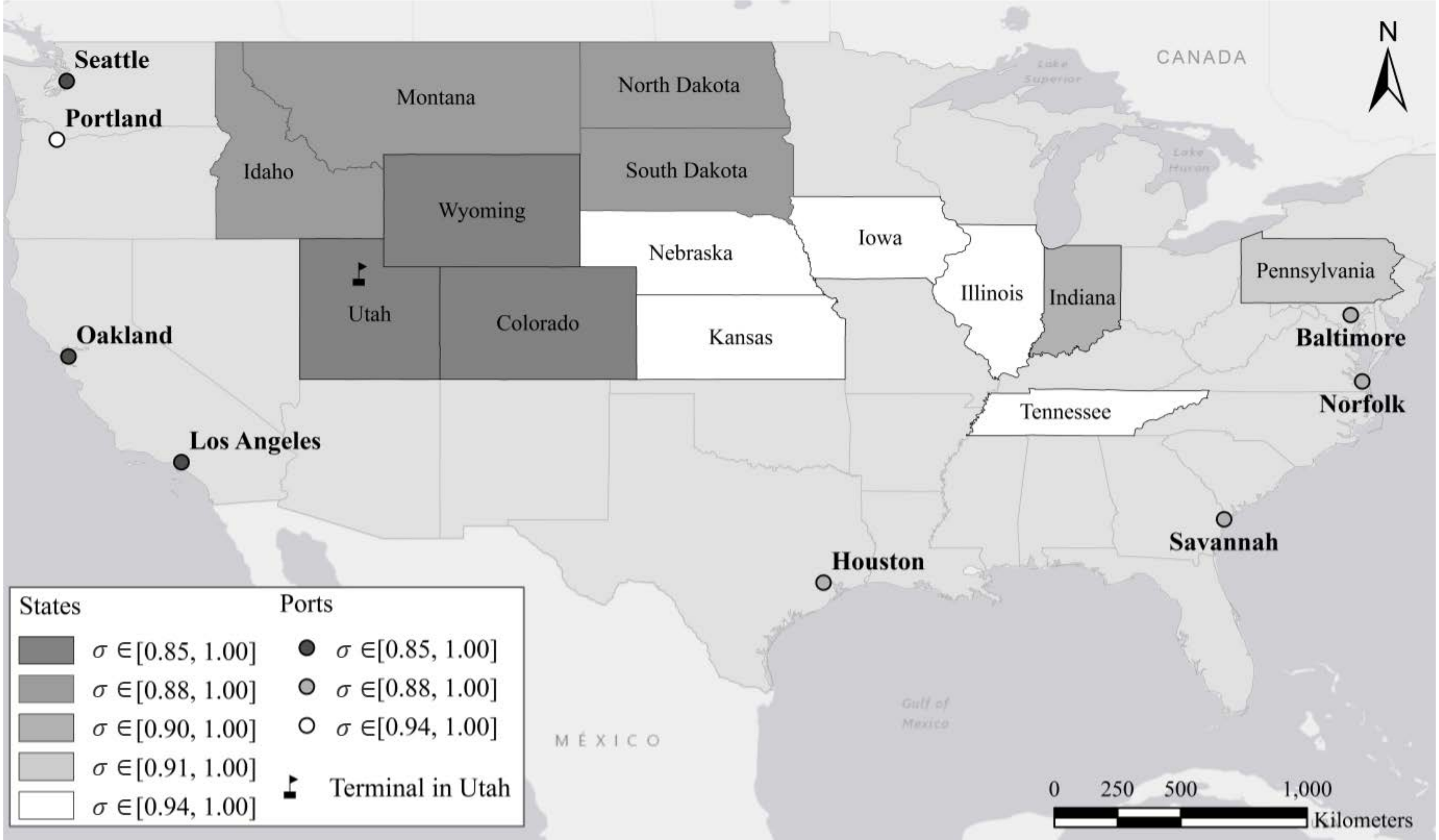

Figure 6 States and ports that have commodity flow from/to terminal in Utah for different allowed system level downside risk values for $\boldsymbol{\sigma} \in [0.85; 1.00]$ under OE estimates of future international trade

Starting from $\sigma = 0.88$, the Utah intermodal project is replaced in the intermodal facility investment plan by four intermodal projects in California: the Los Angeles/Long Beach port and three terminals in California. The low utilization of the port of Los Angeles/Long Beach in some scenarios induces downside risk and prevents the port intermodal project in Los Angeles/Long Beach from being selected when the allowed system level downside risk is capped at a lower level. The three terminal intermodal projects in California are efficient only when the port of Los Angeles/Long Beach is selected.

If we further relax the downside risk constraint (to $\sigma = 0.94$), the Jacksonville port intermodal project is selected. If the Nova Scotia Port is constructed, the Jacksonville port utilization is in the range 58-74% under WTO estimates of future international trade, and 100% in other scenarios. The downside risk induced in those scenarios prevents the port intermodal project in Jacksonville from being selected when the allowed system level downside risk is capped at a lower level. However, in other scenarios, Jacksonville is fully utilized and the improvement of Jacksonville leads to a significant decrease in maritime transportation costs, as the intermodal facility investment project in Jacksonville will allow bigger vessels to call at the port. These results indicate that investing in ports is preferable to investing in terminals when higher downside risk is allowed as ports can provide significant savings in terms of expected system costs but are associated with higher risk.

The following intermodal projects are not selected in all cases whether downside risk is considered or not: port Wilmington, and terminals in Connecticut, Illinois, Indiana, Massachusetts, Maine, Michigan, Nevada, New York and Virginia. It suggests that these intermodal projects should be treated as low priority projects as these terminals and port can have lower commodity flow in some or all of the considered scenarios.

Cost variance and expected system costs across all eight scenarios for $\sigma \in [0.85,1.00]$ are shown in Figure 7. The expected system costs across all scenarios increase with the decrease in the allowed system level downside risk. Similar results are obtained for system costs in each scenario and for expected system costs across the scenarios for a specific estimate of future international trade. The expected system costs under higher estimate of future international trade has larger increase (2.14%) if the allowed system level downside risk is lower compared to that under the lower estimate of future international trade (1.38%). As the allowed system level downside risk decreases, several intermodal projects become infeasible due to the high associated risk. This reduces the flexibility in commodity flow distribution and leads to routes that are more expensive. The difference in the expected system cost increase between the two estimates of future international trade is because commodity flows under both these estimates need to be allocated to the same capacity of intermodal facility. Scenarios with a higher estimate of future international trade have less flexibility in commodity flow distribution through the available routes. Hence, flows are allocated to more expensive routes in scenarios with a higher estimate of future international trade. Consequently, these scenarios experience higher increases in system costs.

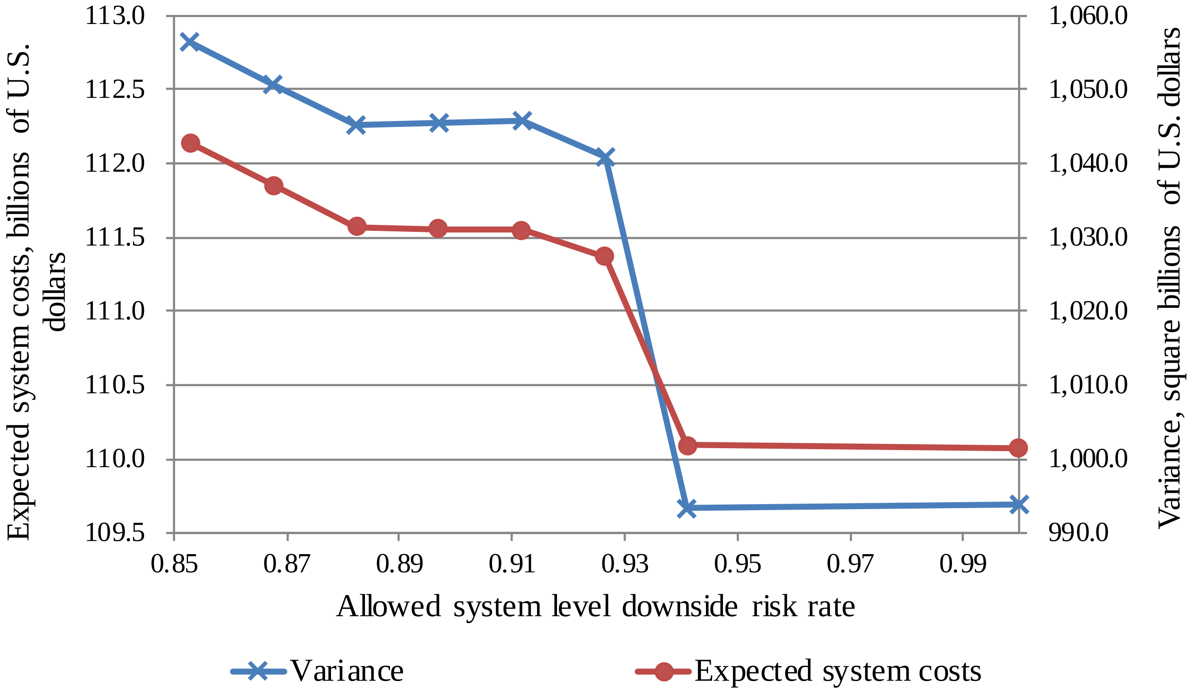

Figure 7 Expected system costs and variance associated with different allowed system level downside risk values for $\boldsymbol{\sigma} \in [0.85,1.00]$

Figure 8 depicts the system costs for the eight considered scenarios. The results for the two different estimates of future international trade are plotted using vertical axes on either side with same scale but different ranges.

Scenarios with the same estimate of future international trade have varying increases in system costs with decreasing allowed system level downside risk due to different realizations of emerging infrastructure projects. In particular, the Panama Canal expansion project allows more commodity flows to go through it and allows bigger vessels to be deployed on routes through the Panama Canal. The construction of the Nova Scotia Port allows bigger vessels to be used to transport commodities to the east coast of the North America. Hence, the scenarios considering either one or both of these projects have more flexibility in commodity flow distribution outside the U.S., leading to lower increases in system costs for the same estimate of future international trade. It contributes to increase in cost variance across all scenarios with decreasing allowed system level downside risk.

The following insights are obtained from the downside risk analysis. First, investing in intermodal terminals is preferable to investing in ports under low allowed system level downside risk. Terminal intermodal projects have lower risk values because they provide more flexibility to absorb commodity flows coming from different ports and states. Second, port intermodal projects tend to be associated with high downside risk, but can reduce expected system costs significantly, and are hence preferable under higher allowed system level downside risk. The expected system costs increase with the decrease in downside risk as fewer intermodal projects are feasible under it, and this reduces the flexibility in commodity flow distribution. Fourth, the cost variance increases with the decrease in allowed system level downside risk due to the need to fully allocate commodity flows for different realizations of emerging infrastructure projects. Fifth, the optimal solution is highly dependent on the allowed system level downside risk. Different sets of investment plans are obtained by varying this parameter.

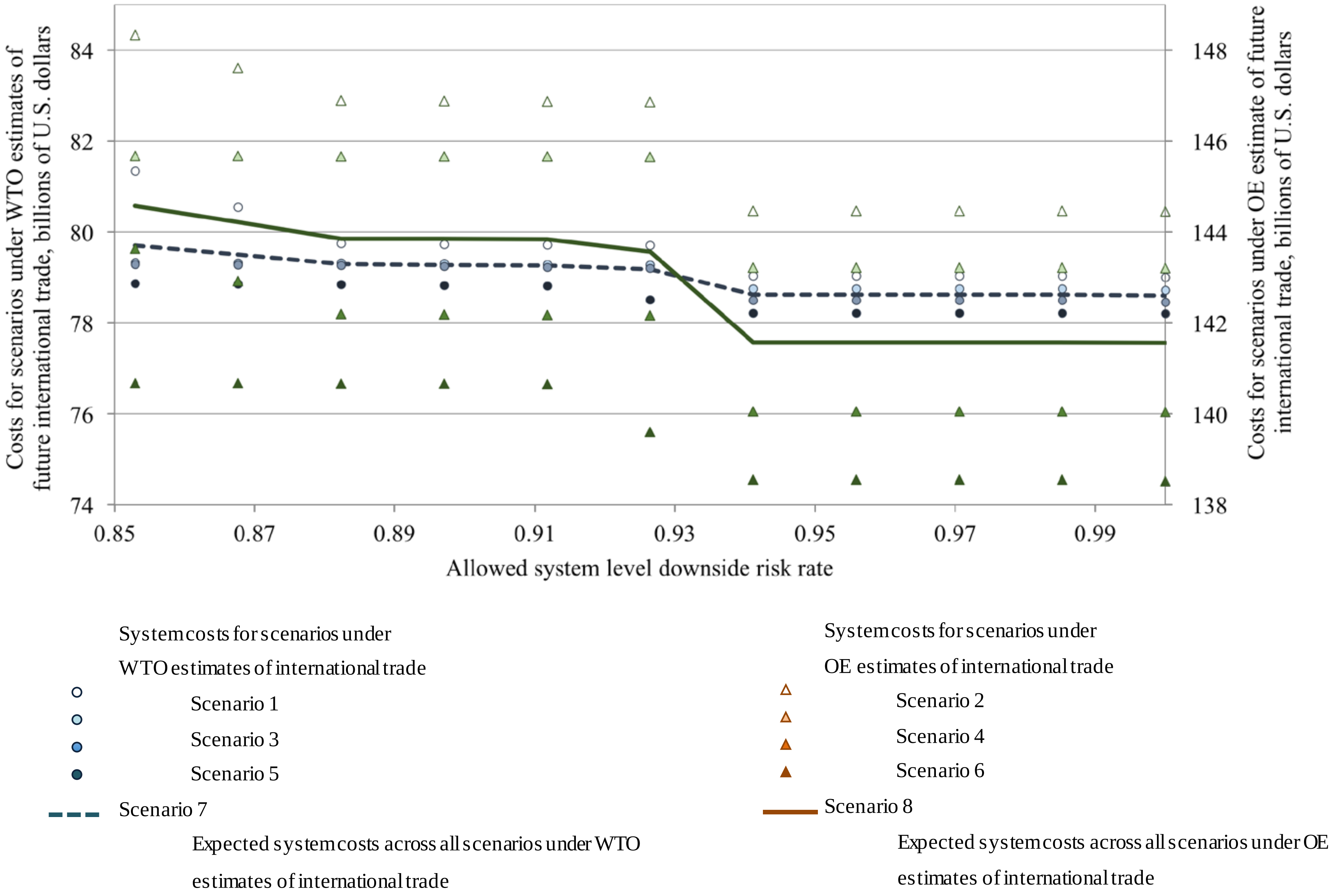

Figure 8 System costs for different values of allowed system level downside risk for $\boldsymbol{\sigma} \in [0.85,1.00]$

CHAPTER 5. CONCLUDING COMMENTS

This study proposes a mixed integer dynamic capacitated intermodal facility location model that incorporates downside risk management to facilitate the strategic intermodal facility investment decision-making process under uncertainty in commodity flow. A uncoordinated and/or myopic strategic intermodal facility investment planning approach may lead to inadequate or wasteful intermodal facility investment. To address limitations of such an approach, this study proposes a holistic system level approach for strategic intermodal facility investment planning. The proposed approach incorporates systematic and coordinated decision-making for strategic intermodal facility investment planning. The proposed methodology provides national-level policymakers with tools to develop policy and regulatory decisions. It also enables local and regional stakeholders to make coordinated, more informed investment decisions that maximize their investment potential.

The IFLMD can also be used to address several real-world issues in the design of the strategic intermodal facility investment plan, including: uncertainty in commodity flow due to different estimates of future international trade, changes in commodity flow distribution due to congestion, system-level congestion reduction, the impact of emerging infrastructure development on commodity flow distribution within the region of interest, and the impact of empty container repositioning cost on commodity flow distribution. The downside risk is incorporated in the proposed model to hedge the investment risk associated with commodity flow uncertainty due to different estimates of future international trade and different emerging infrastructure projects. Downside risk analysis is used to identify different intermodal facility investment plans that are consistent with different risk tolerance levels of system level strategic intermodal facility investment decision-makers or policy-makers. The obtained intermodal facility investment plans illustrate trade-offs between two objectives: minimizing expected system costs and reducing downside risk. To perform the downside risk analysis, different allowed system level downside risk values are considered.

Numerical experiments are used to estimate the optimal strategic intermodal facility investment plan for ports and terminals in the U.S. using national level data. The scenario-based solution approach is used to characterize the uncertainty in commodity flow. Eight scenarios are created, where each scenario captures the uncertainty in commodity flow due to the estimates of future international trade (forecasts from World Trade Organization and Oxford Economics) and the various realizations of two emerging infrastructure projects (Panama Canal expansion and the construction of the Nova Scotia Port). As noted earlier, the results of numerical experiments without downside risk analysis indicate that projects involving the development of ports in New Orleans, Charleston and Boston may be suitable for prioritization. The results also suggest that the project involving the development of the Los Angeles/Long Beach port entails high priority, but with the simultaneous development of relevant terminals. In addition, the results show that the projects involving the development of the Wilmington and Jacksonville ports are sensitive to the construction of the Nova Scotia Port and may lose commodity flow when it opens.

Results for different allowed system level downside risk values are analyzed to rank intermodal projects based on the associated risk. This helps to categorize at national level intermodal projects into several groups: (i) intermodal projects with low risk (six terminal projects: Arizona, Florida, Georgia, New Jersey, Pennsylvania, and Texas; and three port projects: Charleston, Boston, and New Orleans), (ii) intermodal projects that are not optimal in any scenario regardless of allowed system level downside risk (port project in Wilmington, terminal projects in Connecticut, Illinois, Indiana, Massachusetts, Maine, Michigan, Nevada, New York and Virginia), (iii) intermodal projects that may or may not be included depending on the allowed system level downside risk (port projects in Jacksonville and Los Angeles / Long Beach, terminal project in Utah, and three terminal projects in California).

Insights from the numerical experiments suggest that investing in terminals is preferable when the allowed system level downside risk is low. When the allowed system level downside risk is on the higher side, port intermodal projects become more preferable. The results also show that with lower allowed system level downside risk, the expected system costs and cost variance increase due to more restrictive conditions imposed on commodity flow distribution as fewer investment plans are feasible. Further, the optimal intermodal facility investment plan can change significantly due to uncertainty in commodity flow and different risk perceptions of the system level strategic intermodal facility investment decision-makers.

At a more fundamental level, of significant importance to maritime and intermodal infrastructure decision-makers at the local level and policy makers at the regional or national levels, the proposed study illustrates that decisions on significant investments in new infrastructure or enhancements to existing infrastructure should be based on holistic system level evaluations that incorporate important interacting factors and developments that may geographically far removed. That is, isolated local-level evaluations and uncoordinated decisions (related to such investments) due to the potential for competition for freight transportation demand among the various proposed projects can significantly enhance the risk of underperformance relative to the forecast growth strategies while making such investments. This further suggests that there may be an important role for regional- or national-level policymakers in terms of conducting appropriate studies and coordinating strategies, or providing advisories, in conjunction with the local and regional stakeholders. Further, the current study results using the numerical experiments are based on specific trend scenarios and the available data; more exhaustive data sets or other trend scenarios can seamlessly be incorporated in the proposed IFLMD model and may illustrate other infrastructure investment choices.

Future research directions are as follows. First, the estimation of the difference between coordinated decisions at a national level and decentralized decisions at the individual intermodal facility level can aid regional and national policymakers to make decisions related to the strategic planning of intermodal facilities. Second, the vulnerability of the intermodal transportation system in the U.S. can be analyzed by adding scenarios with facility disruptions.

REFERENCES

Alumur, S. A., B.Y. Kara, and O.E. Karasan. Multimodal Hub Location and Hub Network Design. *Omega*, Vol. 40, No. 6, 2012a, pp. 927–939.

Alumur, S.A., S. Nickel, and F. Saldanha-da-Gama. Hub Location Under Uncertainty. *Transportation Research Part B,* Vol. 46, 2012b, pp. 529–543.

American association of port authorities. Port industry statistics. [ONLINE] Available at: http://www.aapa-ports.org/unifying/ (Accessed 28 June 2016).

Benedyk, I.V., Peeta, S., Zheng, H., Guo, Y. and Iyer, A.V. Dynamic Model for System-Level Strategic Intermodal Facility Investment Planning. *Transportation Research Record Journal of the Transportation Research Board,* No. 2548, 2016.

Bill summary & status 103rd Congress (1993 - 1994) H.R.1758. [ONLINE] Available at: https://www.congress.gov/bill/103rd-congress/house-bill/1758/text (Accessed 28 June 2016).

Bontekoning, Y.M., Macharis, C. and Trip, J.J. Is a New Applied Transportation Research Field Emerging? – A Review of Intermodal Rail-Truck Freight Transport Literature. *Transportation Research Part A: Policy and Practice,* Vol. 38 No. 1, 2004, pp. 1-34.

Camargo, R.S. de, Miranda Jr., G., Ferreira, R.P.M. and Luna, H.P. Multiple Allocation Hub-and-Spoke Network Design under Hub Congestion. *Computers & Operations, Research* Vol. 32 No. 12, 2009, pp. 3097-3106.

Campbell, J. F. Hub Location for Time Definite Transportation. *Computers & Operations Research,* Vol. 36 No. 12, 2009, pp. 3107–3116.

Contreras, I., Cordeau, J.-F. and Laporte, G. Stochastic Uncapacitated Hub Location. *European Journal of Operational Research,* Vol. 212 No. 3, 2011, pp. 518–528.

Contreras, I., Fernández, E. and Marín, A. The Tree of Hubs Location Problem. *European Journal of Operational Research,* Vol. 202 No. 2, 2012, pp. 390–400.

Correia, I., S. Nickel, and F. Saldanha-da-Gama. The Capacitated Single-Allocation Hub Location Problem Revisited: A Note on a Classical Formulation. *European Journal of Operational Research,* Vol. 207, No. 1, 2010, pp. 92–96.

Crainic, T., and K. Kim. Intermodal Transportation. *Handbooks in Operations Research and management Science: Transportation,* Vol. 14, 2007, pp. 446–538.

Cullinane, K., and M. Khanna. Economies of Scale in Large Container Ships. *Journal of Transportation Economics and Policy,* Vol. 33, No. 2, 1998, pp. 185–207.

Eppen, G.D., Martin, R.K. and Schrage, L. A Scenario Approach to Capacity Planning. *Operations Research*, Vol. 37 No. 4, 1989, pp. 517-527.

European conference of ministers of transport. (1993) The European conference of ministers of transport 1953-1993: past, present and future. Paris: OECD.

Fan, L., W.W. Wilson, and B. Dahl. Congestion, Port Expansion and Spatial Competition for US Container Imports. *Transportation Research Part E: Logistics and Transportation Review*, Vol. 48, No. 6, 2012, pp. 1121–1136.

Felicio, J.A. and Caldeirinha, V.R. The Influence of the Characterisation Factors of the European Ports on Operational Performance: Conceptual Model Testing. *International Journal of Shipping and Transport Logistics,* Vol. 5 No. 3, 2013, pp. 282-302.

Florida's strategic intermodal system strategic plan, 2010. The Florida Department of Transportation. [ONLINE] Available at: http://www.dot.state.fl.us/planning/systems/programs/ (Accessed 28 June 2016).

Fransoo, J.C. and Lee, C.-Y. The Critical Role of Ocean Container Transport in Global Supply Chain Performance. *Production and Operations Management,* Vol. 22 No. 2, 2013, pp. 253-268.

Freight Facts and Figures 2013. FHWA-HOP-14-004. SAIC, U.S. Departments of Transportation Federal Highway Administration, 2014. http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures/pdfs/fff2013_highres.pdf. Accessed July 29, 2015.

Guo, Y., and S. Peeta. Rail-Truck Multimodal Freight Collaboration: Truck Carrier Perspectives in the United States. *Journal of Transportation Engineering,* Vol. 141, No. 11, 2015, pp. 1-11.

Guo, Y., & Peeta, S. (2017). Impacts of interactive accessibility information intervention strategy on residential location choice and travel-related behavior. In compendium of *Transportation Research Board 96th Annual Meeting,* Washington D.C., U.S., 2017.

Guo, Y., Peeta, S., and Mannering, F. Rail-Truck Multimodal Freight Collaboration: a Statistical Analysis of Freight-Shipper Perspectives. *Transportation Planning and Technology,* Vol. 39 No. 5, 2016, pp. 484-506.

Guo, Y., Agrawal, S., Peeta, S., & Somenahalli, S. (2016c). Impacts of property accessibility and neighborhood built environment on single-unit and multiunit residential property values. *Transportation Research Record: Journal of the Transportation Research Board, 2568*, 103-112.

Guo, Y., Wang, J., & Peeta, S. (2016d). The impacts of household registration and head of household travel behavior on travel mode choice in China. In compendium of *Transportation Research Board 95th Annual Meeting*, Washington D.C., U.S., 2016.

Hancock, K. L., and A. Sreekanth. Conversion of Weight of Freight to Number of Railcars. In *Transportation Research Board: Journal of the Transportation Research Board, No. N1-1768*, Transportation Research Board of the National Academies, Washington, D.C., 2001, pp. 1–10.

HSBC Bank plc. US trade forecast report - HSBC global connections. [ONLINE] Available at: https://globalconnections.hsbc.com/global/en/tools-data/trade-forecasts/us (Accessed 28 June 2016).

Huang, S.T., Bulut, E. and Duru, O. Service Quality Assessment in Liner Shipping Industry: an Empirical Study on Asian Shipping Case. *International Journal of Shipping and Transport Logistics*, Vol. 7 No. 2, 2015, pp. 221-242.

Huynh, N., and F. Fotuhi. A New Planning Model to Support Logistics Service Providers in Selecting Mode, Route, and Terminal Location. *Polish Maritime Research*, Vol. 20, 2013, pp. 67–73.

Ishfaq, R. and Sox, C.R. Hub Location–Allocation in Intermodal Logistic Networks. *European Journal of Operational Research*, Vol. 210 No. 2, 2011, pp. 213–230.

Ishfaq, R., and C.R. Sox. Intermodal Logistics: The Interplay of Financial, Operational and Service Issues. *Transportation Research Part E: Logistics and Transportation Review*, Vol. 46, No. 6, 2010, pp. 926–949.

Karimi, H., and M. Setak. Proprietor and Customer Costs in the Incomplete Hub Location-Routing Network Topology. *Applied Mathematical Modeling*, Vol. 38, No. 3, 2014, pp. 1011–1023.

Kaveshgar, N., and N. Huynh. A Genetic Algorithm Heuristic for Solving the Quay Crane Scheduling Problem with Time Windows. *Maritime Economics & Logistics*, advance online publication, 2014, pp. 1–23, DOI: 10.1057/mel.2014.31.

Kaveshgar, N., and N. Huynh. Integrated Quay Crane and Yard Track Scheduling for Unloading Inbound Containers. *International Journal of Production Economics*, Vol. 159, 2015, pp. 168–177.

Lüer-Villagra, A. and Marianov, V. A Competitive Hub Location and Pricing Problem. *European Journal of Operational Research*, Vol. 231 No. 3, 2013, pp. 734–744.

Meng, Q., and X. Wang. Intermodal Hub-and-Spoke Network Design: Incorporating Multiple Stakeholders and Multi-Type Containers. *Transportation Research Part B: Methodological*, Vol. 45, No. 4, 2011, pp. 724–742.

Moving ahead for progress in the 21st century (MAP 21). Freight-related provisions. [ONLINE] http://www.dot.ca.gov/hq/tpp/offices/. (Accessed 28 June 2016).

National freight strategic plan. Draft for public comments. [ONLINE] https://www.transportation.gov/freight/NFSP. (Accessed 28 June 2016).

Owen, S.H. and Daskin, M.S. Strategic Facility Location: a Review', *European Journal of Operational Research*, Vol. 111 No. 3, 1998, pp. 423-447.

Panama Canal Expansion Study. Phase I Report: Developments in Trade and National and Global Economies. U.S. Department of Transportation Maritime Administration. 2013. http://www.marad.dot.gov/wp-content/uploads/pdf/Panama_Canal_Phase_I_Report_-_20Nov2013.pdf. Accessed July 29, 2015.

Sharif, O., and N. Huynh. Yard Crane Scheduling at Container Terminals: A Comparative Study of Centralized and Decentralized Approaches. *Maritime Economics & Logistics*, Vol. 14, 2012, pp. 139–161.

Sharif, O., N. Huynh, and J.M. Vidal. Application of El Farol Model for Managing Marine Terminal Gate Congestion. *Research in Transportation Economics*, Vol. 32, No. 1, 2011, pp. 81–89.

Snyder, J.D., K. Doyle, and P. Toor. The Potential Impacts of the Panama Canal Expansion and Evolving Post - Panamax / Super Post - Panamax Container Ship Routes on Michigan Freight and Hub Logistics. Center for Community and Economic Development. Michigan State University. Michigan, August 2013. [ONLINE]. Available at: http://knowledgeplanning.org/upload/Panama%20Canal%20Expansion%20Paper%20%20FINAL%20AUG%2030%20w%20authors.pdf. (Accessed 29 July 2015).

SteadieSeifi, M., N.P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi. Multimodal Freight

Transportation Planning: A Literature Review. *European Journal of Operational Research*, Vol. 233, No. 1, 2014, pp.1–15.

Taylor, G.D. *Logistics Engineering Handbook*. Taylor & Francis Group, LLC. Boca Raton, 2008.

Transportation Statistics Annual Report. 2012. U.S. Departments of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, 2013. [ONLINE] Available at: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/tsar_2012.pdf.pdf. (Accessed 29 July 29 2015).

Tversky, A. and Kahneman, D. Advances in Prospect Theory: Cumulative Representation of Uncertainty. *Journal of Risk and Uncertainty*, Vol. 5 No. 4, 1992, pp. 297–323.

Tyndall, G.R., J. Cameron, and R.C. Taggart. *Strategic Planning and Management Guidelines for Transportation Agencies*. NCHRP-331, Transportation Research Board, National Research Council, 1990.

U.S. Census Bureau. U.S. trade online. Washington, D.C. [ONLINE] Available at: https://usatrade.census.gov (Accessed 28 June 2016).

U.S. Merchandise Trade: Selected Highlights, December, 2013. FT920, U.S. Department of Commerce. [ONLINE] Available at: http://www.census.gov/foreign-trade/Press-Release/2013pr/12/ft920/ft920.pdf. (Accessed 29 July 29 2015).

World fright rates. Freight calculator. [ONLINE] Available at: http://worldfreightrates.com (Accessed 28 June 2016).

World Shipping Council. *Container Supply Review*. 2011. [ONLINE] Available at: http://www.worldshipping.org/public-statements/2011_Container_Supply_Review_Final.pdf. Accessed July 29, 2015.

World Trade Organization. International trade statistics 2013. [ONLINE] Available at: http://www.wto.org/english/res_e/statis_e/its2013_e/its13_toc_e.htm (Accessed 28 June 2016).

Zhai, H., Liu, Y. and Chen, W. Applying Minimum-Risk Criterion to Stochastic Hub Location Problems. *Procedia Engineering*, Vol. 29, 2012, pp. 2313-2321.

Contacts

For more information:

Srinivas Peeta
Principal Investigator
Professor of Civil Engineering & Director
NEXTRANS Center, Purdue University
Ph: (765) 496 9726
Fax: (765) 807 3123
peeta@purdue.edu
https://engineering.purdue.edu/~peeta/

NEXTRANS Center
Purdue University - Discovery Park
3000 Kent Ave.
West Lafayette, IN 47906
nextrans@purdue.edu
(765) 496-9724
www.purdue.edu/dp/nextrans