Scenario-Based Dynamic Model of System Level Strategic Intermodal Facility Investment Planning under Freight Transportation Demand Uncertainty

Irina V. Benedyk  
Lyles School of Civil Engineering/NEXTRANS Center, Purdue University  
3000 Kent Avenue  
West Lafayette, IN 47906  
Tel: +1-765-496-9768  
Email: birina@purdue.edu

Srinivas Peeta, Ph.D. (Corresponding Author)  
Lyles School of Civil Engineering, Purdue University  
550 Stadium Mall Drive  
West Lafayette, IN, 47907-2051  
Tel: +1-765-494-2209  
Fax: +1-765-496-7996  
peeta@purdue.edu

Hong Zheng  
NEXTRANS Center, Purdue University  
3000 Kent Avenue, West Lafayette, IN, 47906  
Tel: +1-765-496-9768  
Email: zheng225@purdue.edu

Yuntao Guo  
Lyles School of Civil Engineering/NEXTRANS Center, Purdue University  
3000 Kent Avenue  
West Lafayette, IN 47906  
Tel: +1-765-496-9768  
Email: guo187@purdue.edu

Ananth V. Iyer  
Krannert School of Management, Purdue University  
403 W State St., West Lafayette, IN, 47907  
Phone: +1-765-494-4514  
aiyer@purdue.edu

Submitted for Presentation and Publication Consideration  
Revised, November 2015

Word Count: 5,995 words + 6*250 (2 figures + 4 tables) = 7,495
ABSTRACT

This paper proposes a scenario-based mixed integer dynamic capacitated intermodal facility location model (IFLM) to determine the optimal strategic intermodal facility investment planning strategy that accounts for freight transportation demand uncertainty. The proposed model seeks to assist high-level policymakers in strategic intermodal facility investment planning at a regional- or national-level, and foster coordinated strategies and policies for intermodal facility development from a systems perspective. A scenario-based approach is used to characterize demand uncertainty induced by global trade changes and emerging infrastructure development projects. Dynamic demand is incorporated in the model to capture the impact of differences in the evolution of different scenarios on the system level strategic intermodal investment planning. The proposed IFLM also captures the impact of congestion in ports and terminals, transshipment costs, changes in capacity of intermodal facilities, economies of scale, and empty container repositioning costs on freight transportation demand and strategic intermodal investment planning. Three numerical experiments are designed to demonstrate the potential applicability of the proposed model. Each experiment presents a realization of potential future freight transportation demand and emerging infrastructure development project. In addition, the impacts of freight transportation facility service level changes of some regions on the freight transportation demand for other regions and the optimal intermodal investment planning strategy in the United States are also explored. The results show that the proposed model can assist decision-makers in strategic intermodal facility investment planning by prioritizing capacity expansion of ports and terminals. They also illustrate the importance of system level and coordinated planning in strategic intermodal investment decision-making process. The proposed strategic planning model can further be integrated with operational planning models to improve the investment decision-making process.
INTRODUCTION
The maritime global trade corridors have changed substantially and continue to evolve. While reasons for these changes range from the opening of new routes (e.g., Panama (1) or Suez Canals) to World Wars, the main driving force in global trade is the economy. The world manufacturing center has moved across time, from North America and Europe, first to Japan, then to South Korea, and later to China and Malaysia (2). More recently, India and the Association of Southeast Asian Nations are also competing to increase their share of the world’s manufacturing production (2). The majority of the United States (U.S.) import/export freight volume is transported using the maritime transportation mode. In 2012, over 70% of all the U.S. international freight volume was carried by maritime transportation (3, 4). Rapid containerization of maritime transportation of general cargo has occurred in the last 20 years (5, 6). Intermodal freight transportation accounted for more than 42.1% of the import/export freight volume in 2013 (7). The Bureau of Transportation Statistics (4) predicts that the volume of intermodal freight transportation will increase 3.25 times by 2040. However, the potential growth in freight transportation demand also entails challenges for decision-makers to plan intermodal infrastructures investment strategies due to the uncertainty of the global trade changes; for instance, further development of China, growth of export from India because of low wages levels, or maybe the rapid development of the African economy. There continues to be much debate regarding the most likely scenario to unfold in the future.

To accommodate the uncertainty in global trade changes and the steady increase in freight transportation demand in the future, it is important to conduct strategic intermodal facility (including container seaports and inland intermodal terminals, referred to as ports and terminals hereafter) investment planning at the national level. 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 (e.g. the Panama Canal expansion) on freight transportation demand. In this study, a scenario-based mixed integer dynamic capacitated intermodal facility location model with multiple allocations (IFLM) is proposed to account for the aforementioned aspects. To demonstrate the performance of the proposed model, three national level experiments that consider different port/terminal projects are designed and analyzed. The purpose of conducting national level experiments is to explore the impacts of changes in freight transportation facility service levels in some regions on the freight transportation demand in other regions in the investment decision-making process of intermodal facilities. Each experiment contains four different case studies: with and without the Panama Canal expansion, and with and without the construction of a new port in Nova Scotia, Canada.

The remainder of the paper is organized as follows. The next section reviews the literature in the multimodal freight transportation planning domain. The proposed IFLM is mathematically formulated thereafter. Then, three numerical experiments are discussed and results for four different case studies are analyzed. Finally, some concluding comments and practical implications are discussed.

LITERATURE REVIEW
A recent study (8) provides a comprehensive review of multimodal freight transportation planning. Previous studies related to multimodal freight transportation planning can be classified
into three different levels based on the planning horizon: operational level, tactical level, and strategic level (8). Strategic planning relates to making longer term investment decisions on the present intermodal facilities, tactical planning involves shorter term plans for the optimal utilization of given infrastructure, and operational planning deals with real-time planning, and reaction and adjustment to any kind of disturbances (8). The proposed study focuses on strategic intermodal facility investment planning. Intermodal transportation is a specific type of multimodal transportation in which the commodity is transported in the intermodal transportation unit without handling the commodity itself (9).

Based on the literature review, this study identifies five research needs in modeling the investment decision-making process of intermodal facilities at the strategic level; they include: (i) factoring the impacts of congestion in ports and terminals on container flow distribution and mode choice (8); (ii) considering transshipment costs as a factor for container flow distribution (8); (iii) incorporating the costs of relocating empty containers (8); (iv) identifying different sources of uncertainty; and (v) integrating dynamic changes in freight transportation demand for intermodal facility investment over a long time horizon. None of the existing studies address all five of these research needs simultaneously.

Several studies have shown that congestion at intermodal facilities can affect commodity flow distribution due to increase in transportation costs caused by delays. To reduce the potential congestion, some studies (10, 11, 12, 13) proposed different operational level planning methods to increase port productivity, including productivity improvement at truck gates, yard, and quay cranes. Sharif et al. (10) investigated various strategies using an agent-based approach to manage truck gate congestion at ports. Sharif and Huynh (11) compared the results of centralized and decentralized approaches for modeling yard crane scheduling at container terminals, and conclude that the centralized approach outperforms the decentralized approach due to complete and accurate information on future truck arrivals. Kaveshgar and Huynh (12) developed a genetic algorithm to manage quay crane scheduling to improve the productivity of quay cranes. Kaveshgar and Huynh (13) proposed an integrated model that identifies the optimal operational plan for truck gates, yard, and quay cranes simultaneously. Fan et al. (14) studied the impacts of congestion in ports and terminals 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 at an operational level, to the best of our knowledge there are none that focus on strategic intermodal facility investment planning by factoring congestion. Other studies (15, 16) modeled capacity limits of transit hubs but did not consider the congestion effect. It is important to consider both the facility capacity and congestion effects. Some studies (17, 18, 19, 20) only consider transshipment costs (the second need) without factoring congestion costs. For shippers, the costs of both transshipment and delay (due to congestion) can significantly impact container transportation decisions.

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.

Studies considering freight transportation demand uncertainty (the fourth need) in modeling the investment decision-making process of intermodal facilities are sparse (21, 22, 23).
I. Benedyk, S. Peeta, H. Zheng, Y. Guo, and A. Iyer

Contreras et al. (21) modeled the uncertainty in freight transportation demand and transportation costs using a Monte Carlo simulation-based method on a hypothetical network. Eppen et al. (22) used a scenario-based approach to account for demand uncertainty to aid capacity configuration for four assembly plants of General Motors. Alumur et al. (23) considered two types of uncertainty: freight transportation demand uncertainty and uncertainty in setup costs. Previous studies do not incorporate capacity changes of intermodal facilities in other regions (e.g. opening of new ports, or expansion of existing ports and terminals). Decision-makers need to consider different sources of uncertainty to hedge the risks associated with intermodal facility investment. In our study, the freight transportation demand uncertainty is modeled using a scenario-based approach. The scenario-based approach helps decision-makers to design the optimal intermodal investment strategy that minimizes the expected system costs across all of the scenarios considered (22). In addition, it allows decision-makers to evaluate the impact of a particular scenario on the system performance and intermodal investment decision-making process. However, the results of the scenario-based approach also depend on the scenarios considered. Also, if only a subset of possible scenarios is considered, the model solution may be suboptimal. If a large number of scenarios is included in the model, it can entail additional computational effort. Moreover, the scenario-based approach cannot find the optimal investment strategy that minimizes the probability of unfavorable outcomes of system performance (22). For example, the optimal investment strategy identified by the scenario-based approach may have low expected system costs across all possible scenarios, but can have high system costs in some scenarios. Few studies consider dynamic demand for intermodal facilities over long time horizons (the fifth need). Instead, 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.

The proposed IFLM seeks to address all of the aforementioned needs. The transshipment costs for different congestion levels are incorporated into the IFLM using a piecewise linear approximation similar to Fan et al. (14), 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.

MODEL FORMULATION

Problem Description
The mixed integer dynamic capacitated IFLM with proposed in this study is used for long-term strategic investment planning for intermodal facilities at the national level such that the system can accommodate future freight transportation demand and total system costs (including transportation costs, congestion costs, handling costs, empty container repositioning costs, and investment costs) are minimized. The freight transportation demand is split into import and export demand, and represents the total volume that needs to be shipped between two terminal nodes. Terminal nodes represent origins of export demand and destinations of import demand. The capacity of transit nodes (such as intermodal facilities and canals) is bounded for each mode.
of transportation. The proposed model allows for multiple allocations, which implies that commodity flows can be split and assigned to more than one transit node. Various parts of a commodity flow can be routed through different sets of transit nodes. The IFLM seeks to capture the commodity flow changes due to congestion in transit nodes, and capacity changes of transit nodes in other regions.

To hedge investment risk due to freight transportation demand uncertainty, different scenarios of commodity flow have been incorporated in the model, where each scenario represents the prediction of commodity flow changes in the future. We incorporate dynamic demand in the model to capture the impacts of differences in the evolution of different scenarios of commodity flow on the investment decision-making process. We assume that there is a finite set of scenarios with known probabilities.

To model commodity flow changes due to the use of vessels of different sizes, the study introduces five maritime modes corresponding to five vessel types of different sizes. The economies of scale associated with using larger vessels provide lower transportation costs per unit of commodity (24). Hence, each vessel type has different associated transportation costs. Therefore, in the proposed graph-based IFLM, the five maritime modes are represented by five different links where each link corresponds to a specific vessel type. Then, a link cost represents the transportation cost and the link flow represents the commodity flow transported for a vessel type.

To capture the congestion effect at transit nodes, the study introduces three congestion levels. The first congestion level is associated with the basic transfer cost specified by operators of the ports, terminals and canals, and corresponds to an annual volume less than $3/5$ of the capacity. Commodity flows associated with the second and third congestion levels have higher handling costs ($14$). The second congestion level handles an annual volume of between $3/5$ and $4/5$ of the capacity. Under it, the facility suffers moderate congestion, and hence shippers pay an extra cost due to the delay at the facility. The extra cost consists of the costs of storage and demurrage for using container, and the delay cost. The third congestion level handles an annual volume of between $4/5$th capacity to full capacity. Under it, the facility is highly congested, leading to even higher costs for transferring commodity for the shippers.

To capture the impact of handling costs on commodity flows, we assigned a fixed handling cost to each transit node for each mode. Empty container repositioning costs are captured by multiplying the difference between incoming and outgoing commodity flows with the unit empty container repositioning cost for each transit node. Investment costs are specified for each time period to identify when a candidate project is implemented if it is selected.

In this study, the shipper’s mode and route choices are based on two of the most important factors that influence them, transportation costs, and value of time. However, other factors that may be of interest to shippers (such as commodity characteristics, past experience with particular mode or route, etc.) are not considered due to the non-availability of data.

**Model Notation**

Let the global trade corridors be represented by a graph with $P$ nodes, where $P$ consists of two mutually exclusive and collectively exhaustive subsets: terminal nodes (which include the sets $A$ and $B$) and transit nodes ($r \in R$). Nodes are connected by links which denote commodity transportation by either the maritime or the ground transportation modes. The ground transportation mode can be split into rail and truck transportation. Transshipment between an origin and a destination must pass through at least one transit node. Table 1 summarizes the
notation used in the proposed IFLM. Transit nodes represent ports, terminals and canals.

**TABLE 1 Sets and Parameters**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sets</strong></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>Set of terminal nodes representing origins for import demand and destinations for export demand;</td>
</tr>
<tr>
<td>$B$</td>
<td>Set of terminal nodes representing origins for export demand and destinations for import demand;</td>
</tr>
<tr>
<td>$R$</td>
<td>Set of transit nodes, including ports, terminals and canals;</td>
</tr>
<tr>
<td>$P = A \cup B \cup R$</td>
<td>Set of nodes;</td>
</tr>
<tr>
<td>$E$</td>
<td>Set of links;</td>
</tr>
<tr>
<td>$G$</td>
<td>Set of commodities;</td>
</tr>
<tr>
<td>$S$</td>
<td>Set of possible scenarios;</td>
</tr>
<tr>
<td>$M$</td>
<td>Set of modes;</td>
</tr>
<tr>
<td>$M' \subseteq M$</td>
<td>Subset of maritime modes; $M' := {m'_1, m'_2, m'_3, m'_4, m'_5}$ denotes five maritime modes associated with five vessel types in the increasing order of size;</td>
</tr>
<tr>
<td>$M'' \subseteq M$</td>
<td>Subset of ground transportation modes, consisting of the rail and truck modes;</td>
</tr>
<tr>
<td>$T$</td>
<td>Set of time periods;</td>
</tr>
<tr>
<td>$l_r$</td>
<td>Set of project configuration plans for transit node $r$;</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Set of congestion levels; $\Gamma := {1, 2, 3}$ denotes three congestion levels in the increasing order of congestion;</td>
</tr>
<tr>
<td><strong>General parameters</strong></td>
<td></td>
</tr>
<tr>
<td>$\Theta_s$</td>
<td>Probability of scenario $s \in S$;</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Unit empty container repositioning cost;</td>
</tr>
<tr>
<td>$w_{gij}^{st}$</td>
<td>Demand of commodity type $g \in G$ from terminal node $i$ to terminal node $j$ in scenario $s$ in time period $t$; where $i \in A$ and $j \in B$ for import demand, and $i \in B$ and $j \in A$ for export demand</td>
</tr>
<tr>
<td>$u_{rtm}^{st}$</td>
<td>Capacity of transit node $r$ for mode $m \in M$ in scenario $s$ in time period $t \in T$;</td>
</tr>
<tr>
<td>$\mu_g$</td>
<td>Loading rate of commodity type $g$ in units of tons per twenty-foot equivalent unit (TEU) (25);</td>
</tr>
<tr>
<td><strong>Project configuration</strong></td>
<td></td>
</tr>
<tr>
<td>$\varphi$</td>
<td>A specific project configuration, $\varphi \in l_r$;</td>
</tr>
<tr>
<td>$h_{t}^{\varphi rm}$</td>
<td>Extra capacity of configuration $\varphi$ at transit node $r$ for mode type $m$ in time period $t$;</td>
</tr>
<tr>
<td>$k_{t}^{\varphi r}$</td>
<td>Investment cost to setup configuration $\varphi$ of transit node $r$ in time period $t$;</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
</tr>
<tr>
<td>$c_{gmt}^{ij}$</td>
<td>Transportation cost per TEU for commodity type $g$ from node $i$ to $j$ through mode $m$ in time period $t$;</td>
</tr>
<tr>
<td>$d_{rmt}$</td>
<td>Terminal handling cost per TEU in port $r$ for mode $m$ at congestion level $\tau \in \Gamma$;</td>
</tr>
</tbody>
</table>

Each project involves investment to increase the capacity of transit nodes and/or to accommodate larger vessels at ports. A port can have $l_r$ investment projects, and each
investment project is called a configuration, denoted as \( \varphi \). Two different configurations can represent the same improvement but with different schedules of implementation. The configuration is associated with two vectors \( h^{\varphi \text{q} \text{m} \text{t}}_r \) and \( k^{\varphi \text{q} \text{m} \text{t}}_r \), which specify the extra capacity and setup cost for mode \( m \) in time period \( t \) due to the \( \varphi \)th configuration respectively. Note that investments are specified for each time period \( t \), so we can model the temporal investment decisions for a particular port or terminal.

**Decision Variables**

The variables in the IFLM are summarized in Table 2. The commodity flow on a link \( ij \) is denoted by \( x^{\alpha \text{g} \text{m} \text{s} \text{t}}_t \) for import flow and \( y^{\beta \text{g} \text{m} \text{s} \text{t}}_t \) for export flow, in tons. Indices \( \alpha \) and \( \beta \) specify the origin terminal node, and they are used to ensure that demand for each \( w^{ij}_{gst} \) is satisfied.

The main decision variable in the model is the binary variable \( z^{\varphi}_r \), which is 1 if the \( \varphi \)th configuration is implemented for port \( r \), and ‘0’ otherwise. The summation of all commodity flows is represented by \( y_{rst} \); it is the summation of import commodity flows \( \delta^{\alpha \text{g} \text{m} \text{s} \text{t} \tau}_{gmst} \) and export flows \( \zeta^{\beta \text{g} \text{m} \text{s} \text{t} \tau}_{gmst} \), which reflect the flows at the congestion level \( \tau \). To maintain a linear model structure, two dummy variables are used: imbalance variables \( \Delta^+_{rst} \) and \( \Delta^-_{rst} \). These variables are discussed later in this section. Every new configuration will lead to capacity changes, while new capacity for a node is represented by \( u^{rm}_{st} \).

**TABLE 2 Variables**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x^{\alpha \text{g} \text{m} \text{s} \text{t}}_t )</td>
<td>Import commodity flow of commodity ( g ) from ( i ) to ( j ) with origin ( \alpha \in A ), for mode ( m ) and scenario ( s ) in time period ( t );</td>
</tr>
<tr>
<td>( y^{\beta \text{g} \text{m} \text{s} \text{t}}_t )</td>
<td>Export commodity flow of commodity ( g ) from ( i ) to ( j ) with origin ( \beta \in B ), for mode ( m ) and scenario ( s ) in time period ( t );</td>
</tr>
<tr>
<td>( z^{\varphi}_r )</td>
<td>1 if configuration ( \varphi ) is selected for transit node ( r ); 0 otherwise;</td>
</tr>
<tr>
<td>( u^{rm}_{st} )</td>
<td>Updated capacity for transit node ( r ) for mode ( m ) and scenario ( s ) in time period ( t );</td>
</tr>
<tr>
<td>( \delta^{\alpha \text{g} \text{m} \text{s} \text{t} \tau}_{gmst} )</td>
<td>Import commodity flow of ( x^{\alpha \text{g} \text{m} \text{s} \text{t}}_t ) at congestion level ( \tau );</td>
</tr>
<tr>
<td>( \zeta^{\beta \text{g} \text{m} \text{s} \text{t} \tau}_{gmst} )</td>
<td>Export commodity flow of ( y^{\beta \text{g} \text{m} \text{s} \text{t}}_t ) at congestion level ( \tau );</td>
</tr>
<tr>
<td>( y_{rst} )</td>
<td>Sum of the import and export commodity flows at transit node ( r ) for mode ( m ) and scenario ( s ) in time period ( t ) at congestion level ( \tau );</td>
</tr>
<tr>
<td>( \Delta^+<em>{rst}, \Delta^-</em>{rst} )</td>
<td>Dummy variables to model import and export imbalances;</td>
</tr>
</tbody>
</table>

**Intermodal Facility Location Model Formulation**

**Objective Function**

The IFLM objective function is as follows:
To determine the optimal decision for investments in ports and terminals, the objective function seeks to minimize the total system costs that include: (i) expected transportation costs (the first and second terms in Eq. (1)); (ii) expected congestion costs (the third term); (iii) investment costs (the fourth term); and (iv) costs for empty container repositioning (the fifth term).

The constraints are as follows, and include mass balance, non-negativity, capacity, maximum number of selected project configurations, and imbalance constraints.

**Commodity Flow Mass Balance Constraints**

These constraints ensure flow conservation at each node:

- at origin nodes (for import and export):

\[
\sum_{r \in R} \sum_{m \in M} x_{gms}^{\alpha r} = \sum_{j \in B} w_{gst}^{ij} \quad \forall \alpha = i \in A, g \in G, s \in S, t \in T \tag{2}
\]

\[
\sum_{r \in R} \sum_{m \in M} y_{gms}^{\beta j} = \sum_{i \in A} w_{gst}^{ij} \quad \forall \beta = j \in B, g \in G, s \in S, t \in T \tag{3}
\]

- at destination nodes (for import and export):

\[
\sum_{r \in R} \sum_{m \in M} x_{gms}^{\alpha r} = w_{gst}^{ij} \quad \forall \alpha = i \in A, j \in B, g \in G, s \in S, t \in T \tag{4}
\]

\[
\sum_{r \in R} \sum_{m \in M} y_{gms}^{\beta r i} = w_{gst}^{ij} \quad \forall \beta = j \in B, i \in A, g \in G, s \in S, t \in T \tag{5}
\]

- at intermediate transit nodes (for import and export):

\[
\sum_{i \in A \cup R} \sum_{m \in M} x_{gms}^{ar} - \sum_{j \in B \cup U} \sum_{m \in M} x_{gms}^{ar} = 0 \quad \forall \alpha = A, r \in R, g \in G, s \in S, t \in T \tag{6}
\]

\[
\sum_{i \in B \cup U} \sum_{m \in M} y_{gms}^{br} - \sum_{j \in A \cup R} \sum_{m \in M} y_{gms}^{br} = 0 \quad \forall \beta = B, r \in R, g \in G, s \in S, t \in T \tag{7}
\]
Non-negativity of Decision Variables (for import and export):
\[ x_{gmst}^{\alpha ij} \geq 0 \quad \forall \alpha \in A, i, j \in P, g \in G, m \in M, s \in S, t \in T \quad (8) \]
\[ y_{gmst}^{\beta ij} \geq 0 \quad \forall \beta \in B, i, j \in P, g \in G, m \in M, s \in S, t \in T \quad (9) \]

1

Capacity Constraints

The capacity at a transit node may change if a project configuration is chosen. The new node capacity is the sum of the initial capacity and the extra capacity after node expansion \( h_t^{\text{prm}} \).

\[ z_r^\varphi \] indicates whether a configuration is implemented, and is a 0-1 binary variable.

\[ v_{st}^{rm} = u_{st}^{rm} + \sum_{\varphi \in \Gamma_r} z_r^\varphi \times h_t^{\text{prm}} \quad \forall r \in R, m \in M, s \in S, t \in T \quad (10) \]

Three congestion levels \( \tau \) reflect the congestion costs. Thereby, the commodity flows traversing through a transit node are split into three components because each component has a different handling cost. Eqs. (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 divided by the loading rate \( \mu_g \). In Eqs. (11) and (12), \( \mu_g \) is used to convert tons into TEUs.

\[ x_{gmst}^{\alpha ij} \frac{1}{\mu_g} = \sum_{\tau} \delta_{gmst}^{\alpha ij} \quad \forall \alpha \in A, i \in A \cup R, j \in R \cup B, g \in G, m \in M, s \in S, t \in T \quad (11) \]
\[ y_{gmst}^{\beta ij} \frac{1}{\mu_g} = \sum_{\tau} \zeta_{gmst}^{\beta ij} \quad \forall \beta \in B, i \in R \cup B, j \in A \cup R, g \in G, m \in M, s \in S, t \in T \quad (12) \]

\[ \delta_{gmst}^{\alpha ij} \geq 0 \quad \forall \alpha \in A, i \in A \cup R, j \in R \cup B, g \in G, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \quad (13) \]
\[ \zeta_{gmst}^{\beta ij} \geq 0 \quad \forall \beta \in B, i \in R \cup B, j \in A \cup R, g \in G, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \quad (14) \]

The total volume of commodity flows traversing through a particular transit node at each congestion level is obtained by adding the import and export commodity flow components:

\[ \sum_{\alpha \in A} \sum_{i \in A \cup R} \sum_{g \in G} \sum_{\tau} \delta_{gmst}^{\alpha ij} + \sum_{\beta \in B} \sum_{i \in A \cup R} \sum_{g \in G} \sum_{\tau} \zeta_{gmst}^{\beta ij} = \gamma_{rmst} \quad \forall r \in R, m \in M, s \in S, t \in T, \tau \in \{1,2,3\} \quad (15) \]

The upper bounds for \( \gamma_{stmr} \) for the three congestion levels (\( \tau \)) are defined in Eqs. (16)-(18) and (20)-(22). The upper bounds for each congestion level for maritime transportation are:

\[ \frac{3v_{st}^{rm1'}}{5} \geq \sum_{m \in M'} \gamma_{rmst1} \geq 0 \quad \forall r \in R, s \in S, t \in T \quad (16) \]
\[ \frac{v_{st}^{rm2'}}{5} \geq \sum_{m \in M'} \gamma_{rmst2} \geq 0 \quad \forall r \in R, s \in S, t \in T \quad (17) \]
\[
\frac{v_{st}^{-rm}}{5} \geq \sum_{m \in M'} Y_{rmst3} \geq 0 \quad \forall r \in R, s \in S, t \in T \quad (18)
\]

Summing up the LHS and RHS of Eqs. (16)-(18), the maritime capacity constraint is obtained as:
\[
\sum_{t \in \{1,2,3\}} \sum_{m \in M'} Y_{rmst} \leq v_{st}^{-rm} \quad \forall r \in R, s \in S, t \in T \quad (19)
\]

The upper bounds for each congestion level for ground transportation are:
\[
\frac{3v_{st}^{-rm}}{5} \geq Y_{rmst1} \geq 0 \quad \forall r \in R, m \in M', s \in S, t \in T \quad (20)
\]
\[
\frac{v_{st}^{-rm}}{5} \geq Y_{rmst2} \geq 0 \quad \forall r \in R, m \in M', s \in S, t \in T \quad (21)
\]
\[
\frac{v_{st}^{-rm}}{5} \geq Y_{rmst3} \geq 0 \quad \forall r \in R, m \in M', s \in S, t \in T \quad (22)
\]

Summing up the LHS and RHS of Eqs. (20)-(22), the ground transportation capacity constraint is obtained as:
\[
\sum_{t \in \{1,2,3\}} Y_{rmst} \leq v_{st}^{-rm} \quad \forall r \in R, m \in M', s \in S, t \in T \quad (23)
\]

**Maximum Number of Selected Configurations**

Eq. (24) specifies that at each transit node at most one project configuration can be chosen. Eq. (25) constrains \(z_r^\varphi\) to be a 0-1 binary variable.
\[
\sum_{\varphi \in l_r} z_r^\varphi \leq 1 \quad \forall r \in R \quad (24)
\]
\[
z_r^\varphi \in \{0,1\} \quad \forall \varphi \in l_r, r \in R \quad (25)
\]

**Imbalance Constraint**

To determine the number of empty containers that require repositioning, Eqs. (26)-(28) are introduced.
\[
\Delta_{rst}^+ - \Delta_{rst}^- = \sum_{i \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{A}, \mu \in \mathcal{A}} \sum_{m \in M} \sum_{a \in \mathcal{A}} \frac{X_{air}}{\mu_g} - \sum_{j \in \mathcal{B} \cup \mathcal{R} \cup \mathcal{B}, \mu \in \mathcal{A}} \sum_{m \in M} \sum_{\beta \in \mathcal{B}} \frac{Y_{gms}^{\beta \mu}}{\mu_g} \quad \forall r \in R, s \in S, t \in T \quad (26)
\]
\[
\Delta_{rst}^+ \geq 0 \quad \forall r \in R, s \in S, t \in T \quad (27)
\]
\[
\Delta_{rst}^- \geq 0 \quad \forall r \in R, s \in S, t \in T \quad (28)
\]

\(\Delta_{rst}^+\) measures the imbalance of the surplus of empty containers for a transit node corresponding to imports being more than exports, and \(\Delta_{rst}^-\) measures the imbalance of deficit of empty containers for a transit node corresponding to imports being less than exports. Only one of these variables can be positive for a transit node for a scenario \(s\) in time period \(t\). It is possible that both of these variables can be zero simultaneously. The RHS computes the difference between the import and export commodity flows. Hence, the LHS surplus or deficit imbalance can be captured using the difference in the import and export commodity flows. The variables \(\Delta_{rst}^+\) and \(\Delta_{rst}^-\) are incorporated in the objective function and multiplied by \(\Phi\) to capture the empty
container repositioning costs.

NUMERICAL EXPERIMENTS AND RESULTS

Experiment Setup

Three national level experiments are designed to explore the impact of freight transportation facility service level changes in some regions on the freight transportation demand in other regions so as to provide insights for strategic intermodal facility investment planning. This impact cannot be explored if numerical experiments are conducted for a smaller region. The proposed model is used to identify the projects to invest in among the candidate port and terminal projects. The first experiment considers only six candidate port projects, while the second includes the projects in the first experiment and five candidate terminal projects. The third experiment considers twenty-five projects, including the six ports and five terminals from the second experiment, and another fourteen candidate terminals. Other inputs are the same for all three experiments. The candidate projects being considered are summarized in Table 3. These candidate projects are selected based on government reports (5) and information from Internet searches.

Each experiment contains four different cases: (i) case with the Panama Canal expansion, and the construction of a new port in Nova Scotia, Canada; (ii) case without the Panama Canal expansion, but with the construction of a new port in Nova Scotia; (iii) case with the Panama Canal expansion, but without the construction of a new port in Nova Scotia; and (iv) case without the Panama Canal expansion, or the construction of a new port in Nova Scotia.

An optimization software package CPLEX is used to solve the model on one cluster node with four 2.3 GHz 12-Core AMD Opterom 6176, 192 GB RAM per node. The model has between 6 to 25 binary variables and about 390.6 million continuous variables. It takes about 8.2 hours to solve the model to an optimality gap 0.05.

The IFLM is solved for a horizon of ten years. The ten-year horizon is chosen based on the recommendation by Tyndall et al. (26) that a minimum of ten years should be used for the strategic transportation investment planning horizon. The horizon is divided into five time periods and each time period represents every other year. Thereby, the freight transportation demand is used for every other year: 2015, 2017, 2019, 2021 and 2023.

The network consists of 185 nodes; including 57 terminal nodes and 128 transit nodes. Terminal nodes (representing origins and destinations) inside the U.S. are represented by the capitals of the 48 contiguous states and the District of Colombia. The world outside the U.S. is divided into eight economic and geographical regions. These regions represent terminal nodes outside the U.S., and include: Africa, Australasia & Oceania, Europe, North America (excluding the U.S.), South & Central America, East & Southeast Asia, Middle East, and South Asia. Commodity from East & Southeast Asia, the Middle East and South Asia can be shipped to the east coast of Northern America through either the Panama Canal or the Suez Canal.

Port capacity information for ports in the U.S. was collected from the Port Import Export Reporting Service (27). The Port Import Export Reporting Service provides complete capacity information for each port in the U.S. in year 2014. Port capacity information for ports in Mexico and Canada was collected from the official website for each port. If a port or canal cannot handle a specific vessel type, the capacity of the node for corresponding mode is set to zero. Five vessel types are considered in the experiments, including: (i) Post Panamax and smaller (with size up to 6,000 TEUs), (ii) Post Panamax Plus (6,000-12,500 TEUs), (iii) New Panamax (12,500-15,000 TEUs), and (iv) Panamax Super (15,000-22,500 TEUs).
I. Benedyk, S. Peeta, H. Zheng, Y. Guo, and A. Iyer

TEUs), (iv) Post New Panamax (15,000-18,000 TEUs), and (v) Triple E (from 18,000 TEUs)

(28).

TABLE 3 List of Port and Terminal Projects

<table>
<thead>
<tr>
<th>Project number</th>
<th>Port / Terminal</th>
<th>Project description</th>
<th>Capacity expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Port projects considered in all three experiments</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Boston</td>
<td>Depth increasing (from 40 ft/12.2 m till 48-50 ft/14.6-15.2 m); planned date of commencement is not defined.</td>
<td>3rd maritime mode will be allowed</td>
</tr>
<tr>
<td>2</td>
<td>Wilmington</td>
<td>Depth increasing (from 42 ft/12.8 m till &gt;42 ft/12.8 m); planned date of commencement is not defined.</td>
<td>2nd maritime mode will be allowed</td>
</tr>
<tr>
<td>3</td>
<td>Charleston</td>
<td>Depth increasing (from 44 ft/13.7 m till &gt;47 ft/14.3 m); planned date of commencement is not defined.</td>
<td>2nd maritime mode will be allowed</td>
</tr>
<tr>
<td>4</td>
<td>Jacksonville</td>
<td>Depth increasing (from 40 ft/12.2 m till &gt;47 ft/14.3 m); planned date of commencement is not defined.</td>
<td>2nd maritime mode will be allowed</td>
</tr>
<tr>
<td>5</td>
<td>Los Angeles/Long Beach</td>
<td>Construction of a new port terminal; planned date of commencement is not defined.</td>
<td>Additional capacity of 1 million TEUs</td>
</tr>
<tr>
<td>6</td>
<td>New Orleans</td>
<td>Depth increasing (from 45 ft/13.7 m till 50 ft/15.2 m); planned date of commencement is not defined.</td>
<td>3rd maritime mode will be allowed</td>
</tr>
</tbody>
</table>

|                |                          | Terminal projects considered in the second and third experiments                      |                                        |
| 7              | Illinois                 | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 8              | Indiana                  | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 9              | Michigan                 | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 10             | Texas                    | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 11             | Utah                     | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |

|                |                          | Terminal projects considered only in the third experiment                             |                                        |
| 12             | Arizona                  | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 13             | California, Los Angeles  | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 14             | California, San Francisco| Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 15             | California, Santa Cruz   | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 16             | Connecticut              | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 17             | Florida                  | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 18             | Georgia                  | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 19             | Massachusetts            | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 20             | Maine                    | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 21             | New Jersey               | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 22             | Nevada                   | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 23             | New York                 | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 24             | Philadelphia             | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
| 25             | Virginia                 | Construction inland intermodal terminal; planned date of commencement is not defined. | Double capacity                        |
Commodity flows from/to different parts of the world to/from the contiguous U.S. are obtained from the U.S. Census Bureau (29) for the year 2014. The data from the U.S. Census Bureau (29) provides the volume of containerized commodity flow from/to each state in the U.S. to/from each country in each year. Maritime transportation rates are obtained from the World Freight Rates (30), because it contains maritime transportation rates from/to all ports in the U.S. To hedge investment risks due to freight transportation demand uncertainty, two different scenarios of commodity flow are considered. The two scenarios are considered as equally likely in the model. The first scenario is a low commodity flow growth forecast from the World Trade Organization (WTO). The WTO reported that future growth rate of containerized commodity flow will be 3% per year (31). The second scenario is the forecast modeled by Oxford Economics (OE) and based on the HSBC Global Research macro data (32). Oxford Economics provided a prediction for U.S. trade between 2014 and 2030. The prediction forecasted a 6.5% average annual growth in exports and a 7% average annual growth in imports, with detailed information for different regions and three time periods (from 2014 to 2016, from 2017 to 2020, and from 2021 to 2030).

Results and Insights

To validate the proposed IFLM, 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 4. The variation in results across the different cases indicate the significant impact of the Panama Canal expansion and the construction of a new deep port in Canada on the investment decision-making process of intermodal facilities in the U.S. The variation in results in the three different experiments demonstrates the impact of changes in freight transportation facility service level in some regions on the freight transportation demand in other regions in the investment decision-making process of intermodal facilities.

Three port projects, Boston, Charleston, and New Orleans, were chosen in all instances (experiments and cases), indicating their importance. The decisions related to the port project of Wilmington vary across the cases and experiments. For example, it was not chosen if the new port in Nova Scotia is considered. This indicates that the port in Nova Scotia will compete with that of Wilmington for commodity flow by providing lower maritime transportation costs due to the usage of larger vessels. Figure 1 illustrates the impact of the construction of a new port in Nova Scotia 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 a new port is constructed in Nova Scotia. The commodity flow volume through Wilmington with the construction of a new port in Nova Scotia is 55% lower than without it. Hence, Wilmington does not require capacity expansion if a new port is constructed in Nova Scotia.
Increased Panama Canal capacity will allow additional commodity flow from East Asian ports to ports on the east coast of the U.S. In the third experiment, the investment project in Jacksonville is not selected. This result indicates the impact of the Panama Canal expansion on the investment decision-making process of intermodal facilities. 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 investment project in Jacksonville is not selected in the cases where the construction of the new port in Nova Scotia 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 commodity volume will be attracted to these ports. Coupled with the choice of the deep port in Nova Scotia, this will make improvements in Wilmington and Jacksonville less cost effective.
FIGURE 1 The impact of the construction of a new port in Nova Scotia on Wilmington.
The second possible reason is the selection of a project in the Los Angeles/Long Beach port 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 by the model. These improvements will attract additional commodity volume to the west coast ports of the U.S. and decrease volume at the east coast ports, including Wilmington and Jacksonville. This result indicates that improvements in the port of Los Angeles/Long Beach 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 terminal project in Arizona is considered only in the third experiment, the terminal project in Utah is chosen in the second experiment. It suggests that investing in a terminal project in Arizona may be more effective than investing in a terminal project in Utah. It also indicates that terminal projects in Utah and Arizona interact in the investment decision-making process of intermodal facilities. This result indicates the importance of comprehensive analysis in the investment decision-making process of intermodal facilities at the national level. Limiting the case study to specific geographical regions without considering the impact of changes in freight transportation 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 2 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 2, 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 port project in Los Angeles/Long Beach is selected for expansion, along with the projects of nearby terminals, to accommodate the increasing commodity flow in Los Angeles/Long Beach. The model results show that the construction of the new deep port in Nova Scotia 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.
FIGURE 2 Capacitated terminals in all four cases and three experiments.
CONCLUDING COMMENTS

This study proposes a scenario-based mixed integer dynamic capacitated intermodal facility location model to assist high-level policymakers in strategic intermodal facility investment planning at a regional- or national-level. The proposed model identifies which port and terminal projects would be economically efficient under uncertainty, while exploring the commodity flow changes due to congestion in transit nodes, changes in capacity of transit nodes, transshipment costs, economies of scale in maritime transportation, and empty container repositioning costs. The model solves the transportation problem for the U.S. and considers commodity flows at the national level for ten years. To account for freight transportation demand uncertainty, the study considers two scenarios of commodity flow. The numerical experiments are used to demonstrate the potential applicability of the proposed model. The national level numerical experiments are considered to explore the impact of changes in freight transportation facility service levels in some regions on the freight transportation demand in other regions in the investment decision-making process of intermodal facilities. As noted earlier, the results of numerical experiments 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 port of Los Angeles/Long Beach entails high priority, but with the simultaneous development of relevant terminals. In addition, the results show that the projects involving the development of the ports of Wilmington and Jacksonville are sensitive to the construction of the new deep port in Nova Scotia and may lose commodity flow when it opens.

Other possible applications of the proposed model are as follows. Evaluation of possible commodity flow changes due to the addition of capacity to the existing ports or new ports in Canada or Mexico. The proposed model could also investigate the impacts of various events (e.g. bankruptcy or natural disasters) that can decrease capacity of the existing ports or terminals. In addition, the proposed model could evaluate the efficiency of the U.S. Maritime highways for container transportation and aid in determining optimal pricing policies. The model could also be used to assist in global or local investment decision processes by evaluating possible freight transportation demand under the implementation of particular projects.

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 IFLM model and may illustrate other infrastructure investment choices.

There are various research directions for future work. First, a solution algorithm can be developed for the proposed model by using the obtained optimal solution as a benchmark. Second, the capacitated terminals identified in this study (Figure 2) can be prioritized for
capacity expansion. Third, terminal operational planning can be integrated with system level strategic intermodal facility investment planning to further improve the intermodal investment decision-making process. Fourth, the impact of deploying mega-container ships in U.S. ports can be estimated.

ACKNOWLEDGMENTS

This work is based on funding provided by the U.S. Department of Transportation through the NEXTRANS Center, the USDOT Region 5 University Transportation Center. The authors are solely responsible for the contents of this paper.

REFERENCES


