Verification Simulation and Development of New Marine Transport Model

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Abstract. The structure of the global supply chain creates an imbalance in trade between regions of the world. It creates many empty containers on the ocean shipping route. Focusing on this problem, we will develop an empty container relocation plan for empty containers in a marine container logistics network connecting multiple bases and propose a model that minimizes the total cost of container transportation. The proposed model was verified by the simulation designed and developed in this study, and the effectiveness of the proposed model was shown by the data of the marine transportation company.

Keywords: Model, routing, algorithm, simulation, validation.

1. Introduction

With globalization of the world’s economy, international maritime transport is becoming increasingly popular [1]. The global supply chain is configured to carry goods manufactured in East Asia to locations throughout the world. As a result, container transport has become active and there is an imbalance in the directionality of container travel. There are container shortages in East Asia, because exports exceed imports. Surplus containers accumulate in ports with an excess of imports. That is, while there are some ports with room to stack empty containers, there are other ports with no room. It therefore becomes necessary to circulate and rearrange empty stacked containers on surplus land.

As an existing approach to this problem, classified empty container relocation into three groups. The first focuses on empty container transport in a maritime container logistics network. The second considers inland container transport networks or empty container transport in integrated transport including inland transport. The third incorporates decision-making problems. We studied empty container transport as a constraint. Song et al also used dynamic programming to consider uncertain demands and to establish an optimal inventory management method that is responsive to acceptable shortage rates [2–3]. Zhang et al. found optimal combinations of ports with supply and demand for empty containers in a maritime container network by reducing the assignment problem in multiple ports [4–7].

In this research, we take a different approach from the existing research, focus on the current situation of shipping containers, and consider the relocation plan of the marine container network connecting multiple bases, the number of containers exchanged between ports and container inventory management. Propose a new model that minimizes the cost of moving empty containers. We consider both macro and micro perspectives. Macroscopically, we consider work from the perspective of product flows in the supply chain. In the network formed by container ship services connecting each port at the micro level, empty containers taken as stock at each port are interchanged. The aim is to minimize the cost of relocating empty containers by restricting empty container inventory shortage rates to below a certain level depending on the supply and demand of empty containers at each port. In addition, verification is
performed using actual data obtained as part of industry-academia collaboration involving shipping companies, and the academic and practical values of the proposed method are shown.

2. Model Approach

2.1. Modeling and Entities
Under the constraint that the empty container shortage rate at each port remains below a certain level, let the objective function be cost minimization for empty container relocation. Furthermore, the optimal allocation of empty containers must consider port space and container vessels. The following entities are in this model:

① Shipping company: A company engaged in the shipping business.
② Harbor: A company involved in port management.
③ Container leasing company: Consider containers owned by container leasing companies.
④ Container manufacturing company: Shippers tend to prefer new containers.
⑤ Cargo owner: Cargo owners are customers requesting ocean transportation.

2.2. Demand Forecasting for Empty Containers
First, we define empty container demand. As a premise, the occurrence of empty containers in ports is considered as “production,” and “consumption” is when goods are loaded on empty containers. Empty containers are considered as stock until loading. Because empty containers are “consumed” when transport demand occurs, the number of inventory changes in each port is the number of empty containers returned minus the number of empty containers transported from the port. Here, the empty container demand is the same value as the decrease in empty container stock. In a given port \((p)\), empty container demand \(\text{Demand}_{p,d}\) in a certain period \((d)\) is calculated using the transport demand \(\text{Transport}_{p,d}\) and the number of empty container returns \(\text{Return}_{p,d}\), expressed as a formula. As mentioned above, the manufacture and disposal of empty containers are not considered.

\[
\text{Demand}_{p,d} = \text{Transport}_{p,d} - \text{Return}_{p,d}
\]

\(\text{Transport}_{p,d}\): Empty container consumed (transportation demand)
\(\text{Return}_{p,d}\): Empty container refilled (stock replenishment)

2.3. Empty Container Inventory
Containers have economic value because they are used for marine logistics and generate profits. There are idle periods where they are not used for transport or at ports, and during that period they can be regarded as inventory that does not generate profits. The main objective of inventory management is to minimize total costs. There are various factors related to the cost of inventory control, but in this study, we mainly classify three.

① Inventory maintenance cost: In this study, we consider the cost per day of one empty container.
② Ordering cost: In this study, on the premise of regular container ships, container ships enter ports on specific days without a fixed number of empty containers.
③ Out-of-stock costs: We formulate a plan under the constraint that the shortage rate in each port must be kept below a certain level.

2.4. Empty Container Flexibility and Inventory
The ordering system mainly includes a quantitative ordering point system and a regular ordering point system. The former is for placing a fixed number of orders when the order interval is not fixed. The latter places periodic orders at different quantities. Considering the ordering method for empty container inventory, the interval of the ordering period of the empty container inventory at each port is determined by the schedule of the container ship calling on port.

In this study, on the premise of fixed-day service, the number of container ships determines the travel schedule. For example, assume it takes 21 days to complete a route and three container vessels will provide fixed-day service. In this case, one container ship will arrive each week.

The amount of accommodation between a port \(p \in P\) and a container ship \(l \in L\) is defined as \(x_{i,p}\) as in
Equation 2, and takes a positive or negative integer value. \( x_{lp} \) assumes positive values when an empty container is transferred from a container ship to a port. As a result, it is possible to formulate the amount of interchange without distinguishing between supply or demand ports. Even in the same port, since \( x_{lp} \) can take a positive or negative value for each container ship, transshipment in a hub port can be reproduced. When link \( l \in L \) does not call at port \( p \in P \), \( x_{lp} \) becomes 0, so the corresponding \( x_{lp} \) is set to 0, thereby speeding up the calculation.

\[
X = \begin{pmatrix}
  x_{1,1} & \cdots & x_{1,p} & \cdots & x_{1,P} \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  x_{l,1} & \cdots & x_{l,p} & \cdots & x_{l,P} \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  x_{L,1} & \cdots & x_{L,p} & \cdots & x_{L,P}
\end{pmatrix}
\] (2)

\( x_{lp} \): Number of empty containers accommodated between link \( l \in L \) and port \( p \in P \)

In addition, inventory fluctuation can be calculated as the number of transferred empty containers minus the number of required empty containers. We therefore consider the total number of transferred empty containers and the total number of required empty containers. To handle the number of empty containers transferred at each port as a time series, we introduce a calendar constant \( C_p \) that creates a schedule from the number of transferred empty containers at ports (Equation 3). The element \( e_{ld}^p \) defines the case where container ship \( l \in L \) calls at port \( p \in P \) on day \( d \) as 1 and other cases as 0. According to this, \( C_p \) can be calculated for each port from the liner service schedule.

\[
C_p = \begin{pmatrix}
  e_{11}^p & \cdots & e_{1d}^p \\
  \vdots & \ddots & \vdots \\
  e_{pd}^p & \cdots & e_{pd}^p
\end{pmatrix}
\]

\( c_{ld}^p = \begin{cases} 
1 & \text{if the Link } l(\in L) \text{ calls at the Port } p(\in P) \text{ on the Day } d(\in D) \\
0 & \text{if it does not}
\end{cases} \) (3)

The number of orders \( O_{p,d} \) on day \( d \) at port \( p \) in \( P \) can be obtained by Equation 4 for a planning period of \( D \) days.

\[
O_{p,d} = \sum_{l \in L} x_{lp} \cdot c_{ld}^p \text{ for each } p \in P, d \in D
\] (4)

The cumulative order quantity \( T O_{p,d} \) from 0 \( \in D \) to \( d \) \( \in D \) can be obtained from the order placement schedule as Equation 5.

\[
T O_{p,d} = \sum_{d'=1}^{D} O_{p,d'} = \sum_{d'=1}^{D} \sum_{l \in L} (x_{lp} \cdot c_{ld}^p) \text{ for each } p \in P, d' \in D
\] (5)

To express the amount of stock transition using the flexible variable, regarding demand for empty containers at port \( p \in P \), let the forecasted average cumulative demand from 0 \( \in D \) to \( d \) \( \in D \) be Demand\(_{pd} \). Variation (standard deviation) in predictions uses the concept of “safety stock,” that is, the optimal order quantity such that the shortage rate \( \beta \) remains below a certain level. Make a stock plan. Safety stock is calculated by multiplying a safety factor by the standard deviation \( \sigma \) of the accumulated demand in the planning period, and can be expressed as the second term on the right side of Equation 6. If the forecasted date is in the future, this safety stock will be larger than it is the future. A total demand forecast amount \( k_{demand} \) considering safety stock is defined as the sum of the above and the average cumulative demand forecast amount\( \text{Demand}_{pd} \). Here, "determining the optimal order quantity under the condition that the shortage rate \( \beta \) becomes lower than a certain level over the future" is "the cumulative order quantity minus the cumulative demand forecast quantity considering safety stock" "It is always positive during the planning period."

This condition can be expressed as Equation 7.

\[
K_{demand} = \text{Demand}_{pd} + k \cdot \sigma \cdot \sqrt{d}
\] (6)

\[
T O_{p,d} - K_{demand} \geq 0
\] (7)

We next consider how to represent shipboard stock using a flexible variable. First, according to the schedule of a given container ship \( l \in L \), the port that calls at \( d \in D \) is expressed as \( PC_{l,d} \in P \) as in Equation 8. When no port is called, \( PC_{l,d} = 0 \).
Denoting shipboard stock fluctuation for a container ship \( l \in L \) in \( d \in D \) as \( SB_{l,d} \), the container ship \( l \in L \) is the \( PC_{l,d} \in \mathcal{P} \), which is equal to the empty container accommodation amount \( -x_{l,PC_{l,d}} \). When \( PC_{l,d}=0 \) the container ship does not call at the port, so \( SB_{l,d} \) becomes 0. Therefore, \( SB_{l,d} \) is expressed as in Equation 9.

The onboard inventory \( TSB_{l,d} \) at \( d \in D \) is the sum of the cumulative amount of \( SB_{l,d} \) at \( d \in D \) and the initial onboard inventory (defined as ISB), as in Equation 10. This formula can represent the stock volume transition on a container ship using a flexible variable.

\[
PC_{l,d} = \begin{cases} 
p(\text{if Link } l \text{ calls Port } p) \\
0(\text{if the Link does not call any Port}) 
\end{cases} 
\]

\[
SB_{l,d} = \begin{cases} 
-x_{l,PC_{l,d}}(\text{if Link } l \text{ calls Port } p) \\
0(\text{if the Link does not call any Port}) 
\end{cases} 
\]

\[
TSB_{l,d} = ISB + \sum_{d=0}^{d} SB_{l,d} 
\]

3. Modeling and Simulation
We formulate planning optimization methods. The following describes formulated objective functions and constraints.

3.1. Setting of Objective Function
The following constants are defined for the set \( P \) of ports to be designed, the set \( L \) of container ships, the set \( S \) of price stages in the stage charge system, and the period \( D \) for planning.

\[
l \in L \quad \text{Container ship} \\
p \in P \quad \text{Port} \\
s \in S \quad \text{Price stage} \\
d \in D \quad \text{Number of days until the forecast target date [days]} \\
c_p \quad \text{Calendar constant [dimensionless]} \\
IP_p \quad \text{Inventory management cost [yen/unit]} \\
LE_p \quad \text{Lease expenses [yen/unit]} \\
SP_{p,s} \quad \text{Additional charge [yen/unit]} \\
B \quad \text{Number range of each price stage} \\
CHC_p \quad \text{Container handling cost [yen/unit]} \\
FC_l \quad \text{Container ship fuel cost [yen/unit]} \\
LC_{l,d} \quad \text{Container ship loading limit [units]} \\
\mu_p \quad \text{Empty container average demand volume [units/day]} \\
\sigma_p \quad \text{Standard deviation of empty container demand quantity}
\]

To facilitate description of the formulation, the following describes the storage cost, the empty container purchase cost, the empty container handling cost, and the stepwise charging cost. The cost for storage is shown in Formula 12 as \( C_{Stock} \). The port will require a maintenance storage fee according to the daily stock quantity. It is thus necessary to calculate the daily stock amount, which is obtained by subtracting the accumulated demand amount from the accumulated order amount.

Equation 13 shows the cost of handling empty containers at a port as \( C_{Loading} \). The cargo handling volume at the port is considered to be proportional to the number of empty containers transferred between the port and the container ship. Therefore, the cargo handling amount \( z_{l,p} \) is considered as the absolute value of the empty container interchange amount. The cargo handling cost per TEU is set as \( CHC_p \) for each port and multiplied by the cargo handling cost.

The stage charge cost is shown in Equation 14 as \( C_{stageCharge} \). Formulation follows the concept of staged charges as described above. Restrictions on the staged charges will be described later. The cost for container shipping is shown in Formula 15 as \( C_{Shipping} \), and is calculated for each container ship from the onboard inventory transition formulated as described above. In addition, the forecasted cumulative demand considering safety stock will be shown again. The forecasted cumulative demand is shown on a daily basis as a \( K_{demand_{p,d}} \) number sequence.
The objective function is set as Equation 16. The optimal solution does not change even if terms that do not change due to variables in the objective function are eliminated. Therefore, the term related to the accumulated demand for the variable among the storage costs is eliminated, and Equation 17 is the solution to the minimization problem. This is because the cumulative demand forecast amount considering the safety stock is a forecast value until boredom and is treated as a constant value in forecasts. Storage costs are thus determined by the cumulative order quantity and the cumulative lease quantity represented by the variables.

\[
\begin{align*}
C_{stock} &= \sum_{p \in P} \left( W_p \left( \sum_{d \in D} TD_{p,d} - \sum_{d \in D} Kdemand_{p,d} + \sum_{d \in D} (D - d + 1)y_{p,d} \right) \right) \\
&= \sum_{p \in P} \left( W_p \left( \sum_{d \in D} (D - d + 1) \sum_{l \in L} (x_{lp} \cdot c_{l,d}^p) - \sum_{d \in D} Kdemand_{p,d} + \sum_{d \in D} (D - d + 1)y_{p,d} \right) \right) \\
C_{lease} &= \sum_{p \in P} (LP_p \sum_{d \in D} y_{p,d}) \\
C_{loading} &= \sum_{p \in P} (CHC_p \sum_{l \in L} z_{lp}) \\
C_{stagecharge} &= \sum_{p \in P} \sum_{s \in S} (SP_{ps} \cdot w_{ps}) \\
C_{shipping} &= \sum_{l \in L} (FC_l \sum_{d \in D} TSB_{ld}) \\
\end{align*}
\]

The objective function is set as Equation 16. The optimal solution does not change even if terms that do not change due to variables in the objective function are eliminated. Therefore, the term related to the accumulated demand for the variable among the storage costs is eliminated, and Equation 17 is the solution to the minimization problem. This is because the cumulative demand forecast amount considering the safety stock is a forecast value until boredom and is treated as a constant value in forecasts. Storage costs are thus determined by the cumulative order quantity and the cumulative lease quantity represented by the variables.

\[
\begin{align*}
\min (C_{stock} + C_{lease} + C_{loading} + C_{stagecharge} + C_{shipping}) \\
\sum_{p \in P} \left( W_p \left( \sum_{d \in D} (D - d + 1) \sum_{l \in L} (x_{lp} \cdot c_{l,d}^p) + \sum_{d \in D} (D - d + 1)y_{p,d} \right) \right) \\
&= \sum_{p \in P} \left( W_p \left( \sum_{d \in D} LP_p \sum_{d \in D} y_{p,d} \right) + \sum_{p \in P} \left( CHC_p \sum_{l \in L} z_{lp} \right) + \sum_{p \in P} \sum_{s \in S} \left( SP_{ps} \cdot w_{ps} \right) \right) + \sum_{l \in L} \left( FC_l \sum_{d \in D} TSB_{ld} \right) \\
\end{align*}
\]

3.2. Setting Constraints

There are four constraints, for the stock shortage rate, ship size, cargo volume, and stage rate system. Equation 18 is a constraint that reduces the stock shortage rate to below a certain value during the planning period. The upper limit on the shortage rate is set using safety coefficient \( k \), and formulation is performed according to the stock transition calculation method. Formula 19 sets lower and upper limits on the number of empty containers on a container ship. The amount of space on the container ship sets the upper limit value in chronological order. Although \( x_{lp} \) can take a negative value to indicate the amount of accommodation, the number of empty containers on a ship must be a nonnegative value, so the lower limit is 0. Equation 20 is set for the definition of \( z_{i,l} \) that represents the amount of cargo handling. The cargo handling volume at the port is expressed as an absolute value of the porting volume of the container ship, so setting it as Equation 20 allows \( z_{i,l} \) to be handled in linear programming. It can be treated as an absolute value of Equation 21 is an equation for a tiered billing system, set up to incorporate a system for staged charging.

\[
\begin{align*}
\sum_{d=1}^{d} (\sum_{l \in L} (x_{lp} \cdot c_{l,d}^p) + y_{p,d}) + FirstStock_p - Kdemand_{p,d} &\geq 0 \\
&\text{(for a Day } d \in D \text{ and Port } p \in P) \\
0 &\leq TSB_{ld} \leq LC_{ld} \text{ (for Link } l \in L \text{ and Day } d \in D) \\
-z_{lp} &\leq x_{lp} \leq z_{lp} \\
\text{predicted stock} - \sum_{s=n+1}^{s} w_{ps} &\leq B + n \text{ (for Port } p \in P \text{ and Stage } s \in S) \\
\end{align*}
\]
The variables are $x_{i,p}$, $y_{p,d}$, $z_{l,p}$, $w_{p,s}$ for each port $p \in P$, each container ship $l \in L$, and each price stage $s \in S$. We set the variables at the time of planning formulation as follows.

- $x_{l,p}$: Number of containers transferred from container ship $l \in L$ to port $p \in P$
- $0 \leq y_{p,d}$: Number of containers leased at port $p \in P$
- $0 \leq z_{l,p}$: Handling amount (absolute value of $x_{l,j}$)
- $0 \leq w_{p,s} \leq B$: Number of containers to which price stage $s$ applies

3.3. Setting of Target Period and Simulation Design

This is a period of guarantee that the stock shortage rate $\beta$ will be below a certain level at the time of planning. That is, the constraint is that during the planning period, the probability of shortage will be less than or equal to $\beta$. The following simulation is performed by the above-mentioned modeling.

4. Verification with Actual Data

The following simulation verifies the proposed formulation model using actual data.

| ID | Name     | $\mu$ | $\sigma$ | IP  | CHC  |
|----|----------|-------|----------|-----|------|
| 1  | Shanghai | 100   | 10       | 800 | 30000|
| 2  | Singapore| 100   | 10       | 0   | 7000 |
| 3  | Tokyo    | 100   | 10       | 1500| 30000|
| 4  | Yokohama | 90    | 9        | 1500| 30000|
| 5  | Nagoya   | 80    | 8        | 1500| 30000|
| 6  | Manila   | 50    | 5        | 1500| 30000|
| 7  | LA       | -520  | 52       | 1200| 30000|

Figure 2 shows the results of a one-year simulation for the planning period. As the period considered in planning grows, it becomes possible to perform appropriate planning and reduce total costs. After 21 days, the fluctuation range of the total cost becomes smaller, and it becomes possible to formulate a container ship management plan.
5. Conclusion
In this study, we proposed a new empty container rearrangement model and formulation method in consideration of real companies such as Shipping company, Harbor, Container leasing company, Container manufacturing company, and Cargo owner. We also developed a simulation of the current state of container transportation and model validation. Furthermore, the validity of the proposed model was verified using actual data.
We proposed a new model and formulation method for relocation of empty containers, and developed a simulation that can be reproduced and verified. We were able to verify the effectiveness of the proposed method using actual data.

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