PROCESS ANALYSIS IN CONTAINER SHIPPING NETWORK STRUCTURE FORM CHANGE

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Abstract: Being aimed at the influence of ship-size and cargo-demand changes on container shipping networks, to reveal the evolution process of container shipping networks structure form, this paper respectively designed the operation models for two major container shipping networks structure forms: Multi-port-calling network and Hub-and-spoke network, to maximizing the investment efficiency. Based on the above models, a comprehensively integrated operation model of container shipping networks is built and the evolution process of container shipping networks structure form with changing of both ship-size and cargo demands is analyzed. Finally, through a case study, results show that the comprehensive integrated operation model is very effective in the analysis of evolution process of container shipping networks structure forms.

Keywords: comprehensive integrated operation model (CIO model), container shipping networks structure form, investment efficiency, Multi-Port-Calling network, Hub-and-Spoke network.

1. Introduction

Ship large-sizing has become a leading approach to enlarging transport capacity and lowering transport cost. However, when cargo-demand growths between the ports cannot be synchronized with the ship-size growth, in order to guarantee the ships fully loaded, operators generally face the following choices: whether adding the number of calling ports and keeping the network structure unchanged, or reducing the number of calling ports and making the network structure change. The former makes for increasing the voyage revenue at the expense of prolong the voyage time, but the latter makes for improving voyage operation efficiency at the expense of decreasing the voyage revenue. Therefore, how to make the choice optimal has become a primary problem of container shipping network optimization scheme and design. The analysis in the evolution process of container shipping network structure form is an effective method of dealing with this problem to promote the investment profit rate and make the network structure form more optimal.

In most existing studies, researches on the evolution process of container shipping network structure form are rather limited. Bendall and Stent (2001) propose a shipping operation model for determining the optimal fleet configuration and associated fleet deployment plan in a containership hub-and-spoke application. Imai et al. (2006) formulate the construction of Multi-Port-Calling and Hub-and-Spoke networks with the objective

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of the minimization of O–D traffic travel length (in time) weighted by traffic volume. Shintani et al. (2007) formulate a two-stage model to solve the container shipping network design problem and develop a genetic algorithm-based heuristic for it. Hsu and Hsieha (2007) construct a shipping cost model to analysis the optimal decision between shipping directly or through a hub. Imai et al. (2009) discuss the container shipping network design problem considering empty container repositioning by constructed shipping operations models in both Multi-Port-Calling and Hub-and-Spoke networks. Chao and Chen (2010) explore the container shipping network designing under changing demand and freight rates by formulate a dynamic shipping operation model.

Chao and Ya (2010) have studied the transformation between the Multi-port-calling structure and Hub-and-spoke structure with ship-size increasing under condition of fixed cargo-demands. Thus, researches, which consider the ship-size and cargo-demand as influencing factors at the same time to study the evolution process of optimal route structure forms, are relatively less, and how to build a comprehensive integrated model which can compare the route operation effects under different route structures is a key issue in the analysis problem of evolution processes of container shipping route structure form.

Aiming at the influence of ship-size and cargo-demand change, this paper will study the evolution processes between the Multi-Port-Calling network and Hub-and-Spoke network mutually. First, the two major route structure forms' shipping operation models are established respectively, and then a route comprehensive integrated model is built with objective of maximizing the investment profit rate. After that, we use those models to analyze the evolution process of optimal route structure form between Multi-Port-Calling network and Hub-and-Spoke network. Finally, we prove the effectiveness of the proposed approach and model through a case experiment.

2. Problem Description

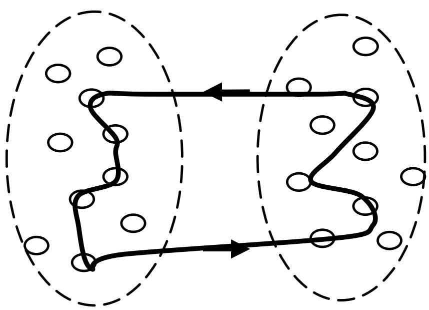
In the initial stage of the evolution process of container shipping route structure form, there only exists the Point-to-Point route structure. When the ship-size grows quickly while the cargo-demands among ports cannot increase synchronously, in order to lowering transportation costs and achieve the scale economy effect of large ship, a new route structure emerges as the time requires, in which larger-size ships are deployed and more than two ports are called. We usually referred to this structure form as Multi-Port-Calling networks. They are mainly applied to intercontinental container shipping network designs. As the ship-size further grows and more calling ports are added, in order to reserve the sailing frequency, more ships should be deployed in the Multi-Port-Calling network. However, it leads to the extension of the voyage time and the decrement of the operation and investment efficiency. When the ship-size reaches to a certain scale, the Hub-and-Spoke networks are applied in order to promote the operation and investment efficiency. In Hub-and-Spoke networks, ships only call several hub ports in the main routes, and cargos are collected in the feeder routes. In recent years, as many larger size ships enter into the market, many intercontinental routes have developed to this form. Fig. 1 shows the structure forms of Multi-Port-Calling networks and Hub-and-Spoke networks. The selection of these two forms is mainly affected by ship-size and cargo-demand, besides distances, freight rates and shipping costs among ports in the same region. Therefore, ship-size and cargo-demand directly determine the optimal selection of route structure forms and the optimization of other specific elements in routes.

3. Model Formulations

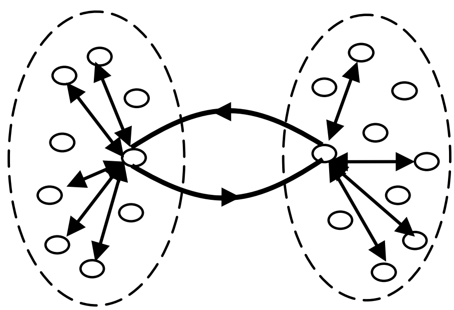
Considering characteristics of the two networks, we assume that the number of candidate ports is enough, cargo-demand from each port is same, freight rate between port pairs is same too, there is no cargo flows among ports in the same region of area, and waiting time in every port is same and fixed. If the ship-size and the cargo-demand are chosen as variables, the investment profit models of Multi-Port-Calling network and Hub-and-Spoke network could be formulated respectively as following sections.

3.1. Multi-Port-Calling Networks

If the trade area is divided into two regions which are denoted by *A, B* respectively, let $i=1,2,3\ldots,n$ be the ports in region *A* and $j=1,2,3\ldots,m$ be the ports in region *B; P* investment profit rate; *CAP* ship-size; X_{ij} the quantity of loaded containers from port *i* to port *j; Y_{ji}* the quantity of loaded containers from port *j* to port *i*; $D_{ij}^{\ a}$ cargo-demand from port *i* in *A* to port *j* in *B;* $D_{ji}^{\ b}$ cargo-demand from port *j* in *B* to port *i* in *A*; C_{FO} and C_{DO} denote the average daily fuel oil (FO) consumption and the average daily diesel oil (DO) consumption respectively; P_{FO} and P_{DO} average prices of FO and DO; *T* denotes the closed voyage time, T_m and T_s denote the sailing time of ships and waiting time at ports respectively; P_{ia} and P_{ib} denote the charge rate at port *i* in *A* and the charge rate at port *j* in *B;* N_i and M_j are binary variables. N_i=1 if port *i* is called and 0 otherwise; M_j=1 if port *j* is called and 0 otherwise; α and β are the coefficient of capital cost; θ is the coefficient of waiting time, in this paper θ =1.5 which means 1 day for a ship sailing from one port to the next in the same region, and 0.5 day for cargo handling at each port. With above sets, Multi-Port-Calling investment profit rate model can be formulated as follows:



a. Multi-Port-Calling Network



b. Hub-and-Spoke Network

Fig. 1.
Two Types of Networks

Objective:

$$\max P_1 = \frac{1}{CAP \cdot T}[\sum_i^m \sum_j^n r_{ij} \cdot X_{ij} + \sum_j^n \sum_i^m r_{ji} \cdot Y_{ji} - (\alpha \times CAP + \beta) \cdot T - C_{FO} \cdot P_{FO} \cdot T_m - C_{DO} \cdot P_{DO} \cdot T - (\sum_{i=1}^m N_i P_i^a + \sum_{j=1}^n M_j P_j^b) \cdot CAP)] \tag{1}$$

S.t.

$$T = T_m + T_s, \qquad T_s = \theta \cdot (\sum_{i=1}^m N_i + \sum_{j=1}^n M_j) \tag{2}$$

$$\sum_j^n X_{ij} = \sum_j^n Y_{ji}, \qquad \sum_j^m Y_{ji} = \sum_i^m X_{ij} \tag{3}$$

$$X_{ij} \leq D_j^a, \qquad Y_j \leq D_j^b \tag{4}$$

$$\sum_i^m \sum_j^n X_{ij} \leq CAP, \quad \sum_i^m \sum_j^n Y_j \leq CAP \tag{5}$$

$$N_i = \begin{cases} 1, & while \ \sum_j^n X_j \neq 0; \\ 0, & while \ \sum_j^n X_j = 0; \end{cases} \tag{6}$$

$$M_j = \begin{cases} 1, & while \ \sum_i^m Y_j \neq 0; \\ 0, & while \ \sum_i^m Y_j = 0; \end{cases} \tag{7}$$

Objective function (1) is to maximize the unit ship-slot profit; Constraint (2) expresses the closed voyage time; Constraint (3) is the port handling quantity; Constraint (4) represents the cargo-demand limited; Constraint (5) is the ship capacity limited; Constraint (6) and (7) are binary variable equalities, using to count the number of calling ports.

3.2. Hub-and-Spoke Networks

Compared with the route operation in Multi-Port-Calling network, only hub ports are called in Hub-and-Spoke network. So, in this paper, the number of calling ports equals to 2, as θ =1.5, thus T*s*=3, and T*m*, CF are fixed. Other constraints are the same with Multi-port-calling networks'. Thus, the model is constructed as follows:

Objective:

$$\max P_2 = \frac{1}{CAP \cdot T}[r_{ab} \cdot \sum_i^m \sum_j^n X_{ij} + r_{ba} \cdot \sum_j^n \sum_i^m Y_{ji} - (\alpha \times CAP + \beta) \cdot T - (\sum_{i=1}^m N_i P_i^a + \sum_{j=1}^n M_j P_j^b) \cdot CAP - (C_{FO} \cdot P_{FO} + C_{DO} \cdot P_{DO}) \cdot T_m - 3 \cdot C_{DO} \cdot P_{DO}] \tag{8}$$

St.

$$\sum_j^n X_{ij} = \sum_j^n Y_j \,, \qquad \sum_j^m Y_j = \sum_i^m X_j \tag{9}$$

$$X_{ij} \le D_j^a \,, \qquad Y_j \le D_j^b \tag{10}$$

$$\sum_i^m \sum_j^n X_{ij} \le CAP, \ \sum_i^m \sum_j^n Y_j \le CAP \tag{11}$$

Besides the difference in network structure forms, the significant distinction between Hub-and-Spoke network and Multi-Port-Calling network is reflected in the operation profit pattern.

In Multi-Port-Calling networks, the freight rate charged by operators is one of the whole voyage freight. However, in Hub-and-Spoke networks, the freight rate consists of main segment freight and feeder segment freight, and the operator merely gains profit from the main segment freight. Consequently, the relationship between those freight rates can be formed as follows:

$$r_{ab} + r_{asub} + r_{bsub} \le \min(r_{ij}), \quad r_{ba} + r_{bsub} + r_{asub} \le \min(r_{ji})$$

Where: rasub and rbsub denote the feeder segment freight rates in region A and region B respectively. According to the above constraints, we can figure out that the specific position of objective curve for Hub-and-Spoke networks is directly influenced by differently pricing the main segment and feeder segment freight. To guarantee that the transformation between two different networks occurs at the point of the maximum value of Multi-Port-Calling investment profit curve, the model constructed should include following constraints.

When $CAP = CAP_0 \mid (\partial P_1 / \partial CAP = 0)$, $P_2 = P_1$

Then, an integrated model will be developed in the following section, in which the profit rate curve could be insured to increase monotonically, even if the networks are transformed.

3.3. A Comprehensive Integrated Operation Model

According to the analysis above, a binary variable λ is introduced to combine the two network operation models into a comprehensive integrated model (CIO model). Let *CL* signifies capital cost; *CF* flue cost; *CP* port charge cost, the CIO model can be constructed as follows:

Objective:

$$\max P = \frac{1}{CAP \cdot T}\left[R - (CL + CF + CP)\right] \tag{12}$$

S.t.

$$R = \lambda \cdot \left(\sum_i^m \sum_j^n r_{ij} \cdot X_{ij} + \sum_i^m \sum_j^n r_{ji} \cdot Y_{ji}\right) + (1-\lambda) \cdot \left(r_{ab} \cdot \sum_i^m \sum_j^n X_{ij} + r_{ba} \cdot \sum_i^m \sum_j^n Y_{ji}\right) \tag{13}$$

$$CL = (\alpha \times CAP + \beta) \cdot T \tag{14}$$

$$CF = C_{FO} \cdot P_{FO} \cdot T_m + C_{DO} \cdot P_{DO} \cdot T_s \tag{15}$$

$$T = T_s + T_m, \qquad T_s = \theta \cdot \left(\sum_{i=1}^m N_i + \sum_{j=1}^n M_j\right) \tag{16}$$

$$CP = \left(\sum_{i=1}^m N_i P_i^a + \sum_{j=1}^n M_j P_j^b\right) \cdot CAP \tag{17}$$

$$\sum_j^n X_{ij} = \sum_j^n Y_{ji}, \quad \sum_i^m Y_{ji} = \sum_i^m X_{ij} \tag{18}$$

$$X_{ij} \le D_{ij}^{a} \quad , \qquad Y_{ji} \le D_{ji}^{b} \tag{19}$$

$$\sum_{i}^{m}\sum_{j}^{n} X_{ij} \le CAP, \quad \sum_{i}^{m}\sum_{j}^{n} Y_{ji} \le CAP \tag{20}$$

$$N_i = \begin{cases} 1 & while \sum_{j}^{n} X_{ij} \ne 0 \\ 0 & while \sum_{j}^{n} X_{ij} = 0 \end{cases} \tag{21}$$

$$M_j = \begin{cases} 1 & while \sum_{i}^{m} Y_{ji} \ne 0 \\ 0 & while \sum_{i}^{m} Y_{ji} = 0 \end{cases} \tag{22}$$

$$\lambda = \begin{cases} 1 & while \sum_{i}^{m} N_i + \sum_{j}^{n} M_j \ne 2 \\ 0 & while \sum_{i}^{m} N_i + \sum_{j}^{n} M_j = 2 \end{cases} \tag{23}$$

In the CIO model, the evolution process of container shipping route structure form is taken into consideration. An optimal decision of the structure form in the network optimization design can be made by using the CIO model.

4. A Case Study

This section presents a sample case to demonstrate the application of the proposed formulation. The case experiment focuses on container shipping network design in the trade area of Northeast Asia and west coast of North America.

Set Northeast Asia as region *A*, candidate ports are as follows: Guangzhou, Tianjin, Shanghai, Ningbo, Qingdao, Huanghua, Dalian, Guangzhou, Yantai, Rizhao, Lianyungang, Busan, Kobe, Nagoya and Yokohama.

Set west coast of North America as region *B*, candidate ports are as follows: Long Beach, Los Angeles, Seattle, Auckland, San Diego, Tacoma, Portland, Berkeley, Netherlands, Hong Kong, San Francisco, San Jose, Ensenada, Mazatlan and Manzanillo.

Other parameters are set as follows: Freight rates: Multi-Port-Calling route, 1,800 USD/TEU; Hub-and-Spoke route, 1,300 USD/TEU. Average port charge rates, 5×*CAP* USD per ship.

Then, we use the Matlab 7.0 to solve the model of the case experiment, figures and results are obtained as follows: When the ship-size increases from 0 to 3,000 TEU with 500 TEU of cargo-demand from each calling port, the objective value curve is shown as Fig. 2*a.*

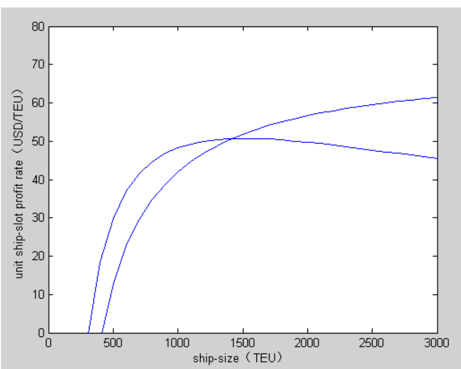
The results demonstrate that when the ship-size capacity exceeds 1,480 TEU, the optimal structure form changes from Multi-Port-Calling networks to Hub-and-Spoke networks, and the objective value at the transforming point is 50.7 USD.

When the cargo-demand increases from 0 to 5,000 TEU with 8,000 TEU capacity of the ship-size, the objective value curve is shown as Fig. 2*b*. The results show that when the cargo-demand exceeds 2,490 TEU, the optimal route structure form changes from Hub-and-Spoke networks to Multi-Port-Calling networks, and the objective value at the transforming point is 64.7 USD.

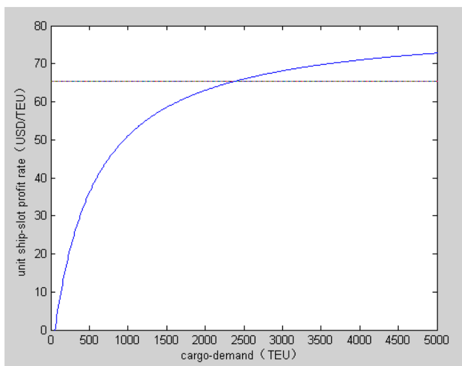
When the cargo-demand and ship-size change simultaneously, the objective value curve is shown as Fig. 3. When the ship-size is small, we can figure out that the optimal structure form is Hub-and-Spoke networks, in fact it is the Point-to-Point route. With the ship-size growth, optimal route structure form firstly transforms to Multi-Port-Calling networks. As the ship-size is growing further, the optimal structure form then changes to Hub-and-Spoke networks.

The intersection curve of two surfaces is shown as Fig. 4. The curve demonstrates the relationship of cargo-demand and ship-size at the transforming points. Obviously, the results prove that the more the cargo-demand, the larger the ship-size at the transforming points.

Applying the CIO model to solve this case, we can obtain the results that are shown in Fig. 5. When the variables vary in the left part of the intersection curve, the Multi-Port-Calling networks is selected as an optimal structure form for the container shipping networks design, otherwise, the Hub-and-Spoke networks.



a. Effects of Ship Size Change



b. Effects of Cargo – Demand Change

Fig. 2.
Effects of Ship Size (a) and Cargo – Demand (b) Change

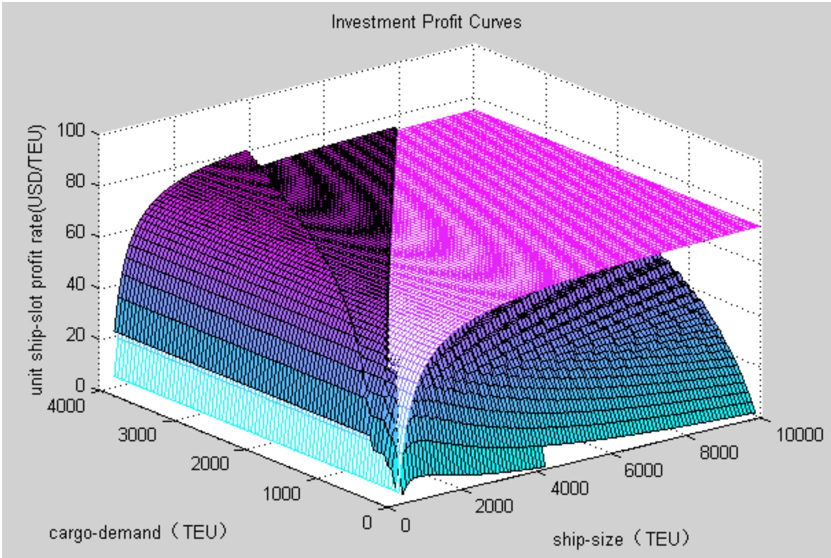


Fig. 3.
Ship-Size and Cargo-Demand Changes

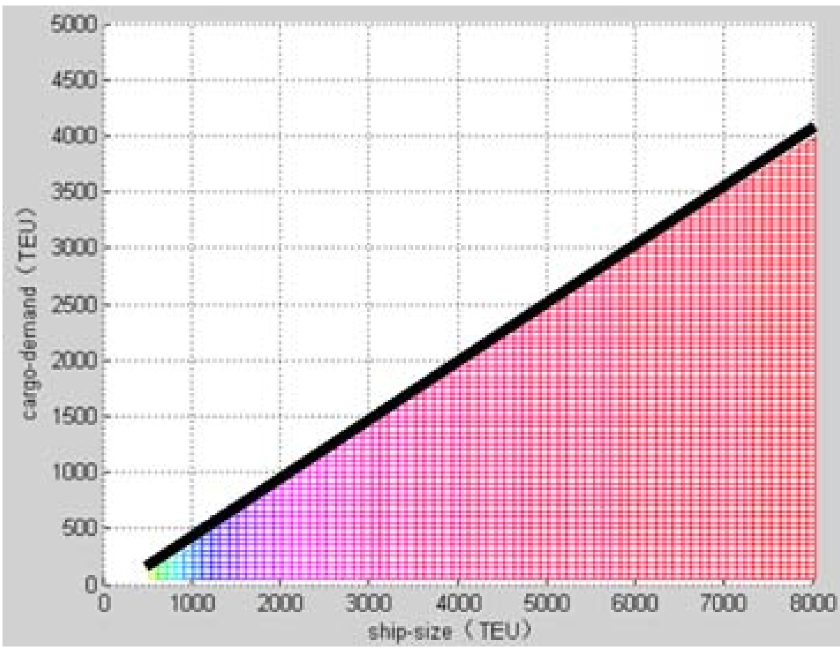


Fig. 4.
Intersection of Two Curve Surfaces

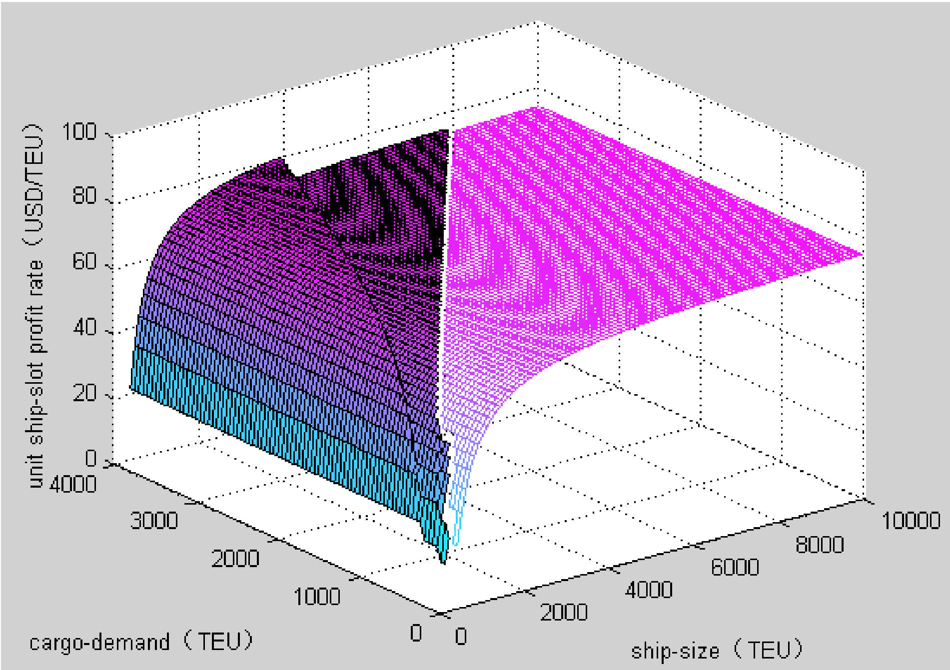


Fig. 5.
Comprehensive Integrated Model Results

5. Conclusion

This study addresses the evolution process of container shipping network structure forms when the ship-size and cargo-demand change at the same time. Through integrating Multi-Port-Calling networks and Hub-and-Spoke networks, the paper builds a comprehensive integrated model with the objective of maximizing investment profit rate. This comprehensive integrated model not only thoroughly reveals the evolution process of container shipping network structure forms, but also adds a function, which plays an important role in selection of optimal network structure forms, to regular route operation optimization models. Finally, through a case study, results demonstrate the effectiveness of the analysis approach and the validity of the proposed comprehensive integrated model.

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PROCESNA ANALIZA U PROMENI STRUKTURE KONTEJNERSKE TRANSPORTNE MREŽE U VODNOM TRANSPORTU

Chen Chao, Yan Wei

Sažetak: S obzirom na sve veći uticaj veličine broda i veličine zahteva za prevozom robe na mreže kontejnerskog transporta, a imajući u vidu razvoj njihove strukture, u ovom radu su prikazani operativni modeli dve osnovne strukture kontejnerskih transportnih mreža (Multi-port-calling mreža i Hub-and-spoke mreža) kojima se omogućava maksimiziranje efikasnosti investicija. Na osnovu pomenutih modela, razvijen je sveobuhvatni integrisani operativni model kontejnerske transportne mreže pomoću koga je izvršena analiza razvoja strukture kontejnerske mreže u funkciji veličine broda i veličine zahteva za prevozom robe. Na kraju, kroz studiju slučaja, rezultati su pokazali da je sveobuhvatni integrisani operativni model vrlo efikasan u analizi procesa razvoja strukture kontejnerskih transportnih mreža u brodarstvu.

Ključne reči: sveobuhvatni integrisani operativni model (CIO model), struktura kontejnerske transportne mreže, efikasnost investicija, Multi-Port-Calling mreža, Hub-and-Spoke mreža.