Journal of
Marine Science and Engineering

MDPI

Article

Vessel Deployment and De-Hubbing in Maritime Networks: A Case Study on Colombo Port and Its Feeder Market

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Abstract: Generally, vessels are deployed as hub-and-spoke networks to achieve high slot utilization and cost efficiency for shipping lines in global maritime container shipping networks. At the Port of Colombo, most transhipment containers originate from and are destined for Indian ports, the export/import container volume of which has been rapidly increasing, and Indian ports have been developed to accommodate vessel enlargement. In such circumstances, the partial or complete abandonment of a hub (Colombo port) in this region is expected, which is known as "de-hubbing." This study aims to clarify the impact of port developments and an increase in container cargo demand from the source country on maritime network selection from the perspective of shipping lines. We develop a mixed integer linear programming model to describe vessel deployment, including transhipment via the Colombo port and direct shipment in Indian ports. As a result of the analysis, the number of direct services to Indian ports is expected to increase when the cargo demand of Indian ports increases and the port development of Indian ports is conducted. The progress of the de-hubbing phenomenon decreases vessel size at Colombo port because the container demand at Indian ports is mostly satisfied by newly deployed trunk lines to Indian ports. This study suggests that if Colombo port expects to maintain its hub status, it is critical to consider various other incentives to attract and retain mainline carriers in addition to expanding its port infrastructure. Similarly, if India expects to receive direct calls from mainlines, it is important not only to develop their port infrastructure but also to increase their cargo demand.

Keywords: vessel deployment; de-hubbing; transhipment; port development; container demand

Citation: Kawasaki, T.; Tagawa, H.; Kavirathna, C.A. Vessel Deployment and De-Hubbing in Maritime Networks: A Case Study on Colombo Port and Its Feeder Market. *J. Mar. Sci. Eng.* **2022**, *10*, 304. https://doi.org/10.3390/jmse10030304

Academic Editor: Mihalis Golias

Received: 18 December 2021
Accepted: 18 February 2022
Published: 22 February 2022

1. Introduction

In maritime container shipping networks, vessels are mostly deployed as hub-and-spoke networks. When shipping lines design maritime networks, vessel deployment is optimized to maximize profits or minimize costs. Aggregating cargo in specific nodes, which is called a hub port in the maritime shipping network, is a vital factor in achieving high slot utilization and cost efficiency for shipping lines [1]. From the perspective of shippers, hub-and-spoke networks require additional navigation distance, time, and port charges compared to point-to-point networks, primarily because the cargo that originates in a spoke must be transported via a hub [2]. However, adopting a hub-and-spoke network is cost-efficient for shipping lines because the freight rate tends to be lower when economies of scale are achieved. Hub-and-spoke networks can connect origin and destination ports through fewer shipping services than point-to-point networks. Accordingly, the configuration of hub-and-spoke networks can reduce network construction costs—aggregation can yield economies of scale and density more easily [3]. However, larger vessels are not always economically effective in hub-and-spoke networks because economies of density may not always exist [4,5]. In such cases, hub-and-spoke networks can be less cost-effective than point-to-point networks in some conditions, particularly the cargo generation of source countries. From the perspective of port authorities, many ports are attempting to be hub ports to influence regional or international economic services [6,7] and establish direct links with large markets via trunk lines [8].

The Port of Colombo, located at the centre of the trunk sea route connecting Europe and Asia, is one of the largest ports in South Asia. In 2015, the ratio of transhipment containers in the port of Colombo was 77.1% on a Twenty-foot Equivalent Unit (TEU) basis [9]. In particular, the ratio of these transhipment containers originating from and destined for the ports of India accounts for more than 75%, which implies that Colombo Port is heavily dependent on Indian containers. When considering the Port of Colombo and its development opportunities, a few development projects are currently underway for adding new berths and terminals in the near future. Particular examples are the addition of the East container terminal, the establishment of a logistics center and a multi-model transport hub adjacent to the port premises, the proposed North port development project, etc. At the same time, the export/import container volume in India has been increasing with rapid economic growth, which would influence the design of the network [10]. As a source country, if an adequate cargo volume is collected from India to fill container vessels, shipping lines would deploy trunk lines for Indian ports instead of using Colombo port as a hub because shipping lines would benefit less from cargo aggregation to/from Indian ports at Colombo port. In addition, Indian ports will invest in accommodating vessel enlargement because some Indian ports do not have the capacity to accommodate large vessels. In these cases, the dominant carrier is expected to abandon a hub, either partially or completely, which is known as "de-hubbing" [11].

Several studies have been conducted on network design problems in maritime transport. For example, the significance of container demand for designing shipping networks where direct and transhipment routes are available is highlighted. Shipping lines provide direct services when they find direct shipping profitable [2]. Moreover, the demand for cargo volume influences the design of shipping networks [1]. The container vessel capacity has a significant influence on the design of maritime networks [12]. There is a tendency to apply hub-and-spoke networks when the capacity of the hub port increases [13]. In these existing works, port development and container demand in the source country would be a significant variable for network design in maritime container transport. However, to the best of our knowledge, no study has attempted to clarify the relationship between the port development and container demand of source countries and network selection. Therefore, this study aims to identify how port development and container demand in container-originated/destined countries impact the de-hubbing phenomenon from the perspective of shipping lines. The case study was conducted by considering India as the source country for container cargoes and Colombo port as a regional hub port. Owing to strong economic growth and a large population, Indian-originated container cargo is predicted to continuously increase in the future. Meanwhile, as a source country, Sri Lanka has a relatively smaller import/export container volume. Therefore, the case study considered India as the source country. In this study, mixed integer linear programming (MILP) was used to model the behavior of shipping lines, which can quantitatively represent the behavior of actual shipping lines. The decision variable of MILP is a binary variable that can represent ports of call of the liner services, using 0 or 1 within the sets of available ports. Once the model was developed, it was applied to multiple scenarios with a range of container demand values from the source country. The relationship between container demand and de-hubbing behavior of shipping lines was observed.

The remainder of this paper proceeds as follows: Section 2 reviews the existing literature on shipping network optimization and container cargo allocation. In Section 3, the model describing the shipping line behavior is developed using MILP. Section 4 addresses the actual situation of the study area, input values, and scenarios. Section 5 presents the results from simulating several scenarios using the developed model. Lastly, the main conclusions of the study and future research directions are presented in Section 6.

2. Literature Review

Several studies have analysed port choice behavior from the perspective of shipping lines (that is, vessel deployment) on several geographical scales for different shipping networks, such as hub-and-spoke and direct networks. Ji et al. (2015) [12] developed a routing optimization problem in hub-and-spoke networks using a genetic algorithm. The study targets involved the ports in the Pearl River Delta. The authors found several critical factors for the routing behavior of shipping lines, including the time deadline, container vessel capacity, and cargo handling capacity of each port. They use a genetic algorithm, but MILP is a widely used method for vessel deployment problems. This is because MILP has a high affinity with the disaggregated port call behavior of shipping lines. The following studies used MILP to forecast the vessel deployment and cargo volumes. Kim et al. (2019) [14] formulated a vessel deployment model using MILP in the ports in Southern Africa and analysed the market share of each liner service and found that sea freight rate affects routing problems in shipping networks. Mulder and Dekker (2014) [15] solved the combined fleet design problem, ship scheduling, and cargo routing problem as a network design problem. Zheng et al. (2015) [16] proposed a vessel deployment model using MILP with cost minimization in a network of 46 ports spread across Asia, Europe, and Oceania, including nine ports as hub ports with given demand. In these studies, a set of hub ports are predetermined, and the possibility of the deployment of large-scale vessels at non-hub ports were not considered. Agarwal and Ergun (2008) [17] and Brouer et al. (2013) [18] formulated a model for vessel deployment to maximize the profit of shipping lines. In these studies, the container demand was fixed, and the vessel deployment for the hub port was predetermined. Kawasaki et al. (2021) [19] considered the port choice model of shippers considering shipping lines' behavior. Research on container cargo allocation in global shipping networks has been conducted. Bell et al. (2008) [20] developed a container allocation model to minimize the cost of shipping lines by considering the container handling charges at ports, container rental costs, and the time value decay cost (that is, inventory cost) under the conditions of given routes, the size of vessels, and the cargo demand. Shibasaki and Kawasaki (2016) [21] developed a model to reproduce global container movements on the international maritime shipping network by applying a network equilibrium assignment method, which ensures cost equilibrium between competitive routes. Moreover, the authors also minimized the total cost of the shipping lines. Wang et al. (2015) [22] proposed a container allocation model that maximizes the profit of shipping lines by setting the freight rate. In the study, it was assumed that vessel sizes are given and container demand is dependent on the freight rate. These models assume that routes and ports called by shipping lines are fixed; however, the routes and ports served by shipping lines would change in accordance with cargo demand, as the present study considered.

Kim et al. (2018) [23] and Zheng and Dong (2016) [24] considered that routes and ports served by shipping lines are changed on the basis of the forecasted cargo demand in the ports. Furthermore, Kim et al. (2018) also developed a model for the route and port selection of shipping lines using MILP with several vessel size scenarios [23]. Zheng and Dong (2016) [24] examined ports along the Yangtze River and estimated the market share of transhipment containers at each hub port. The authors gradually changed the total demand of containers in this area to observe its effect on the volume of transhipment containers. Moreover, studies have been conducted on the selection between direct and transhipped shipments. Yeo et al. (2008) [25] stated that direct service to northern Chinese ports by major shipping lines has considerably reduced the transhipment container cargo at Busan Port. Kim et al. (2018) [23] estimated the market share of direct and transhipment cargo to/from Southern African ports using MILP when shipping lines used different vessel sizes. However, in their model, the trade between Southern African ports and Europe and

Southern African ports and Asia were formulated separately, and the direct route between Asia and Europe was not considered. Therefore, the model is not suitable for ports located on the key routes between Asia and Europe, such as the Port of Colombo in Sri Lanka, which is the main target of the case study.

Existing research on vessel deployment and container allocations from the perspective of shipping lines have been modelled using the MILP method with given conditions for container demand and shipping network. However, no research has analyzed the de-hubbing phenomenon with increasing cargo generation and attraction in source countries. In particular, there has been no research on vessel deployment in container transhipment trends at hub ports considering increases in future container cargo demand and port capacity. Besides, there is no model that evaluates transhipment volume at Colombo port considering the possibility of calling trunk lines between East Asia and Europe for Indian ports. In this study, we develop a model that enables trunk liner services to call for the Indian ports; subsequently, using the developed model, we examine the relationship between de-hubbing and cargo demand in a global shipping network.

3. Model Development

Similar to several previous studies, we applied MILP in this analysis to determine vessel deployment and port selection. We prepared the following two assumptions for the model. Firstly, shipping lines make their decisions on vessel deployment and port selection to maximize their profits. More specifically, it means that the route choices of shippers are not considered for the purpose of simplicity. Several researchers have adopted the assumption mentioned above to calculate the optimum shipping route served by shipping lines [17,18]. We also assume that shipping lines deploy the minimum number of vessels to maintain weekly service in each liner service for profit maximization. Secondly, the shipper pays the freight rate to the main shipping line for the liner service between the origin and destination ports. In other words, the main shipping line does not have to pay charges to the feeder shipping line. Instead, this feeder link cost (FLC) is included as the cost of the main shipping line for simplicity of calculation. The notations for the model are as follows.

In this study, the objective function of the shipping line is to maximize its profits in a week (Ps), for which it has three decision variables. Specifically, the shipping line decides on liner service (r) and vessel type (a) as network information, as well as container cargo volume (x). The shipping line chooses a service from a set of services (R) comprising combinations of target ports considered in the model. Vessel type refers to the deployment of vessel type to the service chosen from the set of vessel types (A). Determination of vessel type is accompanied by vessel size (s^a) and operation and fixed cost (OFC). One of the decision variables of the shipping line to decide the service and vessel type is a binary variable (y_r^a), which takes 1 if service r is served by vessel type a and 0 in the rest of the cases. The binary variable was grouped into vector $\boldsymbol{y}$. The other decision variables are cargo volume transported directly to the port pair (o,d) in service r $\left(\widetilde{x}_{o,d}^r\right)$ and cargo volume transported for the port pair (o,d) with transhipment in service r $\left(\hat{x}_{o,d}^r\right)$. The cargo volumes are grouped in a vector $\boldsymbol{x}$. Therefore, the shipping line decides the vectors $\boldsymbol{x}$ and $\boldsymbol{y}$ to maximize their profits.

Equation (1) shows the profit of the shipping line in a week. The first term consists of revenue, and five types of costs are shown in the second to sixth terms. The revenue of the shipping line (first term) is calculated by the product of container cargo volume $\left(\hat{X}_{od} \text{ and } \widetilde{X}_{od}\right)$ and freight rate ($\hat{F}_{od}$ and $\widetilde{F}_{od}$) obtained from the shipper. The second term in Equation (1) indicates the total bunker cost during the voyage. In this study, the number of deployed vessels in each service is to maintain weekly service. This indicates that the total distance of voyage of all deployed vessels per week equals the total distance of the liner service. Thus, we calculate the navigation time of all vessels per week by dividing the total navigation distance $(D_{r,i})$ between the target ports in the service by the navigation speed (v^a). Each vessel type a has a unique bunker cost (bc^a). The third term in Equation

(1) corresponds to the total loading and unloading costs (lc_p) in origin, destination, and hub port. The fourth term shows the total FLC related to the second assumption mentioned above. The costs of each FLC from ports o to d (fc_{od}) were calculated. The fifth term represents the total vessel cost, which indicates the OFC. The OFC was calculated, which is dependent on the number of vessels deployed in service $r(N_r)$ and each vessel cost (vc^a). The final term in Equation (1) indicates the total port charge, which is calculated as the sum of the port charge and pilotage fee at each port (pc_p).

$$
\begin{aligned}
Ps = & \sum_{(o,d)\in W}\left(\hat{X}_{od} \times \hat{F}_{od} + \widetilde{X}_{od} \times \widetilde{F}_{od}\right) - \sum_{r\in R}\sum_{a\in A}\sum_{i} bc^a \times y_r^a \times D_{r,i}/v^a \\
& - \sum_{(o,d)\epsilon W}\sum_{h}\left((lc_o + lc_d)\left(\widetilde{X}_{od} + \hat{X}_{od}\right) + \sum_{h}\hat{X}_{od} \times lc_h\right) - \sum_{(o,d)\in W}\hat{X}_{od} \times fc_{od} \\
& - \sum_{r\in R}\sum_{a\in A} N_r \times y_r^a \times vc^a - \sum_{a\in A}\sum_{r\in R}\sum_{p\in P} y_r^a \times z_r^p \times pc_p^a
\end{aligned}
\tag{1}
$$

The optimization of the profit of shipping lines was formulated using the MILP model. Constraint 3 guarantees that each service can only have at most one vessel type. Constraint 4 defines container cargo that will not be transported on a service where there is no ship deployment. Constraints 5 and 6 are the sum of transhipment cargo and direct cargo in each service, which is equal to the total container cargo between the origin and destination for each direct and transhipment route. Constraint 7 illustrates that container cargo is transported in either direct or transhipment. The term Q_{od} represents the cargo demand from port o to port d, and the term θ is a coefficient for the scenario analysis of future cargo demand. Under the current conditions, θ was set as 1, and Constraints 8 and 9 indicate that cargo from origin to destination port must be transported in the service, including both the origin and destination. The term $w_{r,i}^{o,od}$ is a binary variable that takes the value of 1 if port o is *the* i-th port in service r; otherwise, it is 0. Constraint 10 defines the cargo volume on the vessel $(q_{r,i})$, and Constraint 11 is a constraint condition that ensures the cargo volume on the vessel is less than the capacity of the vessel. Constraint 12 defines the number of deployed vessels in each service based on the total travel time between the origin and destination ports. The total time is the sum of navigation time and the time spent at the port. The sum of the navigation time is calculated using the navigation distance and speed. Meanwhile, the time spent at the port is calculated by the average vessel turnaround time at port p (T_p). In this term, we introduce the binary variable Z_p^r, which takes the value of 1 if service r calls for port p; it is 0 otherwise. The value of 168 in the denominator is considered to convert from hours to weeks. We calculate the number of deployed vessels as the minimum number of vessels needed to maintain weekly service and satisfy the shipper's demand by Constraint 11 and 12. Constraint 13 denotes the term y_r^a as a binary variable. Constraint 14 ensures that the decision variables are non-negative.

$$
\max Ps(\boldsymbol{x}, \boldsymbol{y}) \tag{2}
$$

Subject to

$$
\sum_{a\in A} y_r^a \le 1 \quad \forall r \in R \tag{3}
$$

$$
M \times y_r^a - \sum_{(o,d)\in W}(\widetilde{x}_{od}^r + \hat{x}_{od}^r) \ge 0 \quad \forall r \in R, \forall a \in A \tag{4}
$$

$$
\sum_{r\in R}\widetilde{x}_{od}^r = \widetilde{X}_{od} \quad \forall (o,d) \in W. \tag{5}
$$

$$
\sum_{r\in R}\hat{x}_{od}^r = \hat{X}_{od} \quad \forall (o,d) \in W \tag{6}
$$

$$\widetilde{X}_{od} + \hat{X}_{od} = \theta \times Q_{od} \quad \forall (o,d) \in W \tag{7}$$

$$(\widetilde{x}^r_{od} + \hat{x}^r_{od}) - \sum_i M \times w^{o,od}_{r,i} \leq 0 \quad \forall r \in R, \forall (o,d) \in W \tag{8}$$

$$(\widetilde{x}^r_{od} + \hat{x}^r_{od}) - \sum_i M \times w^{d,od}_{r,i} \leq 0 \quad \forall r \in R, \forall (o,d) \in W \tag{9}$$

$$q_{r,i} = q_{r,i-1} + \sum_{(o,d)\in W} w^{o,od}_{r,i} \times \widetilde{x}^r_{od} + \sum_{(o,d)\in W} w^{o,od}_{r,i} \times \hat{x}^r_{od} - \sum_{(o,d)\in W} w^{d,od}_{r,i} \times \widetilde{x}^r_{od} - \sum_{(o,d)\in W} w^{d,od}_{r,i} \times \hat{x}^r_{od} \quad \forall i, \forall r \in R \tag{10}$$

$$q_{r,i} \leq \sum_{a\in A} y^a_r \times s_a \quad \forall i, \forall r \in R \tag{11}$$

$$N_r = min\left\{ n \in \mathbb{Z} \middle| n \geq \frac{\sum_i D_{r,i}/v^a + \sum_{p\in P} z^p_r \times T_p}{168} \right\} \quad \forall a \in A \tag{12}$$

$$y^a_r \in (0,1) \quad \forall r \in R, \forall a \in A \tag{13}$$

$$\widetilde{x}^r_{od} \geq 0, \hat{x}^r_{od} \geq 0 \quad \forall (o,d) \in W, \forall i, \forall r \in \mathrm{R} \tag{14}$$

4. Application to India and Colombo Ports

4.1. Study Area

This study focuses on container cargo flow between Europe, East Asia, the Colombo port, and the top 10 Indian ports in 2015 as a base case, since detailed transhipment data at Colombo port are available with 2015 as the latest data. However, our purpose can be sufficiently achieved by using the 2015 database as a base case. The Colombo port is located in Sri Lanka, an island at the centre of the trunk line between Europe and East Asia. It is a regional hub port for the Indian subcontinent (IS). Colombo port has advantages over Indian ports due to its bigger depth of port access channel, ability to handle larger container vessels, and its strategic location on major shipping routes. When considering the port location, although Colombo port has a strategic location with a short deviation from the main sea routes than Indian ports, there is a considerably high cost for the feeder link for connecting Indian feeder ports and Colombo port in a hub and spoke network. If Indian ports can accept larger container vessels by eliminating infrastructure limitations, shipping lines would eliminate the cost associated with feeder links. Therefore, some Indian ports, such as Mundra, Nhava Sheva, etc., are called directly by mainlines, especially in the last decade, possibly due to their infrastructure development and growth in total cargo volume originating from/to India.

Figure 1 and Table 1 illustrate the location and statistics of the Indian and Colombo ports, respectively. According to Table 1, the Colombo port shows the largest total cargo volume and frequency and highlights Colombo port's attractiveness as a hub. As shown in Table 1, ports in northwest India such as Nhava Sheva, Mundra, Pipavav, and Hazira have relatively small ratios of transhipment at Colombo. These ports are geographically farther than Colombo port and have direct shipment services to Europe and Asia. In particular, higher numbers of services are called for Nhava Sheva and Mundra because these ports have higher container volumes. Regarding Pipavav port, a higher frequency of direct shipments to East Asia is observed. Meanwhile, the transhipment ratios are high in ports where the frequency to Europe or East Asia is zero or one, such as Tuticorin and Krishnapatnam ports. In addition, ports geographically close to Colombo port, such as Cochin port, seem to have a higher transhipment ratio similar to that of Colombo port.

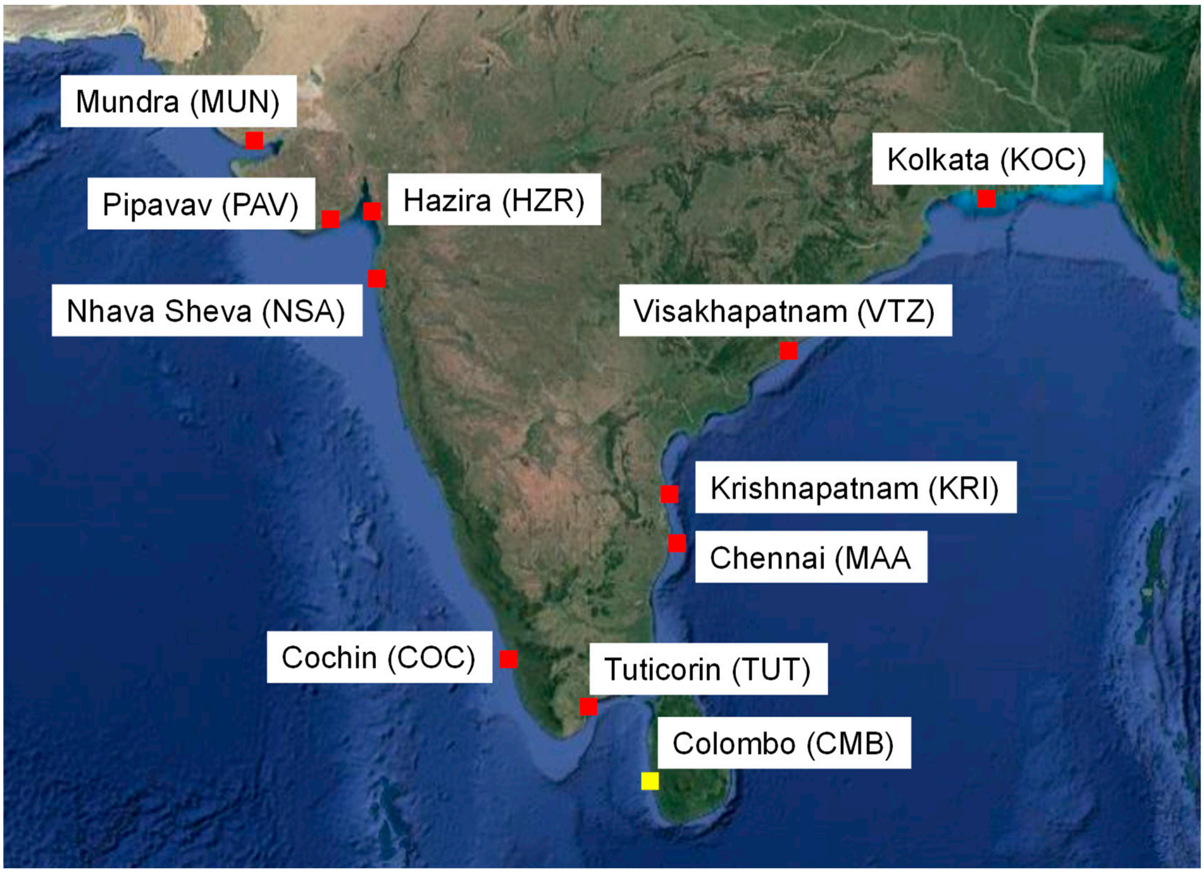

Figure 1. Location of Colombo and Indian ports. Source: Google map modified by authors.

Table 1. Statistics of Colombo and Indian ports in 2015.

Port	Cargo Volume		Frequency [Times/Week]	
	Total (Thousand TEU)	Ratio of T/S at Colombo (%)	Europe	East Asia
Colombo	5103	-	10	30
Nhava Sheva	4480	2.1	10	16
Mundra	2895	2.3	7	9
Chennai	1565	17.6	1	2
Pipavav	695	2.4	2	7
Tuticorin	620	73.5	0	0
Kolkata	577	24.0	0	0
Cochin	429	36.1	1	2
Hazira	303	0	1	1
Visakhapatnam	293	20.7	0	1
Krishnapatnam	119	44.5	0	1

Source: Drewry (2016) [9], Maritime Intelligence (2017) [26], and SLPA (2016) [27].

The following three assumptions are required to apply the proposed model to the study area. Firstly, transhipment was implemented only at the Colombo port. In other words, Indian ports with relatively higher numbers of services, such as Nhava Sheva or Mundra, are not considered transhipment ports. The previous assumption is based on the high cost of the cabotage policy in Indian feeder transport. Secondly, container cargo to/from European ports such as Hamburg and East Asian ports such as Busan are aggregated in Rotterdam and Shanghai, respectively. The third assumption is required to simplify calculations. Finally, the number of calls for South Asian ports (that is, Colombo and Indian ports) in one service is limited to less than three (that is

1 or 2), which is determined based on actual vessel deployment. As shown in Table 2, we developed a set of 265 services for the target origin and destination based on the first to third assumptions above. In addition to including cargo flow between India and other ports, these services also include cargo flow between East Asia and Europe. We grouped these services in a set of liner services (R), which deploys the optimum vessel type and service to transport all container cargoes between origin and destination ports by maximizing their profit.

Table 2. Research target services.

Liner Services	Port of Call
Europe-East Asia service	RTM/SHA/RTM
Europe-South Asiaast Asia service	RTM/IS(1)/SHA/RTM
	RTM/IS(1)/SHA/IS(2)/RTM
	RTM/SHA/IS(1)/RTM
	RTM/IS(1)/SHA/IS(2)/RTM
Europe-South Asia service	RTM/IS(1)/RTM
	RTM/IS(1)/IS(2)/RTM
East Asia-South Asia service	SHA/IS(1)/SHA
	SHA/IS(1)/IS(2)/SHA

RTM: Rotterdam, SHA: Shanghai, IS(n): nth port of call in Indian Subcontinent ports

4.2. Input Values and Scenarios

Several input values were required to conduct the case study. The coefficient of cargo demand (θ) in Constraint 11 was utilized to increase cargo demand, similar to the scenario analysis. Note that cargo demand of each port at base case is listed in Table 1. The value of coefficient θ was prepared for nine cases (1.00, 1.39, 1.78, 2.17, 2.56, 2.95, 3.34, 3.73, and 4.11). According to IHS Global Insight, in 2030, the export/import container cargo demand in India will be 2.56 times higher than the current volume. Thus, we set $\theta = 2.56$. In addition, other values of θ were prepared with equal intervals to observe the effect of cargo demand on the transhipment ratio at Colombo Port. In this study, the shipping line can deploy a vessel (a) to each service from vessel type (A) in Table 3. Each vessel has a distinct gross tonnage, bunker price, and vessel cost. We defined the navigation speed (v^a) as 25 knots for all vessel types. Bunker price per ton is obtained from Ship & Bunker (BP = 661.75 USD/ton). Banker cost is dependent on the navigation speed and vessel size. Navigation speed is changeable in one sailing; however, consideration of such fluctuations makes the optimization process difficult. Thus, we use average speed, which is obtained from the MDS database. Similarly, bunker cost is different from each vessel size; however, as several studies assumed, the design speed is uniformly set if vessel size exceeds a certain size. For example, Akakura and Matsuda (2014) [28] concluded that navigation speed can be uniformly set as 24.6 knots for a 6357 TEU sized vessel and above. Therefore, we use 25 knots as an average navigation speed for all sized vessels. Besides, vessel speed has been reduced from the year 2015. Since vessel speed would be one of the variables to determine vessel deployment, consideration of change in vessel speed is important. This is a future work of this study. Note that the shipping line cannot deploy any vessels in any service owing to physical constraints on the vessels, such as the water depth of the ports.

Table 3. Vessel types (A).

Vessel Size [TEU] (s^a)	Tonnage [ton] (g^a)	Bunker Cost [USD/Hour] (bc^a)	Vessel Cost [USD] (vc^a)
6000	73,518	167	193,931
7500	87,794	209	214,595
9000	102,069	252	235,259
10,500	116,345	294	255,923
12,000	130,620	337	276,587
13,500	144,896	379	297,251
15,000	159,171	422	317,915
16,500	173,447	465	338,579
18,000	187,722	508	359,243
19,500	201,998	551	379,907
21,000	216,273	594	400,571
Source	database of MDS and Marine traffic	Notteboom and Cariou (2009) [29].	ITF (2015) [30]

As shown in Table 4, we consider three scenarios for the maximum vessel size in each port. Scenario 1 indicates the actual maximum vessel size calling at each port determined by the MDS database and Drewry [27]. Scenario 2 is the case where the maximum vessel size is increased by 3000 TEU more than those of Scenario 1 in all ports except the Colombo and Mundra. Moreover, scenario 2 assumes the development of future Indian local ports. For Scenario 3, the maximum vessel size increases for the Mundra and Colombo ports, where the constraints are not relaxed in Scenario 2. Consequently, we assume that in the future, 21,000 TEU-sized vessels can only be accommodated in the Mundra and Colombo ports. It is fair to consider that other ports can also be expanded to accommodate large-sized vessels due to the availability of sufficient hinterland. For example, Visakhapatnam and Krishnapatnam ports have sufficient hinterland for further expansion [31]. However, the demand for these ports is not as high as that of other popular Indian ports, such as Nhava Sheva and Mundra. Accordingly, we prepared scenarios for the maximum vessel size of each Indian and Colombo port. The data of other input values were sourced from SeaRoute.com, including freight rate, FLC, and navigation distance between ports.

Table 4. Scenarios for maximum vessel size for each port.

Port	Maximum Vessel Size [TEU]		
	Scenario 1 (Actual)	Scenario 2	Scenario 3
Nhava Sheva	12,000	**15,000**	15,000
Mundra	18,000	18,000	**21,000**
Chennai	6000	**9000**	9000
Pipavav	6000	**9000**	9000
Tuticorin	3000	**6000**	6000
Kolkata	2000	**5000**	5000
Cochin	6000	**9000**	9000
Hazira	9000	**12,000**	12,000
Visakhapatnam	6000	**9000**	9000
Krishnapatnam	6000	**9000**	9000
Colombo	18,000	18,000	**21,000**

5. Results and Discussion

5.1. Shipping Network

Table 5 shows the results of vessel deployments in Colombo and Indian ports connecting Europe and East Asia. As mentioned before, Europe and East Asia ports are aggregated into Rotterdam and Shanghai ports for simplicity. Note that we consider the total container volumes between the Indian subcontinent and Europe/East Asia, even though ports are aggregated. First, we discuss the impact of the changes in cargo demand, which is expressed by θ. As shown in Table 5, as the cargo demand increased, the number of deployed vessels in Indian ports also increased. Specifically, the number of deployed vessels increased from 4 (θ = 1.0) to 10 or 11 (θ = 2.56). The changing ratio is almost the same as the ratio of changes in cargo demand, such as from 1.0 to 2.56. Meanwhile, there were no drastic changes in the number of vessels deployed in the Colombo port with increasing cargo demand. Vessels deployed to Colombo port increased from three (θ = 1) to four (θ = 2.56) in scenario 1, which does not assume any developments in Indian ports. However, when the maximum vessel size of Indian ports increases, more vessels will be deployed in Indian ports. These results show that the number of direct services to Indian ports is expected to increase when the cargo demand of Indian ports increases. Importantly, the size of deployed vessels decreased in scenarios 2 and 3, which are Indian port development scenarios. In other words, the de-hubbing phenomenon (that is, calling trunk lines for Indian ports and skipping Colombo port) decreases vessel size because the demand originating at Indian ports is mostly satisfied by newly deployed trunk lines to Indian ports. It has significant impacts, particularly for Colombo port because this port has a high dependency on transhipment cargoes and vessels.

Table 5. Results of size of deployed vessels for Colombo and Indian ports.

			Number of Vessels	Deployed Vessel Size [TEU]
Coefficient of cargo demand $\theta = 1.0$.	Colombo	Scenario 1	3	15,000, 10,500, 6000
		Scenario 2	3	18,000, 10,500, 9000
		Scenario 3	3	21,000, 10,500, 6000
	Indian ports	Scenario 1	4	10,500, 6000 (3)
		Scenario 2	4	10,500, 9000, 6000 (2)
		Scenario 3	4	10,500, 6000 (3)
Coefficient of cargo demand $\theta = 2.56$.	Colombo	Scenario 1	4	18,000, 12,000, 10,500, 6000
		Scenario 2	3	9000, 6000 (2)
		Scenario 3	3	9000, 6000 (2)
	Indian ports	Scenario 1	10	12,000 (3), 10,500, 6000 (6)
		Scenario 2	11	13,500 (2), 12,000 (2), 10,500, 9000 (3), 7500, 6000 (2)
		Scenario 3	11	13,500 (2), 12,000 (2), 10,500, 9000 (3), 7500, 6000 (2)

Note (2)/(3): two/three vessels are deployed.

As shown in Table 4, scenario 2 assumes increases in the capacities of Indian ports, whereas scenario 1 reflects the actual status. If the cargo demand does not change in the future ($\theta = 1.0$), shipping lines deploy 9000 TEU-sized vessels in both Colombo and Indian ports in scenario 2, whereas 6000 TEU-sized vessels are deployed in scenario 1. As shown in Table 6, the result implies that the developments of Indian ports also contribute to the de-hubbing of the maritime network in this region under the condition of constant cargo demand ($\theta = 1.0$). Moreover, because larger vessels for Indian ports are deployed as direct calls, there could be significant impacts on the hub status of the Colombo port. The comparison between Scenarios 1 and 2 at θ = 2.56 shows that not only does the number of services calling at Colombo port decrease, but the vessel size also decreases because vessels with more than 10,000 TEUs no longer call at Colombo port. Meanwhile, the number of services calling at Indian ports increases from 10 (Scenario 1) to 11 (Scenario 2), and the vessel size also increases, with 13,500 TEU vessels calling at large Indian ports such as Nava Sheva and Mundra without calling for Colombo port in scenario 2. As shown in Table 1, the Nhava Sheva and Mundra ports have a large container volume in their hinterland; thus, these ports receive direct shipments to Europe and East Asia with large container vessels. In addition, relatively minor Indian ports such as Tuticorin, Krishnapatnam, and Visakhapatnam obtained direct routes to Europe and East Asia when large cargo demand cases and port developments were carried out. In addition, as shown in Table 7, the 13,500 TEU vessel does not call for Colombo port but direct to Europe and East Asia, which indicates that the de-hubbing phenomenon would progress if case cargo demand increases and Indian ports are developed. When comparing the number of vessels deployed at ports in the scenarios, Indian ports indicate a significant increase in the number of vessels when the cargo volume increases, even in the same scenario (scenario 2). For instance, they have only four vessels at a lower cargo demand ($\theta = 1$), which increases to 11 vessels at high cargo demand ($\theta = 2.56$). In contrast, the Colombo port experiences a reduction in vessel sizes, particularly in scenario 2, which has a high cargo demand at Indian ports. It implies that increased cargo demand at Indian ports could be mostly handled by the new mainline vessels calling at Indian ports, which inevitably decreases the overall network concentration at the Colombo port.

Table 6. Results of optimized services at θ = 1.0.

Coefficient of Cargo Demand $\theta = 1.0$			
Vessel Size (TEU)	Port of Call		
	Scenario 1	Scenario 2	Scenario 3
21,000	-	-	RTM/CMB/SHA/RTM
18,000	RTM/SHA/RTM	RTM/SHA/RTM	-
18,000	-	RTM/CMB/SHA/RTM	-
15,000	RTM/CMB/SHA/RTM	-	-
10,500	SHA/NSA/CMB/SHA	SHA/NSA/CMB/SHA	SHA/NSA/CMB/SHA
9000	-	RTM/SHA/MAA/CMB/RTM	-
6000	RTM/KOC/MAA/SHA/RTM	RTM/MUN/NSA/RTM	RTM/MUN/NSA/RTM
6000	SHA/MUN/PAV/SHA	SHA/MUN/PAV/SHA	SHA/MUN/PAV/SHA
6000	RTM/SHA/MAA/CMB/RTM	-	RTM/SHA/MAA/CMB/RTM
6000	RTM/MUN/NSA/RTM	-	-

Table 7. Results of optimized services at θ = 2.56.

Coefficient of Cargo Demand $\theta = 2.56$			
Vessel Size (TEU)	Port of Calls		
	Scenario 1	Scenario 2	Scenario 3
18,000	RTM/SHA/RTM	RTM/SHA/RTM	RTM/SHA/RTM
18,000	RTM/SHA/CMB/RTM	-	-
13,500	-	RTM/MUN/NSA/SHA/RTM	RTM/MUN/NSA/SHA/RTM
13,500			SHA/NSA/SHA
12,000	RTM/NSA/CMB/SHA/RTM	RTM/MUN/NSA/SHA/RTM	RTM/MUN/NSA/SHA/RTM
12,000	SHA/MUN/SHA	SHA/NSA/SHA	SHA/NSA/SHA
12,000	RTM/SHA/NSA/RTM	-	-
10,500	SHA/NSA/CMB/SHA	SHA/MUN/HZR/SHA	SHA/MUN/HZR/SHA
9000	-	RTM/CMB/MAA/SHA/RTM	RTM/CMB/MAA/SHA/RTM
9000	-	RTM/SHA/PAV/MUN/RTM	RTM/SHA/PAV/MUN/RTM
9000	-	RTM/SHA/KOC/NSA/RTM	RTM/SHA/KOC/NSA/RTM
7500	-	SHA/MAA/KRI/SHA	SHA/MAA/KRI/SHA
6000	SHA/CMB/MAA/SHA	SHA/CMB/VTZ/SHA	SHA/CMB/VTZ/SHA
6000	SHA/PAV/NSA/SHA	SHA/TUT/CMB/SHA	SHA/TUT/CMB/SHA
6000	SHA/MAA/VTZ/SHA	-	-
6000	RTM/MUN/MAA/RTM	-	-
6000	RTM/SHA/KOC/MUN/RTM	-	-
6000	RTM/SHA/HZR/PAV/RTM	-	-

Scenario 3 assumes a capacity increase at Mundra and Colombo ports to accommodate up to 21,000 TEU vessels. In Scenario 3, a 6000 TEU vessel is deployed instead of the 9000 TEU vessel deployed in Scenario 2; simultaneously, a 21,000 TEU vessel is deployed in Colombo port in scenario 3. This shows that deploying ultra-large-sized vessels (that is 21,000 TEU) in Colombo port is cost-effective for shipping lines, enabling them to achieve economies of scale. Thus, it is crucial to develop Colombo port to call ultra-large vessels. In the cargo demand increasing case ($\theta = 2.56$), as shown in scenarios 2 and 3 in Table 7, the number and size of deployed vessels in Colombo port decrease with the development of Indian ports. As mentioned before, shipping lines enable the deployment of vessels of various sizes, including direct services to Europe and East Asia from Indian ports, because Indian ports are developed (scenarios 2 and 3). From these results, the development of Indian ports effectively proceeds to the de-hubbing of the maritime network, particularly in the case of increased cargo demand. It also implies that deploying ultra-large vessels (that is 21,000 TEU) at the Colombo port is insufficient to exceed cost-effectiveness than direct shipment in the case of high cargo demand in the future.

Tables 6 and 7 indicate the detailed ports of call related to the services in each scenario when θ = 1.0 and θ = 2.56, respectively. Accordingly, a significant increase in the number of services can be observed for high cargo demand in all three scenarios. Moreover, the number of common services calling at both Colombo and Indian ports has increased with increasing cargo demand, thus reducing the hub role of Colombo because the mainline services mostly called only Colombo before the increase in the cargo demand.

Figure 2 summarizes the annualized slot capacities (ASC) of ports in each scenario to provide a better understanding of the effects of vessel deployment at individual ports in the Indian subcontinent. The ASCs were calculated based on the services and vessel deployments mentioned in Tables 6 and 7, which result from the MILP model. Accordingly, a significant difference could be observed in the ASCs of individual ports when changing cargo demand. The ASC of Colombo indicates a significant drop, while that of the Nhava Sheva indicates significant growth in scenarios 2 and 3. Apart from the Nhava Sheva port, Mundra indicates the second-largest ASC after increasing cargo demand. Moreover, when compared to the actual situation given in Scenario 1, the number of Indian ports directly called mainline vessels increased in scenarios 2 and 3. For instance, ports such as Krishnapatnam, Tuticorin, Vishakhapatnam, and Hazira are not being called mainline vessels in scenario 1 with low cargo demand, although those ports are called by scenarios 2 and 3, particularly with high cargo demand. Apart from the effects on ASC due to port developments in scenarios 2 and 3, a significant increase in ASC can be observed when comparing low and high cargo demands, even in scenario 1 without any port development. When considering Scenario 1, Colombo port still receives the highest ASC from these services, even with the high cargo demand of India. Thus, insufficient port infrastructure in India plays a predominant role in maintaining the hub status of Colombo. Overall, in scenarios 2 and 3, 10 Indian sub-continent ports are referred to as mainline services with high cargo demand when compared to the four ports with low cargo demand, which directly indicates the de-hubbing phenomenon. However, the ASC analysis only indicates the slot capacities of services and does not indicate the actual allocation of slots on individual ports by shipping lines.

5.2. Transhipment Cargo at Port of Colombo

Figure 3a,b show the total cargo volume of transhipment cargo via Colombo and the ratio of transhipment cargo in Colombo port, respectively. As shown in Figure 3a, the amount of transhipment in Scenario 1 increases as cargo demand increases, and those in Scenarios 2 and 3 fluctuate with an increase in cargo demand. This implies that the Colombo port would deal with a larger volume of cargo as cargo demand originating in India increases without the development of Indian ports (scenario 1). However, if Indian ports carry out port developments and enlarge the maximum vessel size accommodated, it would be difficult for the Colombo port to increase the volume of cargo even if Colombo port implements port expansion in scenario 3.

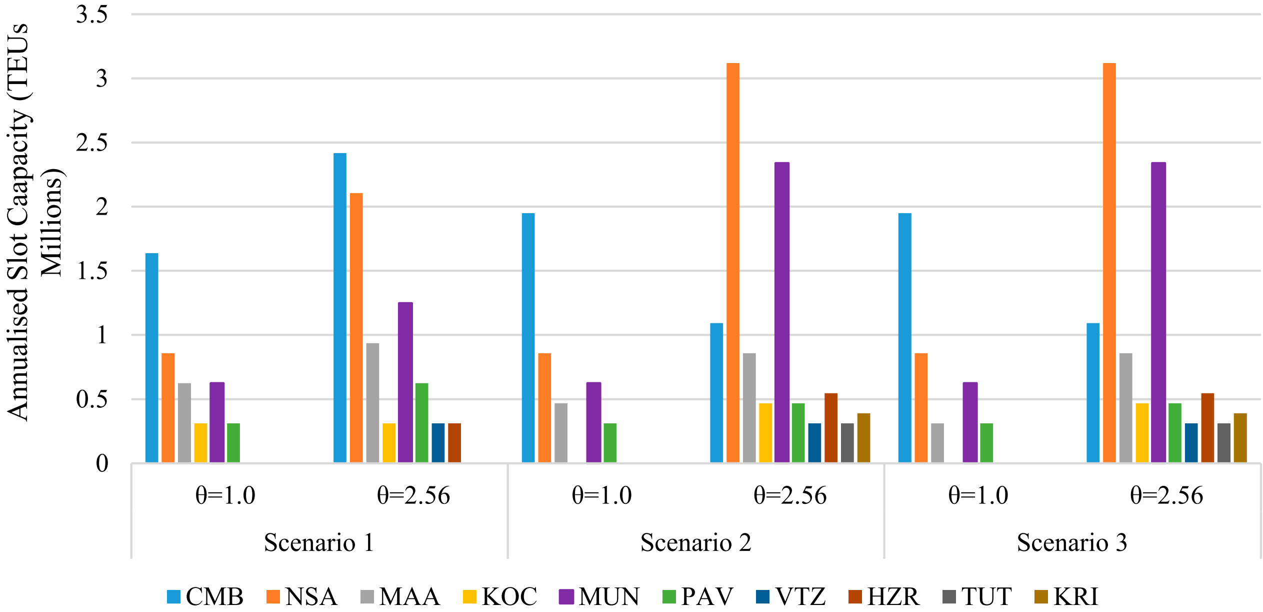

Figure 2. Annualized Slot Capacity of Services Calling at Indian Subcontinent ports.

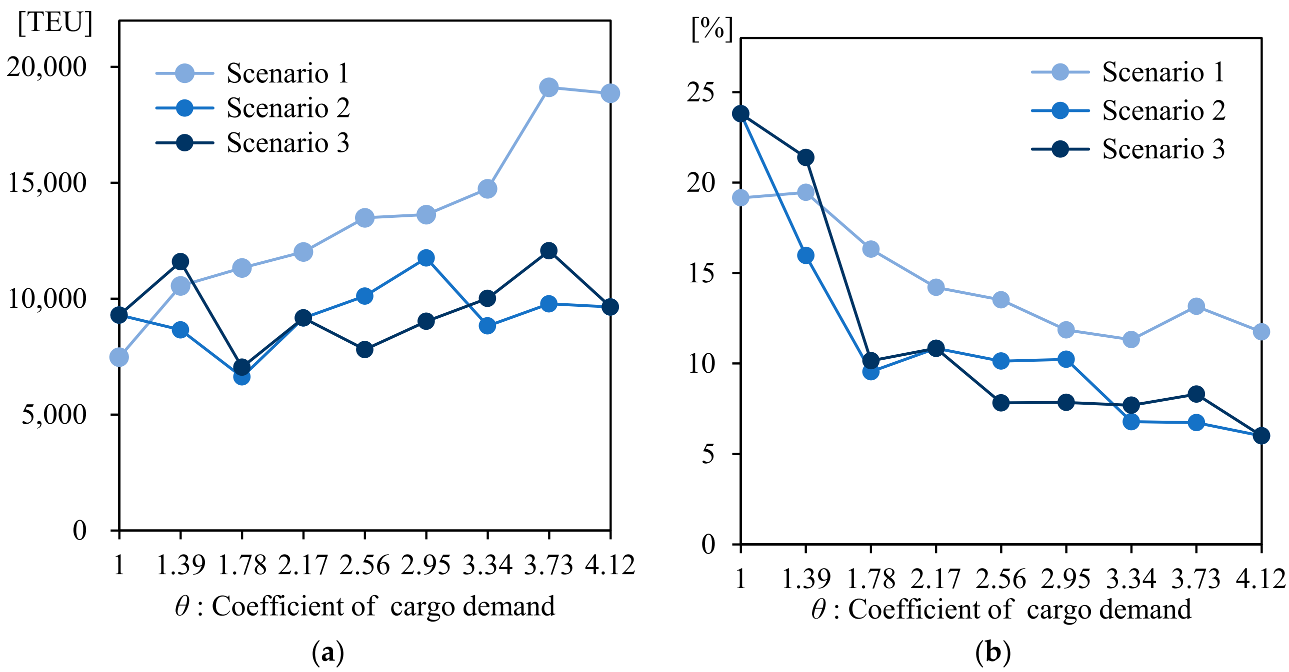

Figure 3. Result of transhipment cargo in each demand. (**a**) Total amount of transhipment via Colombo. (**b**) Ratio of transhipment cargo in Colombo.

Furthermore, as shown in Figure 3b, the transhipment ratios of Colombo port decrease as cargo demand increases in all scenarios. Note that the transhipment ratio in Figure 3b defines the transhipment volume at the Colombo port divided by the total container volume originating at Indian ports. In particular, the transhipment ratio of Scenarios 2 and 3 sharply decreases when the coefficient of cargo demand exceeds 1.78, although the container volume handled in Colombo port neither increases nor decreases, as shown in Figure 3a. However, in Scenario 1, the transhipment volume handled at Colombo indicates a significant increase in cargo demand despite the reduction in transhipment ratio. These results show that the de-hubbing phenomenon proceeds as cargo demand increases. However, the cargo volume at Colombo port remains almost constant despite certain fluctuations, which can be attributed to the increase in the total container demand in this region, particularly in Indian containers. Note that the development of the Hambantota port in Sri Lanka has not been considered in this study because no specific route services of container vessels were identified in our database. However, the Hambantota port may improve Sri Lanka's competitiveness with respect to international hubs because this port is located in the proximity of the main sea route compared to the Colombo port. In this case, the deviation cost for shipping lines is expected to be small and particularly advantageous for the east coast of India. The consideration of the Hambantota port is a critical aspect for future research.

5.3. Sensitivity Analysis

Several input values were set in the simulation results addressed above, and certain input values influence the simulation results. In particular, the feeder link cost (FLC), which indicates the feeder-related cost between Indian ports and Colombo port, and operation and fixed cost (OFC), which indicates the vessel operation costs, would significantly affect vessel deployments and even transhipment volume at Colombo port. However, owing to the lack of actual data, these values were estimated by the authors based on real data such as navigation distance and velocity. Thus, we conducted a sensitivity analysis by assuming a 10% discount and rise for both FLC and OFC in scenario 1 with all container demand cases (θ = 1.0–4.12).

Figure 4 shows the results of the sensitivity analysis as the ratio of transhipment cargo at Colombo port. As shown in Figure 4, drastic changes were not observed by changing the FLC and OFC. However, some fluctuations in the results were observed when the coefficients of cargo demand are 2.56 and 2.95. For θ values of 2.56 and 2.95, because the FLC is 10% lower than the base case, the transhipment ratio at the Colombo port increases by approximately 2 points and 4 points from the base case, respectively. The result was expected and reasonable because the comparative feeder cost of direct shipment is reduced. Specifically, 6000 TEU vessels newly call for Colombo port connecting with East Asian ports by reducing FLC by 10%. In the case of a 10% reduction in OFC, the transhipment ratio at the Colombo port is decreased. Moreover, it is reasonable because direct shipments increased compared to transhipment routes when OFC decreases. In addition, with a lower OFC, shipping lines would not consider a comparatively longer deviation distance of Indian ports as a significant disadvantage because it represents only a minor portion of the total voyage cost; however, they consider the advantages of calling directly in India, which is the ultimate origin/destination of the cargo. This scenario is especially important for shipping lines when India has high cargo demand in the future. From these results of the sensitivity analysis, changes in the FLC and OFC in the transhipment ratio are appropriately obtained, which implies that the model structure may be appropriate.

In addition, as mentioned before, if θ is lower than 2.56 and greater than 2.95, drastic changes in the transhipment ratio at Colombo are not observed by changing FLC and OFC. When θ is lower than 2.56, it may not be economical for shipping lines to increase direct services at Indian ports considering only the changes in FLC and OFC, possibly due to insufficient cargo demand. Therefore, the variation in the transhipment ratio is almost identical to that shown in Figure 3b, which is observed without any changes in the FLC and OFC. Similarly, when θ is greater than 2.95, changes in FLC and OFC are not sufficient to attract more direct services at Indian ports than the level observed in Figure 3b. Moreover, because we conduct sensitivity analysis only with scenario 1 without any development of Indian ports, it is reasonable to not have significant changes in transhipment ratio at Colombo because shipping lines would not have more economic alternatives than using Colombo as a transhipment hub because of insufficient infrastructure at Indian ports.

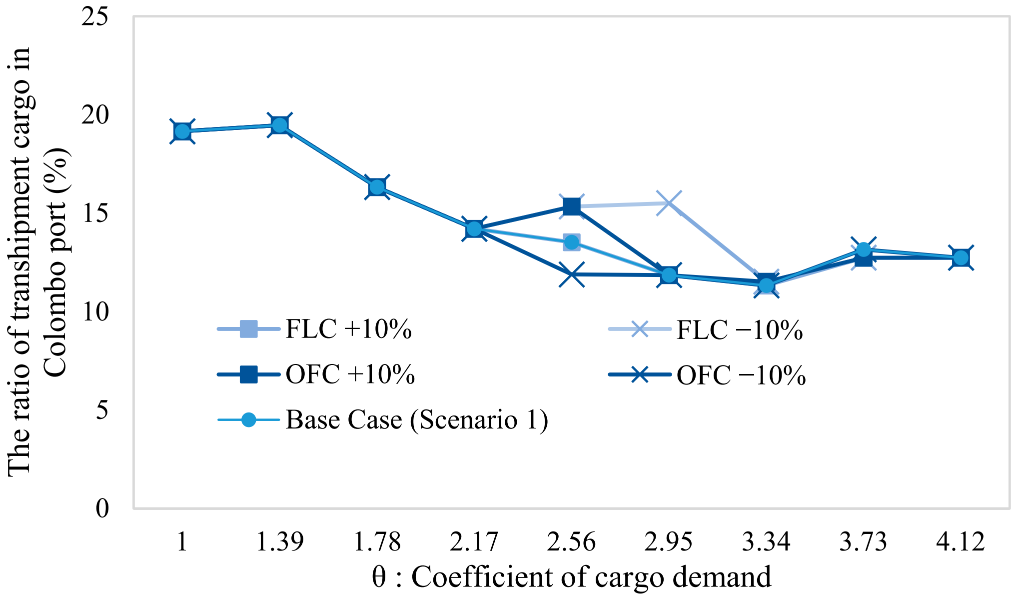

Figure 4. The ratio of transhipment cargo in Colombo port by changing FLC and OFC.

6. Conclusions

This study aims to clarify how port developments and container cargo demand of source countries impact maritime network selection such as de-hubbing from the perspective of shipping lines. The case study considers India as the source country of container cargoes and the Colombo port as a regional hub port. We develop a mixed integer linear programming model to describe the transhipment via the Colombo port and direct shipment in Indian ports. From the scenario analysis of the developed model, the following implications were obtained.

Firstly, the number of deployed vessels, particularly direct shipment services to Europe and East Asia in Indian ports, increased as cargo demand increased. Meanwhile, the number of vessels deployed in Colombo decreased slightly. Vessels deployed to Colombo port increased with increasing container demand in the region in the case of Scenario 1, which reflects the current port status. These results indicate that the number of direct services to Indian ports is expected to increase when the cargo demand of Indian ports increases, and the port development of Indian ports is conducted. The de-hubbing phenomenon decreases vessel size, calling for Colombo port because the demand originating at Indian ports is mostly satisfied by newly deployed trunk lines to Indian ports. Nhava Sheva and Mundra ports exhibit a large container volume in their hinterland; thus, these ports received direct shipments to Europe and East Asia with large container vessels when the container demand increased in this region. Meanwhile, relatively minor Indian ports, such as Tuticorin, Krishnapatnam, and Visakhapatnam, obtain direct routes to Europe and East Asia in case of large cargo demand and when port developments are conducted. Overall, Indian ports have the potential to call larger-sized vessels if cargo demand will increase in the future. However, the ultra-large-sized vessel will not be deployed for Indian ports when the Colombo port is capable of accepting 21,000 TEU vessels primarily because the deployment of an ultra-large-sized vessel to the Colombo port is more cost-effective. When considering transhipment handling, although the transhipment volume handled in Colombo port does not indicate a significant change even with Indian port developments, the transhipment ratio (%) of Colombo port declines considerably due to the growth of Indian cargo demand combined with their port developments.

This study derives significant policy implications on the port development aspects of Indian subcontinent ports by considering the growth of their cargo demand. Currently, several port development projects are being carried out in both Sri Lanka and India, focusing on the target ports included in this study. Therefore, if Colombo port expects to maintain its hub status, it is critical to consider various other incentives to attract and retain mainline carriers in addition to expanding its port infrastructure. Currently, Colombo port deploys several strategies to attract and retain shipping lines, especially by offering favourable berthing windows and dedicated berths and terminals to major shipping lines and involving private sector and global terminal operators with strong networks and market power in the operation of Colombo port by offering concession terminals, etc. Similarly, if India expects to receive direct calls from mainlines, it is important not only to develop their port infrastructure but also to increase their cargo demand. However, the scale of port infrastructure development must still be considered to avoid overdevelopment and underutilized port facilities, because shipping lines are not interested in deploying ultra-large-sized vessels in Indian ports, possibly because of the advantages of the hub-and-spoke network structure centred in Colombo port with high capital and operating costs of those large container vessels.

This study has several limitations. First, we do not consider competition between shipping lines. Because Colombo port is located at the trunk line between Europe and Asia, competition between shipping lines might affect the results. Moreover, although we assumed that the main shipping line does not have to pay charges to the feeder shipping line for simplicity of calculation, feeder link cost would be a significant factor for the de-hubbing phenomenon in the practical scenario. Another limitation is that this study only considers the liner services to Europe or Asia. It is preferable to consider other services to obtain more accurate results, such as North American routes. These issues must be investigated in future studies. Moreover, the development of the Hambantota port of Sri Lanka has not been considered in this study because no specific route services of container vessels were identified in our database. However, considering that the Hambantota port may improve Sri Lanka's competitiveness with respect to international hubs because this port is located in the proximity of the main sea route relative to the Colombo port, the deviation cost for shipping lines is expected to be small and particularly advantageous for the east coast of India. Therefore, the consideration of the Hambantota port is an important aspect for future studies.

Author Contributions: Conceptualization, T.K.; methodology, H.T. and T.K.; validation, T.K. and H.T.; formal analysis, T.K. and H.T.; investigation, T.K. and C.A.K.; resources, T.K.; data curation, T.K. and C.A.K.; writing—original draft preparation, T.K. and H.T.; writing—review and editing, T.K.; visualization, T.K.; supervision, T.K.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by JSPS KAKENHI grant number 20H00286.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

r	Liner service
a	Vessel type
p	Port in research area
o	Origin port
d	Destination port
h	Hub port
R	Set of liner services
A	Set of vessel types
P	Set of ports in research area
W	Set of origin and destination port pairs
$\widetilde{X}_{od}$	Cargo volume transported directly from port o to port d (TEU/week)

$\widetilde{x}_{od}^{r}$	Cargo volume directly transported from port o to port d in service r (TEU/week)
$\hat{X}_{od}$	Cargo volume transported from port o to port d by transhipment (TEU/week)
$\hat{x}_{od}^{r}$	Cargo volume transported from port o to port d by transhipment in service r (TEU/week)
y_r^a	A binary variable which takes 1 if service r is served by vessel type a and otherwise 0
z_r^p	A binary variable which takes 1 if service r includes port p and otherwise 0
$w_{r,i}^{o,od}$	A binary variable which takes 1 if port o is i-th port in service r
Ps	Profit of shipping line in a week (USD)
$\widetilde{F}_{od}$	Freight rate directly transported from port o to port d (USD/TEU)
$\hat{F}_{od}$	Freight rate from port o to port d in transhipment (USD/TEU)
bc^a	Bunker cost of vessel type a (USD/hour)
lc_p	Loading or unloading cost at port p (USD/TEU)
fc_{od}	Feeder link cost (FLC) from port o to port d (USD/TEU)
vc^a	Vessel cost of vessel type a which indicates operation and fixed cost (OFC) (USD)
pc_p	Port charge at port p (USD)
s^a	Vessel size of vessel type a (TEU)
v^a	Navigation speed of vessel type a (TEU)
$D_{r,i}$	Navigation distance from $i-1$ th port to i-th port in service r (hour)
N_r	Number of vessels in service r
T_p	Average vessel turnaround time at port p (hour)
Q_{od}	Container cargo demand from port o to port d (TEU/week)
$q_{r,i}$	Cargo volume on from $i-1$ th port to i-th in service r (TEU)
M	A large positive constant
θ	Coefficient for scenario analysis on future cargo demand

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