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Editorial

POLISH MARITIME RESEARCH is a scientific journal of worldwide circulation. The journal appears as a quarterly four times a year. The first issue of it was published in September 1994. Its main aim is to present original, innovative scientific ideas and Research & Development achievements in the field of:

Engineering, Computing & Technology, Mechanical Engineering,

which could find applications in the broad domain of maritime economy. Hence there are published papers which concern methods of the designing, manufacturing and operating processes of such technical objects and devices as: ships, port equipment, ocean engineering units, underwater vehicles and equipment as well as harbour facilities, with accounting for marine environment protection.

The Editors of POLISH MARITIME RESEARCH make also efforts to present problems dealing with education of engineers and scientific and teaching personnel. As a rule, the basic papers are supplemented by information on conferences, important scientific events as well as cooperation in carrying out international scientific research projects.

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Polish Maritime Research Special Issue on Maritime Freight Transport

A nation's economy relies on its system of highways, ports, railroads, and waterways to swiftly and safely move raw materials, labour, manufactured products, and component parts. This exchange of goods and services underpins almost all economic activities. The unrelenting demand for faster, cheaper and better transportation options brought about by population growth, urbanization and globalization, has strained the global supply chains and the underlying support infrastructure. Bottlenecks at ports, congestion on highways leading to and from ports, inefficient logistic systems, and high transportation costs can strangle economic growth and, if left unchecked, place the nation at a global economic disadvantage.

Ports are absolutely critical assets to a nation's economy, infrastructure, and quality of life. They are a part of the transportation system that serves as the circulatory system of civilization. Specifically, they provide the vital link for transporting export goods produced at factories and farms to consumers overseas and getting imports of goods to domestic consumers. Today, international trade accounts for a significant portion of most countries' Gross Domestic Products, and container vessels move the majority of the trade by volume and value through ports. Ports are also important in that they generate jobs and contribute to the local economy. The impacts of ports go far beyond the communities in which seaports are located. In the U.S., on average, any given state uses the services of 15 different ports around the country to handle its imports and exports.

For the above reasons, there is a need to improve maritime and port operations and logistics to increase operational efficiency while reducing environmental impact, improve end-to-end experience for shippers and other stakeholders such as ocean carriers and truckers, and improve security. By addressing this vital and weak link in the freight supply chain, it would allow the supply chain to operate more efficiently.

The main objective of this special issue is to provide an update on the recent research and development in maritime freight transport. Seven papers have been selected for publication after a thorough peer-review process, according to the standards of the Polish Maritime Research. The papers were selected based on their technical merit as well as their relevance to maritime freight transport. The topics covered by the papers can be categorized as maritime logistics, port operations, and intermodal logistics. An overview of how the papers are advancing maritime freight transport research is provided below.

The increasingly competitive nature of maritime freight transport has stimulated ocean carriers to improve efficiency and lower costs. The larger a carrier the more competitive advantage it has. Therefore, carriers have to form alliances with other carriers so that they can reduce their operational costs due to economy of scale. Such alliances pose a significant business challenge to the carriers. On the one hand, their partnerships with other carriers allow them to improve quality of their service by increasing their network coverage. On the other hand, they have to compete against their partners for businesses. How to form strategic alliances is the research issue addressed by Lin and Huang. In their study, they proposed a theoretical framework for characterizing competition in international maritime shipping and investigated how carriers can manage their business models.

In another paper dealing with maritime logistics, Lun addressed the issue of container vessels making frequent calls to ports in the Pearl River Delta region in China. In her study, she suggested using a green shipping network to trans-ship containers from feeder ports to hub ports to lower the overall carbon dioxide emissions in the region. She investigated how the use of the hub-and-spoke approach and the deployment of mega-ships can be beneficial to port users, both economically and environmentally.

Seaports are a critical link in the freight supply chain. Two of the seven papers selected for this special issue focus on port related issues. In the study by Low et al., the authors provided a new perspective on port efficiency. In particular, the authors contended that port efficiency and service effectiveness should be considered from the viewpoints of both the provider and consumer of the port service. To this end, they proposed a network data envelopment analysis model to evaluate performance of seaports worldwide. The other study performed by Yang et al. is focused on port. It deals with using truck arrival information to

alleviate the gate congestion at container terminals. The authors proposed an integrated planning model and a sequential planning model to coordinate the major terminal planning activities, including berth allocation, yard storage space allocation and truck arrivals. Their work provides important insights on the model development and implementation of port integrated models, which to date has not been accomplished due to modelling complexity and computational constraints.

The last three papers address intermodal logistics in which ports play a critical role. The study by Lam and Song assessed a port's role within the supply chain and its performance from the perspective of shippers and logistics' providers. Their study developed a unified framework for analyzing how well a port is integrated within the global freight supply chains including shipping line networks, hinterland and intermodal transport network, and even urban network. This framework is aimed at supporting a wider group of stakeholders, including terminal operators, port authorities, shippers, shipping companies, inland transport providers, freight forwarders, logistics service providers, and transportation agencies.

Feng and Notteboom studied the role of small and medium-size ports (SMPs) in enhancing the competitiveness and logistics performance of multi-port gateway regions and associated inland logistics systems. They analyzed the role of a SMP in a region using different variables: (a) cargo volume and market share; (b) international connectivity; (c) relative cluster position; (d) port city and hinterland connection; and (e) logistics and distribution function. The five-dimension analysis combined with an in-depth case study provides important information about SMPs.

In the third and final paper on intermodal logistics, Fotuhi and Huynh addressed the freight network design problem. This study takes the perspective of logistics service providers whose task is to serve a multiregional customer base. Of particular interest to these decision makers is the management of shipments between origins and destination through the use of different modes, routes, as well as logistic hubs. At a strategic planning level, the service providers need to develop long-term policies on terminal locations, modes, and routes to lower costs. To this end, the authors proposed a mixed integer linear program to help logistics service providers to jointly select the best location of terminals among a set of candidate places, shipping modes, and route for shipping commodities of different types.

As discussed, the papers published in this special issue represent a collection of inter-related and up-to-date topics on maritime freight transport. We hope that the special issue provides valuable research references and suggests directions for new research in this area.

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Coopetition in international maritime shipping

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ABSTRACT

The increasingly competitive nature of maritime freight transport has stimulated carriers to improve efficiency and lower costs. The industry has gradually matured, and it has recently become the case that the larger a carrier is, the more competitive advantage it has. Therefore, carriers form strategic alliances to collaborate with each other so that they can reduce their operational costs due to economies of scale. At the same time, such alliances allow carriers to improve the quality of their service by increasing their network coverage. Although carriers collaborate to improve their operational efficiency, they compete with each other simultaneously. In other words, a game of coopetition among carriers has developed in international maritime freight transport in recent years. In this study, we propose a theoretical framework for characterizing coopetition in international maritime shipping and investigating how carriers can manage their business models. Empirical studies, together with salient analytical results, are presented and discussed.

Keywords: Coopetition; Maritime freight; International shipping; Jacobi approach; Backward induction

1. INTRODUCTION

In recent years, fundamental changes have taken place in the operational models of international maritime shipping. Traditionally, carriers assign ships of various sizes to pick up containers along the countries of the Pacific Rim. For instance, as Figure 1 illustrates, a ship of 10,000 TEU or over may depart from Japan and pick up loads from Korea, China, Hong Kong and Singapore and then depart Asia for ports in Europe (e.g., Rotterdam). However, the more ports at which a ship stops, the more delay it may potentially incur. Specifically, the ship has to wait during the berthing, loading and unloading processes. The time required for each of these can vary significantly, depending on the efficiency of the stopping ports. As a result, the number of ports at which a ship stops is directly related to the reliability of the shipping time to which the carrier can commit. To improve the reliability of the service provided, carriers have proposed an alternative operational model of daily frequency. The carrier conceptually considers certain ports in the current network associated with high customer demand as mega-hubs (e.g., Pusan, Shanghai, Hong Kong and Singapore) and dispatches its largest ships to pick up and deliver shipments at those ports. Shipments from smaller ports, such as Tianjin, are carried by feeder ships to the mega-hubs.

The new operational model is very similar to hub-and-spoke operation in air transportation and has provided several advantages for maritime freight carriers. First, because the carriers use large ships to service selected major ports, these

large ships (e.g., ships over 10,000 TEU) do not need to operate at full speed between mega-hubs because a large ship can cover a given distance more quickly than a small ship can. Therefore, a large ship can increase its speed when the pre-specified schedule is delayed and improve the reliability of the schedule. This gives the carrier the operational flexibility to improve its service quality. Second, if the number of ships is abundant, carriers can provide pickup and delivery services at the mega-hubs on a daily basis. Presuming that it requires 40 days to travel from the Asian ports to Europe, carriers can provide daily service as long as they have 40 large ships. Thus, a high service frequency greatly improves a carrier's competitive advantage. Third, carriers can achieve economies of scale at the mega-hubs, in the same way that economies of scale are achieved at hubs in a hub-and-spoke air transport network. Lastly, this new business model has implications for energy consumption and environmental impact because the large ships in the network can operate at slower speeds, thereby consuming less energy and generating less pollution.

In a winner-take-all market, carriers need to develop new strategies in response to this new operational model so that they can survive in the market. With this in mind, carriers have proposed collaboration so that the number of ships and the service network can be expanded. As they adopt the collaboration strategy, they compete with each other at the same time because carriers have to defend their own profits. In such a scenario, a game of coopetition develops. In this study, we investigate the coopetition game and analyze its

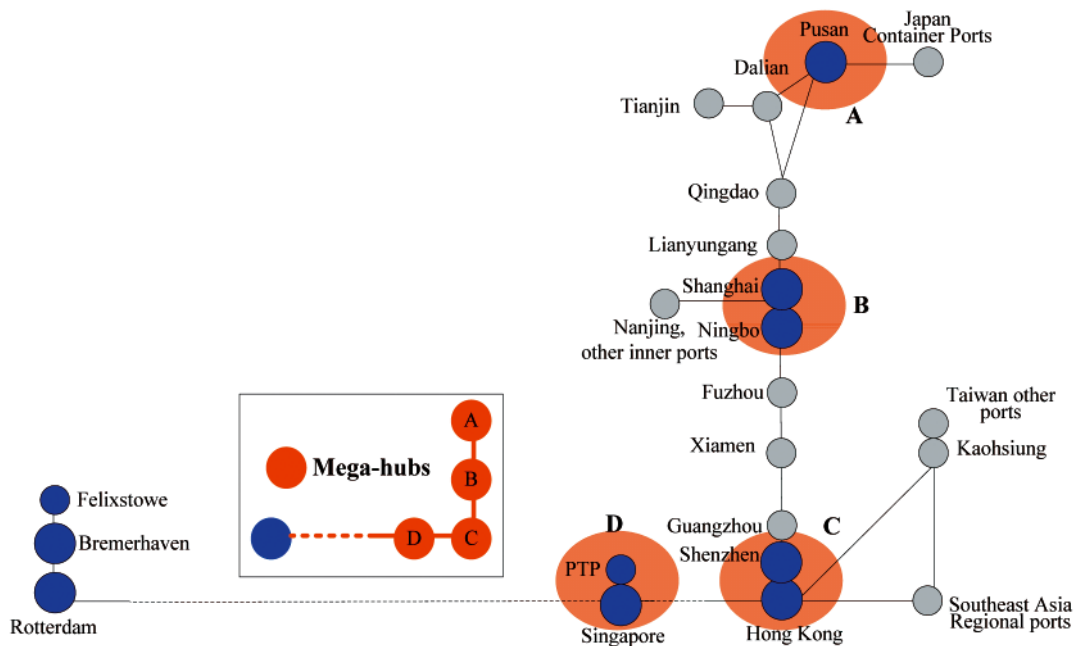


Fig. 1. The new operational model in maritime international shipping (Tai and Lin, 2012)

mathematical properties. Because the game of coopetition is rarely discussed in the literature, we develop its equilibrium condition and solution approach to gain insight into empirical studies of this phenomenon.

The remainder of the paper is structured as follows. Section 2 provides a critical overview of the recent developments in the field of coopetition and maritime freight shipping and related fields of research. Section 3 presents a mathematical model of the coopetition framework. Section 4 presents a proposed solution procedure, a diagonalization algorithm, for finding the solution of the mathematical model described in Section 3. In Section 5, the proposed method is applied empirically to networks with various sets of parameters to demonstrate their efficacy. The final section concludes the paper and suggests potential directions for future research.

2. LITERATURE REVIEW

To survive in the challenging and increasingly competitive maritime freight transportation industry, carriers strive to improve their efficiency and lower their costs. To accomplish these goals, carriers need to consider alternative business models such as competition, cooperation and coexistence/coopetition (Bengtsson and Kock, 1999). A considerable amount of research exists in the field of freight cooperation. For instance, Özener and Ergun (2008) studied cost allocation in shipper alliances. Based on previous work on the lane covering problem, Ergun et al. (2007) developed optimization techniques for identifying collaborative shippers' tours to reduce the probability of empty truck repositions. Such carrier collaboration techniques have been applied in areas such as air and sea cargo [e.g., Agarwal et al. (2010), Agarwal and Ergun, (2008) and Houghtalen et al. (2010)]. The aforementioned cooperation research assumed that collaborators work together to find the optimal solution for the collaborative system. Therefore, conventional optimization techniques (rather than a game-theoretic framework) can be applied.

An alternative line of research has applied the game-theoretic framework to analyzing cooperation and competition strategies. We can further classify the related research into cooperative or non-cooperative game theory research. An extensive review of cooperative game-theoretic models

can be found in Nagarajan and Sosis (2008). Sutton (1986) provided a critical review of non-cooperative game models. An updated overview of non-cooperative game models can be found in Cachon and Netessine (2004). From the literature summarized above, it is apparent that only a limited body of research has been devoted to the game of players cooperating and competing simultaneously, especially in the field of maritime freight transportation. In international air services, airlines have widely adopted the practice of code-sharing that designates its code on aircraft operated by other airlines (Humphreys, 1994). Code-sharing among airlines can supplement their own flight frequencies or establish a new market presence. However, the practice can lower the cost to other airlines and make them more competitive in the industry, which can similarly form a game of coopetition. Further, most of the research in this area focuses on the design of the code-sharing system rather than analyzing the problem from a coopetition game perspective. Luo (2007) explained why coopetition occurs, developed an overall framework to analyze coopetition and presented a typology for understanding the intensity and diversity of coopetition with major global rivals. However, this research is more a conceptual effort than a mathematical or theoretical analysis of coopetition. To the best of our knowledge, the work by Ngo and Okura (2008) is the first of the very few research efforts that have been devoted explicitly to the mathematics of the coopetition game. However, their models, which focused on the coopetition game between a semipublic firm and a private firm in a duopoly market, cannot be applied in the analysis of the coopetition games between private freight carriers in maritime transportation. Therefore, in this research, we develop the theoretical background of the coopetition game in a duopoly market so that the competition and cooperation between maritime freight carriers can be captured with greater fidelity. We next present the mathematical model.

3. COOPETITION MODEL

In this section, we present the mathematical model for the coopetition game. Before presenting the mathematical derivation, we first state the following assumptions on which the model is based:

1. *The game of two carriers.* For simplicity, we consider a game structure with two freight carriers in an oligopoly market. The assumption is not meant to be restrictive but to facilitate explanation of the derivation process. One can easily expand the derivation and algorithm to more than two players in the game.
2. *Carriers are equally competitive.* We assume that there is no leader or follower in this game. Two separate carriers in a duopoly freight transport market offer partially substitutive freight service.
3. *An extensive-form game.* An extensive-form game is a specification of a game in game theory that allows explicit representation of a number of important aspects, such as the sequencing of players' possible moves, their choices at every decision point, the information each player has about the other player's moves when she/he makes a decision, and the payoffs for all possible game outcomes.
4. *A two-stage game.* We consider a typical sequential game with two stages. In the first stage, freight carriers cooperate to decrease the average cost and increase the total market profit. In the second stage, carriers simultaneously choose their competitive effort level to increase the carrier's own market share. This is the common setup for analyzing this stream of problems.
5. *Perfect information.* Two carriers are assumed to have perfect information in cooperate investment and price competition strategies of the market.
6. *Static game.* We do not consider the dynamic features of this game and assume that carriers' decisions do not vary over time.

We next introduce the notations that will be used throughout the rest of the paper.

Notations

- y_i – The cooperative effort level of each carrier i , $i \in \{1,2\}$ that decreases the average cost and increases the total market size.
- x_i – The competitive level of each carrier i , $i \in \{1,2\}$ that can enhance a carrier's own market share
- s_i – The market share of carrier i , $i \in \{1,2\}$. The value of s_i is determined by each carrier's competitive level. For instance, $s_i = x_i/x_i + x_j$ if i and j represent the two carriers in the market.
- $c(y_1, y_2)$ – The average cost for each carrier, which is a function of y_1 and y_2 .
- $q(y_1, y_2)$ – The total market demand, which is a function of y_1 and y_2 .
- $p(q)$ – The equilibrium market price, which is a function of market demand.
- \mathcal{D} – The initial demand before the game.
- k_x – The unit cost of increasing one unit of competitive level.
- k_y – The unit cost of increasing one unit of cooperative level.
- k_{x,x_i} – The cost of expanding competitive efforts for each carrier i , $i \in \{1,2\}$
- k_{y,y_i^2} – The cost of cooperative efforts for each carrier i , $i \in \{1,2\}$. Note that y_i^2 is a mathematical construct that makes the derivation easier when calculating y_i^* at a later stage. One can alter this functional form and obtain similar results rather straightforwardly.

Backward induction

To derive the equilibrium condition of this coopetition game, we use the method of backward induction (McCain,

2010). The concept of backward induction is based on the game-theoretic principle of “think forward and reason backward,” which is similar to the techniques used in solving a dynamic programming problem. The primary difference is that there typically exists only one decision maker in a dynamic program problem, while there are generally two or more players interacting in the context of a game. Essentially, the backward induction reasons backwards in time from the end of a game to determine a sequence of optimal decisions along the sequential process. It proceeds by first considering the last time a decision can be made and then choosing what to do in any situation at that time. Based on the results, game players can then determine what to do at the previous step at the time to make a decision. This process continues backwards until the best action for every possible scenario at every decision point in time has been determined. We next apply the backward induction technique in deriving the equilibrium condition.

Derivation of Equilibrium Condition

We first assume that the total demand of two freight carriers depends on the level of cooperation in the two-stage game. In this static game, both carriers choose their cooperative effort levels to increase total market size in the first stage. In the second stage, carriers choose their competitive levels to increase their corresponding market shares. Therefore, the overall market demand function can be expressed as follows:

$$q(y_1, y_2) = \mathcal{D} + y_1 + y_2 \quad (1)$$

The form of this demand function is based on the work by Ngo and Okura (2008) and can be modified to suit various situations. For readability, we replaced $q(y_1, y_2)$, $c(y_1, y_2)$ and p with Q , C and P so that the derivation process is clearer. The utility/profit functions of carrier 1 and 2 are:

$$\pi_1 = (P - C)Qs_1 - k_x x_1 - k_y y_1^2 \quad (2)$$

$$\pi_2 = (P - C)Qs_2 - k_x x_2 - k_y y_2^2 \quad (3)$$

Again, the functional forms are based on Ngo and Okura (2008) and can be modified if necessary. To make the model reasonable, without loss of generality, we impose the following constraints:

$$P \geq C \geq 0$$

$$x_1 \geq 0, x_2 \geq 0$$

$$y_1 \geq 0, y_2 \geq 0$$

$P \geq C \geq 0$ implies that the price of the service is higher than its cost and should naturally have a positive value. Similarly, the competition levels x_1 and x_2 and the cooperation levels y_1 and y_2 should be greater than zero. As mentioned earlier, to derive the solution of this extensive-form game, we solve the game by backward induction. That is, the equilibrium in the second stage is derived on the basis of the first stage before the first stage has been played. Having derived the equilibrium condition in the second stage, the equilibrium condition in the first stage is derived using the results from the second stage. The second stage of the game is described below. The first-order conditions with respect to x_i required to obtain the corresponding maximum utilities are:

$$\frac{\partial \pi_1}{\partial x_1} = \frac{x_2 Q(P - C)}{(x_1 + x_2)^2} - k_x = 0 \quad (4)$$

$$\frac{\partial \pi_2}{\partial x_2} = \frac{x_1 Q(P - C)}{(x_1 + x_2)^2} - k_x = 0 \quad (5)$$

The cost of expanding the competitive effort for each carrier therefore are:

$$k_x x_1^* = k_x x_2^* = \frac{Q(P - C)}{4} \quad (6)$$

We can conclude that the equilibrium competitive effort levels are:

$$x_1^* = x_2^* = \frac{Q(P - C)}{4k_x} \quad (7)$$

Because an increase in k_x decreases x_1^* and x_2^* , the intuitive interpretation is that the higher the cost level, the lower the competitive effort. Next, we consider the relationship between competitive and cooperative effort levels. From equation (7) the following derivatives can be calculated:

$$\frac{\partial x_1}{\partial y_1} = \frac{\partial x_2}{\partial y_1} = \frac{P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c})}{4k_x} \quad (8)$$

$$\frac{\partial x_2}{\partial y_2} = \frac{\partial x_1}{\partial y_2} = \frac{P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c})}{4k_x} \quad (9)$$

When $P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c}) < 0$, the competitive level decreases when the cooperative level increases. We can conclude that x_i and y_i are substitutes.

On the other hand, when $P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c}) > 0$, the competitive level increases when the cooperative level increases. Thus, we can observe that x_i and y_i are complements.

We next use backward induction to analyze the first stage of the game from the results of second stage. Plugging x_1^* and x_2^* into the carriers' utility functions leads to:

$$\pi_1 = \frac{Q(P - C)}{4} - k_y y_1^2 \quad (10)$$

$$\pi_2 = \frac{Q(P - C)}{4} - k_y y_2^2 \quad (11)$$

Applying the condition that $\partial \pi_i / \partial y_i = 0, \forall i \in \{1, 2\}$, the equilibrium cooperative effort levels are:

$$y_1^* = y_2^* = \frac{P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c})}{8k_y} \quad (12)$$

To summarize the results and replace the notations with the original meanings, we list the following equilibrium condition for this coopetition game:

$$x_1^* = x_2^* = \frac{q(y_1, y_2) \{p(q) - c(y_1, y_2)\}}{4k_x} \quad (13)$$

$$y_1^* = y_2^* = \frac{p(q)(1 + \frac{1}{s_c}) - c(y_1, y_2)(1 + \frac{1}{s_c})}{8k_y} \quad (14)$$

From equations (13) and (14) we can observe that the equilibrium cooperative and competitive levels are identical for both carriers, which suggests that carriers will adopt the same strategies in this coopetition game when reaching equilibrium and the result profits would be identical as well. Therefore, we only present the cooperation, competition and profit levels of a carrier in the section of numerical studies. Next, we present a theorem stating that there exists a unique solution to this coopetition game.

Theorem 1

There exists a unique solution to the game-theoretic model of the coopetition.

Proof. See the Appendix I.■

As mentioned earlier, we consider a game structure with two freight carriers in an oligopoly market to facilitate explanation of the derivation process. However, the assumption is not meant to be restrictive. The extension of the derivation to three carriers is presented in Appendix II. For the cases with more than three carriers, the derivation can be expanded in the same manner.

4. SOLUTION APPROACH: DIAGONALIZATION (JACOBI) ALGORITHM

The iterative diagonalization algorithm by Lin and Hsieh (2012) can be applied to evaluate the model empirically. The fundamental objective of this algorithm is to determine the optimal collaboration and competition efforts of one carrier while assuming that the efforts of other carriers are known and fixed. Given the optimal values for the current carrier, one can then calculate the optimal efforts of the other carriers for the same set of conditions (the values for other carriers are fixed and known). The process repeats iteratively until a pre-specified criterion is satisfied and converges to an equilibrium solution. The typical convergence criterion is that the difference of two consecutive solutions be within a tolerant value. The algorithmic steps can be described as follows:

Step 0: Initialization

We initialize the following parameters required for the algorithms, including the iteration number n , the cost of cooperation k_y , the cost of competition k_x and the initial demand before the game starts \mathcal{D} . Furthermore, we assume that the carriers in this game do not cooperate before the game. In other words, the cooperation level $y_i^n = 0, \forall i \in I$.

Step 1: Diagonalization

At iteration n , we solve the equilibrium competition level, equations (13) and (14) for carrier $i \in I$, by assuming the competition and cooperation levels for other carriers $j \in \setminus i$ are given and unchanged from the previous iteration $n - 1$. This is equivalent to solving the equilibrium problem (equations (13) and (14)) with the diagonal elements of a Jacobian matrix of competition levels, which determines the competition and cooperation levels of carrier $i \in I$.

Step 2: Convergence Test

If the cooperation level of a firm y_i^n between two consecutive iterations is less than a pre-specified level $(y_i^n - y_i^{n-1})/y_i^n \leq 5\%$, report the incumbent solution. Otherwise, $n = n + 1$; go back to **Step 1**.

Note that when cooperation level y_i^n reaches an equilibrium condition, x_i stops changing as well. Thus, y_i^n can be used as the convergence criterion. We next show the convergence of the diagonalization algorithm.

Theorem 2

The diagonalization algorithm converges to a unique solution of this coopetition game.

Proof. Because the profit function of each carrier is concave (shown in **Theorem 1**), the gradient (marginal profit function) is monotonic. For a problem with such an objective function, Dafermos (1983) established that the diagonalization algorithm converges to a unique solution.■

In addition to the convergence behavior established by Dafermos (1983), the convergence of the diagonalization

algorithm can be interpreted in a more intuitive manner. Let us use the competitive level x_i as an example. As the diagonalization algorithm solve the cooperation game iteratively, the competitive level in iteration $n + 2(x_i^{n+2})$ can only be lower than the competitive level in iteration $n(x_i^n)$. Note that x_i^{n+2} essentially uses the competitive level x_i^n as the initial level and the value of x_i^{n+2} involves one step of cooperative effort based on x_i^n . Therefore, x_i^{n+2} is always smaller than x_i^n because the competition level can only be smaller if one step of cooperation is involved. Therefore the convergence of the diagonalization can be expected.

5. NUMERICAL EXPERIMENTS

For the numerical studies, we assume that there are two carriers in the market and that the carriers are in a duopoly market with a linear demand function $q = 100 - p$ and $q = 90 - c$. It is worth noting that, given the above two functions, we make the assumption that the carrier makes a profit with a value of 10 if it sells one unit of its product ($p - c = 10$). Finally, equation (1) is of the form $q = 5 + y_1 + y_2$. The functional form of this equation ($q(y_1, y_2) = \mathcal{D} + y_1 + y_2$) is based on the work by Ngo and Okura (2008). Thus the initial demand (\mathcal{D}) is 5. The unit cost of increasing one unit of competitive level (k_x) and cooperative level (k_y) are 5 and 1 respectively. Using this set of randomly chosen data, we find the equilibrium competition level to be 3.75 units and the cooperation level to be 1.25 units. The resulting profit is 17.5 units. It is worth noting that this value reflects only the magnitude of the efforts that the carriers devote to cooperation and competition. For instance, each carrier decides to devote 75% to competing and 25% to cooperating. To further validate the model's correctness and reasonableness, we present sensitivity analyses of parameters in the following sections.

5.1. Sensitivity analysis of initial demand level

We next perturb the parameters so that we can observe their impact. We first vary the initial demand level \mathcal{D} in equation (1) ($q(y_1, y_2) = \mathcal{D} + y_1 + y_2$) and summarize the impact of this value on the equilibrium results in Table 1.

We can see from Table 1 that the competition level increases and the cooperation level remains constant as the initial demand level \mathcal{D} increases. From equations (13) and (14), we can observe consistent results. As the initial demand level increases, carriers

compete more to increase their own market shares and their cooperation levels do not vary with initial demand. However, with the rising initial demand, both carriers gain more profit.

Tab. 1. Sensitivity Analysis of Initial Demand Level

\mathcal{D}	x^* (competition level)	y^* (cooperation level)	Π (profit)
5	3.75	1.25	17.50
10	6.25	1.25	30.00
15	8.75	1.25	42.50
20	11.25	1.25	55.00
25	13.75	1.25	67.50
30	16.25	1.25	80.00
35	18.75	1.25	92.50
40	21.25	1.25	105.00
45	23.75	1.25	117.50
50	26.25	1.25	130.00

5.2. Sensitivity analysis of cost of competition

As the cost of competition increases, the competition level decreases and the cooperation level remains constant, as shown in Figure 2. In other words, the competition cost only has an impact on the competition level x . However, as equation (14) shows, the competition level does not influence the cooperation level y . Therefore, the cooperation level remains the same even if the competition cost is perturbed. One of the interesting phenomena we observe is that the resulting profits of both carriers are identical even for different competition costs. We believe that carriers adjust their competition strategies in response to changes in the competition cost and can there by achieve the same profit level even when the competition cost varies.

5.3. Sensitivity analysis of cost of cooperation

In this experiment, we perturb the cost of cooperation and summarize the results in Figure 3.

Unlike the competition cost, which has an impact only on the competition level, an increase in the cooperation cost (k_y) decreases both the competition and cooperation levels. We can interpret these results on the basis of equations (13)

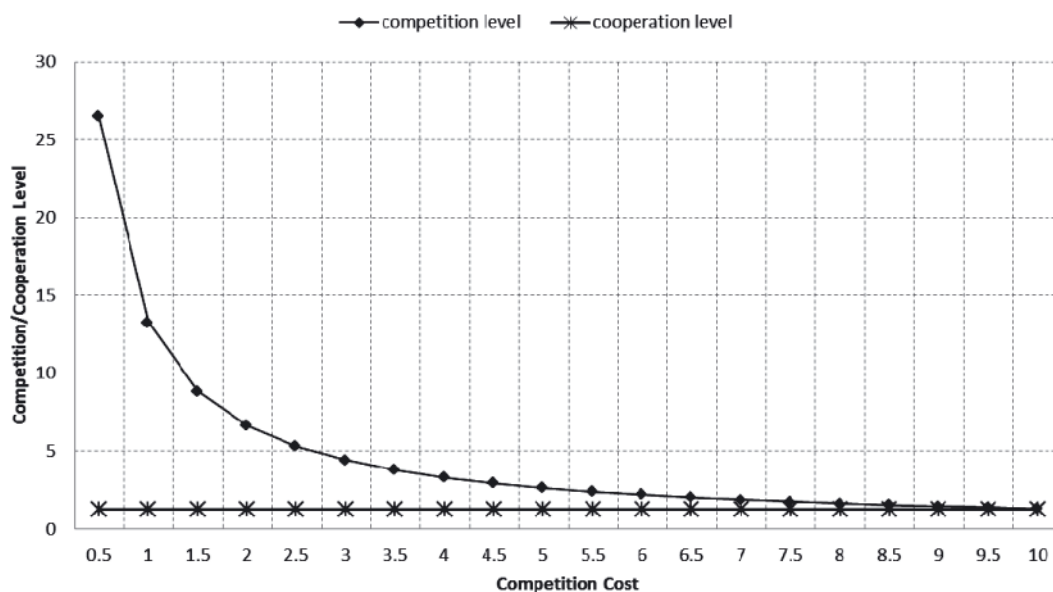


Fig. 2. Sensitivity Analysis of Competition Cost

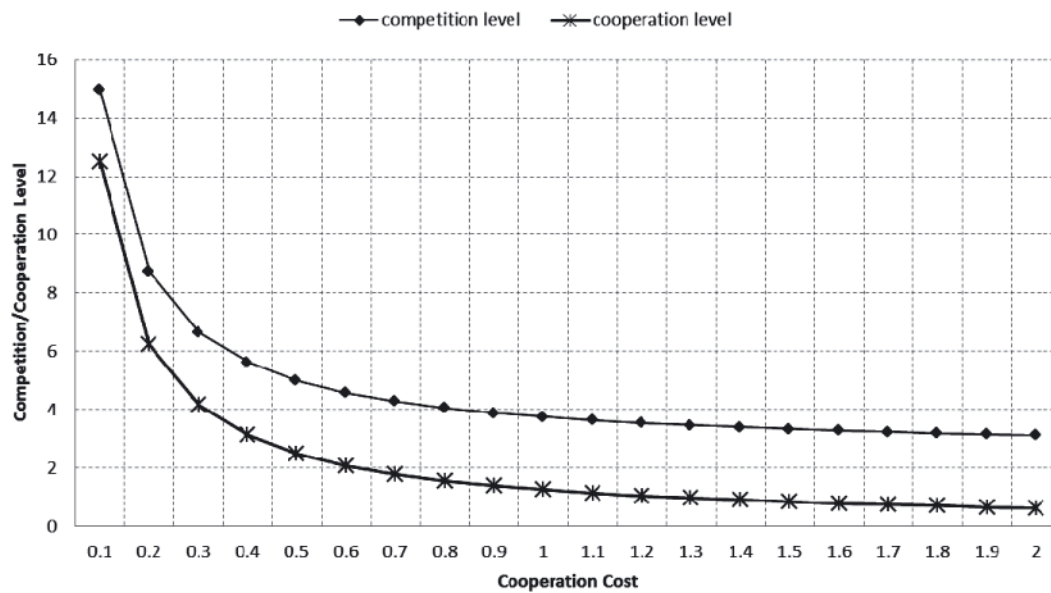


Fig. 3. Sensitivity Analysis of Cooperation Cost

and (14). According to equation (14), a change in the value of k_y changes the equilibrium cooperation levels (y_1^* and y_2^*). Changes in y_1^* and y_2^* then influence $q(y_1, y_2)$ and $c(y_1, y_2)$, which results in changes in competition levels. It seems that the cooperation cost has a greater impact on the cooperation level than on the competition level.

5.4. Sensitivity analysis of parameters in demand function

Finally, we vary the parameters in the demand function and see how the equilibrium competition and cooperation levels change in response. The results are summarized in Table 2.

Tab. 2. Sensitivity Analysis of Parameters in the Demand Function

α	x^* (competition level)	y^* (cooperation level)	π (profit)	ϵ_d (elasticity)
1	3.75	1.25	17.5	-12.3333
1.1	3.316327	1.071429	15.51021	-11.7273
1.2	2.944215	0.909091	13.81198	-11.2222
1.3	2.622874	0.76087	12.3535	-10.7949
1.4	2.34375	0.625	11.09375	-10.4286
1.5	2.1	0.5	10	-10.1111

Essentially, as the value of α increases, shippers' or customers' demand levels become less sensitive to price. In other words, the elasticity of price (ϵ_d) decreases as α increases. In this scenario, carriers are less willing to cooperate (the value of y^* decreases) because cooperation will not change the market size much and because carriers have less incentive to cooperate. At the same time, as carriers decrease their competition level, the resulting profit decreases.

6. CONCLUSION REMARKS

As the maritime freight transportation industry has become increasingly competitive in recent years, carriers have attempted to create more value by changing their business strategies to improve their operational efficiency, decrease their overall costs and increase business profits. One such strategy is cooperation between carriers in which small carriers collaborate with each other so that they can compete with leading carriers. In such a collaboration, small carriers have to collaborate with and compete with each other at the same time so that they can survive in the business. In this study, this carrier cooperation problem is investigated, and the manner in which a carrier determines its cooperation and competition levels is analyzed. The problem is formulated as a two-stage sequential game and empirically applied to example freight networks. The numerical results provide evidence that the model presented can effectively capture the problem and can be a useful tool in analyzing this type of cooperation game.

Although the numerical tests conducted in this study are limited, some interesting conclusions were drawn and insights gained and are presented in the numerical section. However, this study is not without its limitations. For instance, we assume that carriers in this game are equally competent and have identical capacities. In a more realistic scenario, carriers would be differentiated based on their capacities, and the resulting game might be different. Future research can explore possibilities along this line. Further, this study only observes certain impact of related issues (e.g. operation cost) on cooperation level and competition level empirically. Analytical analyses of these issues on the level of cooperation or competition should be explored. Finally, the current research assumes that there are not bargaining power differences among carriers. Including the bargaining power that differs based on carrier size or other factors can be an interesting research topic.

Appendix I: Proof of Solution Uniqueness of the Profit Maximization Program

To prove the uniqueness of the solution of this game-theoretic cooperation model, we need to prove that the program is concave. Because the constraints introduced in the model are of linear form ($P \geq C \geq 0, x_1 \geq 0, x_2 \geq 0, y_1 \geq 0, y_2 \geq 0$), we only need to show that the objective function is concave for the whole program to be concave.

Denoting $\pi_i = (P - C)Qs_i - k_x x_i - k_y y_i^2, i \in \{1, 2\}$ as function $f\{\cdot\}$, we need to show that $f[\theta(x_1^1, y_1^1), (1 - \theta)(x_1^2, y_1^2)] \geq \theta f(x_1^1, y_1^1) + (1 - \theta)f(x_1^2, y_1^2)$ to reach the desired conclusion. The function inequality can alternatively be denoted as follows:

$$f(\theta x_1^1, \theta y_1^1), (1 - \theta)x_1^2, (1 - \theta)y_1^2) \geq \theta f(x_1^1, y_1^1) + (1 - \theta)f(x_1^2, y_1^2) \quad (A1)$$

Let x_B and y_B be the competition and cooperation levels, respectively, of the other carrier.

The left-hand side of inequality (A1) is:

$$f(\theta x_1^1, \theta y_1^1), (1 - \theta)x_1^2, (1 - \theta)y_1^2) = (P - C)[\mathcal{D} + \theta y_1^1 + (1 - \theta)y_1^2 + y_B] \cdot \frac{\theta x_1^1 + (1 - \theta)x_1^2}{\theta x_1^1 + (1 - \theta)x_1^2 + x_B} + \\ - k_x[\theta x_1^1 + (1 - \theta)x_1^2] - k_y[\theta y_1^1 + (1 - \theta)y_1^2]^2$$

The right-hand side of inequality (A1) is:

$$\theta f(x_1^1, y_1^1) + (1 - \theta)f(x_1^2, y_1^2) = (P - C)\theta(A + y_1^1 + y_B)x_1^1/(x_1^1 + x_B) - k_x\theta x_1^1 - k_y\theta(y_1^1)^2 + (P - C) \cdot \\ \cdot (1 - \theta)(A + y_1^2 + y_B)x_1^2/(x_1^2 + x_B) - k_x(1 - \theta)x_1^2 - k_y(1 - \theta)(y_1^2)^2$$

Rearranging the inequality, we obtain the following inequality:

$$(P - C)[\mathcal{D} + \theta y_1^1 + (1 - \theta)y_1^2 + y_B] \frac{\theta x_1^1 + (1 - \theta)x_1^2}{\theta x_1^1 + (1 - \theta)x_1^2 + x_B} + k_y[\theta(1 - \theta)(y_1^1 - y_1^2)^2] \geq \\ \geq (P - C)\theta(\mathcal{D} + y_1^1 + y_B)x_1^1/(x_1^1 + x_B) + (P - C)(1 - \theta)(\mathcal{D} + y_1^2 + y_B)x_1^2/(x_1^2 + x_B)$$

We next simplify the inequality and obtain the following:

$$\frac{\{\theta(1 - \theta)x_B(x_1^1 - x_1^2)[y_1^2(x_1^1 + x_B) - y_1^1(x_1^2 + x_B)] + \theta(1 - \theta)x_B(\mathcal{D} + y_B)(x_1^1 - x_1^2)^2\}(P - C)}{(x_1^1 + x_B)(x_1^2 + x_B)[\theta x_1^1 + (1 - \theta)x_1^2 + x_B]} + \\ + k_y[\theta(1 - \theta)(y_1^1 - y_1^2)^2] \geq 0$$

Note that, given the assumptions of this model, $(x_1^1 + x_B)(x_1^2 + x_B)[\theta x_1^1 + (1 - \theta)x_1^2 + x_B] \geq 0$, $\theta(1 - \theta)x_B(\mathcal{D} + y_B)(x_1^1 - x_1^2)^2 \geq 0$ and $(P - C) \geq 0$. Therefore, we only need to show that $\theta(1 - \theta)x_B(x_1^1 - x_1^2)[y_1^2(x_1^1 + x_B) - y_1^1(x_1^2 + x_B)] \geq 0$ and $(P - C) \geq 0$ for the inequality to hold. Note that the conditions $x_1^1 \geq x_1^2$, $y_1^1 \leq y_1^2$ and $x_1^1 \leq x_1^2$, $y_1^1 \geq y_1^2$ will ensure that $\theta(1 - \theta)x_B(x_1^1 - x_1^2)[y_1^2(x_1^1 + x_B) - y_1^1(x_1^2 + x_B)] \geq 0$. The conditions $x_1^1 \geq x_1^2$ and $y_1^1 \leq y_1^2$ indicate that the carrier can invest fewer resources in competition if it decides to invest more resources in cooperation ($x_1^1 \geq x_1^2$ and $y_1^1 \leq y_1^2$). On the other hand, the carrier can invest more resources in competition if it decides to invest fewer resources in cooperation ($x_1^1 \leq x_1^2$ and $y_1^1 \geq y_1^2$). The second conditions are typically satisfied for a carrier with a fixed quantity of resources.

Based on this result, we show that the profit (objective) function for a carrier is concave. Given the linear form of the constraints, we can conclude that the profit maximization program for a carrier is concave. According to Kinderlehrer and Stampacchia (1980), because the profit function is concave, the marginal profit function (the gradient) is monotonic. Therefore, we can state the existence and uniqueness of the cooperation game based on this property. ■

Appendix II: The Equilibrium Condition for a Three-Carriers Cooperation Game

Similarly, we first assume that the total demand of three freight carriers depends on the level of cooperation in the two-stage game.

$$q(y_1, y_2, y_3) = \mathcal{D} + y_1 + y_2 + y_3$$

For readability, we replaced $q(y_1, y_2, y_3)$, $c(y_1, y_2, y_3)$ and $p(q)$ with Q , C and P so that the derivation process is clearer. The utility/profit functions of carrier 1, 2 and 3 are:

$$\pi_1 = (P - C)Qs_1 - k_x x_1 - k_y y_1^2$$

$$\pi_2 = (P - C)Qs_2 - k_x x_2 - k_y y_2^2$$

$$\pi_3 = (P - C)Qs_3 - k_x x_3 - k_y y_3^2$$

To make the model reasonable, without loss of generality, the following constraints should be imposed:

$$\begin{aligned}
 P &\geq C \geq 0 \\
 x_1 &\geq 0, x_2 \geq 0, x_3 \geq 0 \\
 y_1 &\geq 0, y_2 \geq 0, y_3 \geq 0
 \end{aligned}$$

The first-order conditions with respect to x_i required to obtain the corresponding maximum utilities are:

$$\frac{\partial \pi_1}{\partial x_1} = \frac{Q(P - C)(x_2 + x_3)}{(x_1 + x_2 + x_3)^2} - k_x = 0$$

$$\frac{\partial \pi_2}{\partial x_2} = \frac{Q(P - C)(x_1 + x_3)}{(x_1 + x_2 + x_3)^2} - k_x = 0$$

$$\frac{\partial \pi_3}{\partial x_3} = \frac{Q(P - C)(x_1 + x_2)}{(x_1 + x_2 + x_3)^2} - k_x = 0$$

The cost of expanding the competitive effort for each carrier therefore are:

$$k_x x_1^* = k_x x_2^* = k_x x_3^* = \frac{2Q(P - C)}{9}$$

We can conclude that the equilibrium competitive effort levels are:

$$x_1^* = x_2^* = x_3^* = \frac{2Q(P - C)}{9}$$

We next use backward induction to analyze the first stage of the game from the results of second stage. Plugging x_1^* , x_2^* and x_3^* into the carriers' utility functions leads to:

$$\pi_1 = \frac{Q(P - C)}{9} - k_y y_1^2$$

$$\pi_2 = \frac{Q(P - C)}{9} - k_y y_2^2$$

$$\pi_3 = \frac{Q(P - C)}{9} - k_y y_3^2$$

Applying the condition that $\partial \pi_i / \partial y_i = 0, \forall i \in \{1, 2, 3\}$, the equilibrium cooperative effort levels are:

$$y_1^* = y_2^* = y_3^* = \frac{P(1 + \frac{1}{s_d}) - C(1 + \frac{1}{s_c})}{18k_y}$$

To summarize the results and replace the notations with the original meanings, we list the following equilibrium conditions for this coopetition game:

$$x_1^* = x_2^* = x_3^* = \frac{2q(y_1, y_2, y_3)\{p(q) - c(y_1, y_2, y_3)\}}{9k_x}$$

$$y_1^* = y_2^* = y_3^* = \frac{p(q)(1 + \frac{1}{s_c}) - c(y_1, y_2, y_3)(1 + \frac{1}{s_c})}{18k_y}$$

It can be noted that the equilibrium condition is similar to the condition with two carriers with only minor difference. For the games with more than three carriers, the same process can be applied.

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Development of green shipping network to enhance environmental and economic performance

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ABSTRACT

To secure cargoes, containerships operate double or triple calling of ports in the Pearl River Delta (PRD) region in China. Such shipping operations generate high CO₂ emissions. This paper suggest a green shipping network (GSN) as a useful tool to transship containers from feeder ports to hub ports to lower the overall CO₂ emissions in the region. From the perspective of scale operations from using the hub-and-spoke approach and the deployment of mega ships, developing a GSN within the PRD region can be beneficial, both economically and environmentally, to port users in the container transport chain.

Keywords: Shipping Management; Shipping Network; Environmental Management; Firm Performance

INTRODUCTION

The costs of environmental protection for firms to reduce CO₂ emission have increased considerably since the 1970s. These environmental costs are expected to rise even further. In the context of shipping operations, initiatives to reduce CO₂ emission include: (1) use shore power, (2) reduce vessel speed, and (3) use cleaner fuel. Extra operational costs are incurred for upgrading equipment to use shore power, modifying operational procedures to cope with reduced vessel speed, and complying with environmental regulations. To remain competitive, cost-effective green shipping operations are essential for shipping firms (Lun et al, 2010). Hence, research on environmental management has extended from the focus on pollution control to the emphasis on both economic and environmental performance. Integrating both environmental concerns and commercial operations into shipping management has become increasingly important for shipping firms (Lun, 2011).

To enjoy scale operations, green shipping networks (GSN) can be established by using a hub-and-spoke system to support large containerships running forth and back between major ports (Lun and Browne, 2009). Such a system requires delivery of containers to feeder port first by trucks, then transferred to hub port by barges. In intermodal transport operations, the accessibility of road transport is the highest among all transport modes. However, the level of CO₂ emission for trucking is the highest. Hence, containers should be first truck to the nearest port to minimize environmental damage. From the perspective of container port operations, ports in the region can be classified into feeder ports, hub ports, and direct ports. Under the hub-and-spoke system, feeder ports receive domestic containers

and transport them to hub ports. Hub ports are ports of loading that handle containers from feeder ports and also their direct containers. Benefits of the development of GSN include: (1) removing of mega containership vessels multiple callings port in a region, and (2) lowering CO₂ emissions by using barge delivery between feeder ports and hub ports.

In view of the global community's increasing concern for the environment, there is an urgent need for the PRD region to enhance environmental performance through the development of a GSN. However, establishing a GSN requires the full support of the port users, which in turn needs to adopt green shipping practices (GSPs) for the sustainable development of the shipping related industries. Users in the port community include shipping companies, shippers, terminal operators, and other transport operators (Lun and Caiou 2009). The establishment of a GSN is important to all port users. According to Lun et al. (2011), users in the port community can be characterized into the following types: (1) first-party users are parties that physically own the cargo to transport, e.g., global traders and small domestic exporters, (2) second-party users are parties that own the vehicles and/or facilities to provide logistics and transport services, (3) third-party users are parties that directly offer services to shippers, e.g., freight forwarders, customs brokers, and other value-added service providers, (4) fourth-party users are parties that supervise third-party logistics services providers to provide services to meet customer requirements, and (5) fifth-party users are parties that conduct research studies or provide consultation services to facilitate the development and growth of the region.

Port operations are closed linked with environmental quality (Gallagher, 2009). The challenge of today's shipping

industry is to enhance economic performing while reducing negative environmental impacts. Environmentally sustainable operations have emerged as an important topic for firms to prosper and for policy makers to showcase their commitment to environmentally friendly operations (Sarkis et al., 2010). For the past few decades, the emissions of greenhouse gases have increased by approximately 70% (Metz et al., 2007). Increasing emissions of greenhouse gases due to transportation related activities have become a serious concern. There is an urge for shipping firms to adopt green shipping practices (GSPs) to reduce the environmental damage caused by global trade activities (Lai et al., 2011). Establishing a GSN in the PRD region can also balance the interests between reducing CO₂ emissions and running market-led operations for economic gains. To establish a GSN, it is essential to investigate green shipping practices (GSPs) as organizational antecedents, and to achieve the ultimate goal of developing green shipping hubs (GSHs). This study is important to users in the shipping related industries in two perspectives. The first one concerns the identification of a potential GSN and the development of GSHs in the PRD region. The second one is to advance knowledge in shipping research that GSPs are important to the establishment of GSN.

DEVELOPMENT OF GREEN SHIPPING NETWORK

Liner shipping provides a regular publicized schedule of shipping service between seaports. a function of liner shipping is to satisfy the shipping demand for regular freight transport. Liner ships service international seaborne trade with cargoes consolidated from a large number of consignments from different shippers. a key objective of liner shipping operations is to fully utilize the capacity of their fleets. Operating a large container ship involves huge capital investment and high daily operating costs (Lun and Marlow, 2011). Shipping firms can gain efficiency from improving fleet utilization through ship routing, which is concerned with the assignment of sequences of ports to be visited by ships (Zhang et al., 2011).

The factors needed to be considered by shipping firms to plan liner shipping services include shipping service scope and fleet mix (Lun and Browne, 2009). In planning a liner service route, it is important to decide the type of shipping routes. With increasing significance of pendulum services and transshipment networks, most liner services on the main shipping routes provide the line-bundling service. By the overlay of their roundtrips, shipping firms can offer a desired calling frequency to customers. For instance, OOCL, one of the mega global shipping lines, offers four weekly sailing line-bundling shipping services from South China to North America with its alliance members. The ports of call of these four liner shipping services are illustrated in Table 1. Other global liner shipping companies offer similar line bundling loops to transport containers to and from the PRD region.

Asia is one of the busiest areas for containerized trade. The top container ports of the world in terms of throughput are Shanghai, Singapore, Hong Kong and Shenzhen. Two of these top container ports, namely Hong Kong and Shenzhen, belong to the PRD region and they are adjacently located and economically connected. However, unproductive competition seems to emerge due to unclear roles of individual ports and a serious lack of development of a shipping network among PRD ports. Facing with the environmental concern, it is essential to use all resources efficiently and effectively. From the perspective of shipping operations, use of equipment in the containers terminals and shipping capacity should be used effectively to reduce wastes. Doubling of triple calling of ports involve longer voyage distance which can be considered as a waste of resources.

In addition to using extra shipping capacity, calling more ports in the region leads to extra CO₂ emissions. As shown in Table 1, all the four liner services (i.e., SSX, PNX, PAX, and SCE) call both the ports of Hong Kong and Shenzhen, which incur addition voyages distance in the PRD region. The resultant extra CO₂ emissions can be avoided if a GSN can be developed to reduce the environmental harms associated with shipping routes. As shown in Table 1, it is estimated that an excessive 8.1 million kg of CO₂ is emitted annually because of

Tab. 1. OOCL Liner Shipping Service (South China Outbound to North America)

Weekly Sailing Liner Service	Ship Size	Ports of call in PRD region	Voyage distance between ports in PRD	CO2 emission in PRD region
Super Shuttle Express (SSX)	8,000 TEU	SE ^{a)} → SW ^{b)} → HK ^{c)} to America	SE → SW = 115 km	(115 + 45) x (8000 x 75%) ^{d)} x 86 ^{e)} = = 85,560,000 grams
			SW → HK = 45 km	
Pacific-North-West Express (PNX)	7,500 TEU	SW → HK to America	SW → HK = 45 km	45 x (7500 x 75%) x 86 = = 21,768,750 grams
Pacific Atlantic Express (PAX)	4,800 TEU	SE → HK → SW to America	SE → HK = 70 km	(70 + 45) x (4800 x 75%) x x 86 = 35,604,000 grams
			HK → SW = 45km	
South China East Coast Express (SCE)	4,500 TEU	SW → HK to America	SW → HK = 45 km	45 x (4500 x 75%) x 86 = = 13,061,250 grams
CO ₂ emissions per week (due to double or triple calls at PRD ports)				155,994,000 grams
CO ₂ emissions per year (due to double or triple calls at PRD ports)				8.1 million kg

a) SE = Shenzhen East

b) SW = Shenzhen West

c) HK = Hong Kong

d) Assume 75% load factor

e) Assume CO₂ emission by ocean-going vessel = 86 grams per km/TEU (i.e., twenty-foot equivalent unit)

double or triple calling of PRD ports. Only one shipping line generates such a huge amount of CO₂ emissions. Other shipping lines offering liner services to and from PRD ports also operate similar routing patterns. As a result, there are huge amount of avoidable CO₂ emissions resulting from double or even multiple calling of ports within the PRD region.

Liner shipping service providers make key decision in ship routing to secure cargoes. In international shipping, the head hauls are eastbound route from Asia to America and westbound route from Asia to Europe. To development green shipping network, port operators also play an important role. There are several container terminal operators in the PRD region with Hong Kong and Shenzhen as the key operating areas. The port of Hong Kong is served by five operators where HPH and MTL are the main terminal operators. On the other hand, the port of Shenzhen consists of ports in Shenzhen East (i.e., Yantian) and Shenzhen West (i.e., Chiwan, Dachan Bay, and Shekou). In the port of Shenzhen, the port of Shenzhen East is operated by HPH and the ports of Shenzhen West are operated by MTL.

Estimation of the direct voyage distance between the port of loading and the port of discharge can be a useful tool to identify the relative environmental cost for containership transport between these ports. An alternative route to transport containers is to develop a shipping network to transport the containers from a feeder port to a hub port by barges, and then ship the containers to discharging ports by containerships. Reduction of environmental damage in the PRD region is achieved when the alternative route is shorter than the direct route in terms of the equivalent containership distance (ECD) travelled. These shipping routes also avoid double or triple calling of ports in the PRD region. As a result, the shortest route for any given pair of origin and destination originating in this region is the route with the lowest environmental cost for container shipping.

Appendix 1 illustrates the formulas to determine the voyage distances of a direct voyage and alternative routes between the ports in the PRD region and their discharging ports. This formula is a useful tool to identify the routes with the lowest environmental costs when shipping containers take routes via other ports instead of using direct loading. Based on proposed tool, the green shipping network for head hauls in PRD region is shown in Figure 1. Ports in East of Shenzhen (SE) and Hong Kong (HK) should develop as hub ports to handle eastbound (EB) cargo to America while ports in West of Shenzhen (SW) and Hong Kong (HK) should develop as hub ports to handle westbound (WB) cargo to Europe.

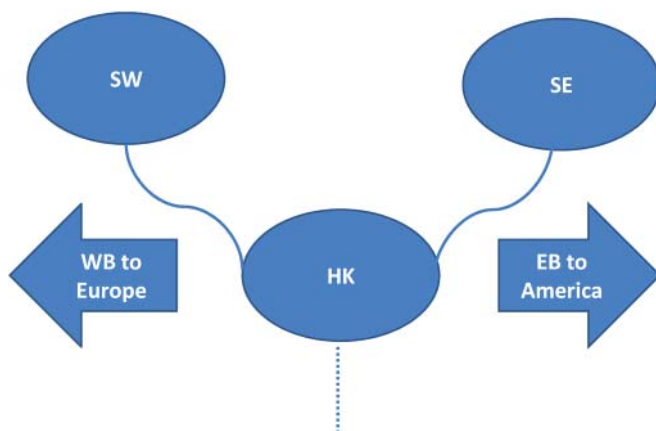


Fig. 1. Proposed Green Shipping Network in PRD

To minimize CO₂ emissions, it is desirable to develop a GSN in PRD ports by using barges to carry containers from feeder ports to hub ports, which helps reduce the total emission volume. With the development of such a GSN,

GSHs in the PRD region can be identified. As trucks produce the highest level of CO₂ emissions, the use of trucking should be minimized. For inland transport, containers should be transported from the shippers' warehouses to the nearest port within the PRD region to reduce CO₂ emissions. Ports can then be classified into feeder ports and hub ports. Feeder ports are ports that have higher external costs when they act as ports of loading for mainland containerships instead of using barges to transport containers to hub ports. Hence, it is worthwhile for feeder ports to transport their containers to a GSH for minimizing the total external cost in the PRD region. Hub ports are ports of loading that handle containers from feeder ports and also their direct containers.

ADOPTION OF GREEN SHIPPING NETWORK

Using CO₂ emissions as the analytical base, ports in the PRD region can be classified as feeder ports or hub ports. To enhance environmental performance, it is desirable to develop GSHs in the PRD region with the objective of having fewer ports of call for larger containerships. The GSN can be operated by large vessels based on scheduling vessels forth and back between major ports and supported by a hub-and-spoke system, where containers are first delivered to a feeder (or spoke) port by trucks, followed by transfer to the hub port by barges. Containers can deliver to the hub port directly if the nearest port is a hub port. a shipping hub is generally well equipped to facilitate the quick turnaround time of a large containership. Such a hub allows the development of linkages between origins and destinations where port users in the port community can achieve operational gains from operating cost through the deployment of larger ships and provide wider service through the development of feeder ports. It can also serve as a transshipment place, where feeder shipping routes are connected with one another with trunk routes for ocean-going voyages. Recently, container shipping firms have established connections with hub ports in order to make their operations cost-effective.

The use of shipping hubs implies the deployment of larger ships to transport containers. Container shipping companies operating larger ships can benefit from reduced cost per TEU. Cost efficiency is one of the most popular size-based strategies for container shipping firms to deploy mega ships. The development of a GSN indicates that huge cargo volumes are available in the hub port, which facilitates the deployment of bigger ships. Reasons for container shipping firms to deploy bigger ships include (1) large ships allow the carriage of a greater cargo volume per ship, (2) large ships equipped with efficient engines improve vessel speed, and (3) greater flexibility in container stowage can be achieved with larger ships. Larger ships are also more energy-efficient, requiring less fuel and emitting less CO₂ per TEU transported.

A shipping network refers to the framework of routes within a system of nodes. Using the main container ports in the PRD region as nodes, this study proposes routes for transporting containers from these nodes to their destinations as a GSN in the PRD region. a corporate shipping network can be seen as strategic interdependence, i.e., "a situation in which one firm has the tangible or intangible resources or capabilities beneficial to but not possessed by the others" (Lun et al., 2009). With the development of shipping hubs in the PRD region, the shipping industry will benefit from using the hub-and-spoke approach. In a shipping hub, firms participate in upstream and downstream activities jointly and their collective economic actions lead to the emergence of a GSN.

The proposed GSN concept in the PRD region can balance the interests of policy makers between reducing CO₂ emissions and pursuing market-led port development. Lun (2011) used a case study to identify the key elements for successful green shipping management. Based on this initial study, three organizational antecedents as GSPs that are identified to the development of a GSN:

1. *Cooperation with business partners*: Sarkis (2003) develops a decision framework for evaluating alternatives of green practices adopted by firms that affect their external relationships with suppliers and customers. It is unlikely for shipping firms to adopt a GSN and change their ship routings when their partners in container operations are not actively involved in the network. Sheu et al. (2005) use a modelling approach to optimize the operations of forward and reverse logistics in a green supply chain. Their model and other similar studies emphasize cooperation with supply chain partners (Wong et al., 2009) and define a variety of characteristics and attributes. To successfully develop a GSN, cooperation between shippers and shipping lines is essential. With support from shippers to change the ports of call and sailing schedules, shipping lines may re-schedule their shipping routes to minimize their voyage distance and reduce the gross CO₂ emissions. Furthermore, Zsidisin and Hendrick (1998) provide empirical evidence and identify several factors that influence green operations such as investment recovery (e.g., freight income from deploying ships), product design (e.g., ship routing), and supply chain relationships (e.g., support from shippers and other business partners). To perform shipping activities, shipping firms have established linkages with other users of the ports (Lun, 2008; Lun et al., 2009). These linkages with upstream and downstream firms in the region can be a factor affecting firms to improve environmental performance (Yang et al., 2009; Lun, 2010) by engaging in a GSN.
2. *Environmentally friendly operations*: Several models of environmentally friendly operations have been developed from the operational perspective. Handfield, et al. (2002) develop a decision model to measure environmental practice by using the multiple attribute utility theory approach. Kainumaa and Tawarab (2006) also use multiple attribute utility theory to assess supply chain performance throughout the life-cycles of materials, facilities, and services. Using life-cycle assessment, Faruk et al. (2002) advance knowledge on adoption of environmentally friendly operations by identifying materials acquisition, pre-production, production, distribution, and disposal as key measures. To assess the adoption of a GSN, it is essential to identify barge operators and feeder terminals, integrate operating system with feeder ports, use green shipping routes that emit less CO₂, and develop a GSN to integrate shipping operations. On the other hand, ship operators may (1) source cleaner fuels at the materials acquisition stage, (2) re-think propeller design at the pre-production stage, (3) optimize ship engine during the voyage, (4) use waste heat recovery systems to reduce fuel consumption, and (5) use ballast water treatment systems to reduce the disposal of undesired organisms into the marine ecosystem. Walton et al. (1998) identify several dimensions to enhance environmental purchasing. From the perspective of GSPs, examples of environmental purchasing include the materials used in facility and equipment design to ensure a high recycling ratio at the time of scrapping barges and the decision processes that shippers use to select shipping services with routes that emit the lowest CO₂ emissions.

Rationalization of liner shipping services to develop a GSN can also be seen as a tool to practice environmentally friendly operations.

3. *Internal management support*: There are a number of studies examining the relationship between green operations and internal management support. Carter et al. (1998) conduct an empirical study to examine green business operations. Their study identifies six key factors related to green business operations including top management support, middle management support, firm's mission, department goals, training for personnel to purchase environmentally friendly input, and evaluation of purchasing management. These findings imply that management support and company goals are factors affecting the adoption of a GSN. In addition, Zhu and Sarkis (2004) identify commitment from senior managers, support from mid-level managers, and cross-functional cooperation from environmental improvements as factors affecting internal environmental management. In short, previous studies (Shrivastava, 1995; Guimaraces and Liska, 1995) suggest that a number of benefits can be achieved by integrating environmental issues with corporate strategy. Hence, support by management team is one of the key elements to influence the adoption of a GSN. For instance, a leading global container terminal operator is committed to GSPs. The management team clearly defines its environmental policy as follows: (1) Legal Compliance, i.e., to comply with environmental regulations and set guidelines to achieve good environmental performance, (2) Pollution Protection and Waste Minimization, i.e., to incorporate environmental concerns in planning operational decisions to prevent pollution and reduce energy consumption, (3) Continual Monitoring and Improvement, i.e., to conduct periodic internal and external audits to monitor the environmental performance, and (4) Sustainable Development, i.e., communicate environmental objectives throughout the firm and its business partners in pursuit of green management practices. The resources commitment by top management is crucial to the implementation of environmental initiatives such as developing a GSN.

DISCUSSIONS

Shipping firms actively engaged in GSPs are more likely to outperform their competitors that are less supportive of a GSN. Environmental protection activities are embedded in business operations, where improving business operations efficiency to develop a GSN may bring benefits to firms. Thus, improvement in performance (e.g., shorten voyage distance to reduce waste of shipping capacity and related operating cost) may be one of the drivers for firms to implement a GSN. The subject of performance has received increasing interest from both academics and policy makers (Panayides and Lun, 2009). Potential benefits gained through pursuing GSPs include decreased fuel cost, waste treatment, and waste discharge. Benefits may also be generated by using larger ships to carry containers to and from PRD ports. a proactive pursuit of GSPs can prepare an enterprise for superior performance through reducing environmental risk and the development of capabilities for continuous environmental improvement. a number of findings support the view that GSPs are positively related to firm performance (Alvarez et al., 2001; Klassen and McClaghlin, 1996; Judge and Douglas, 1998). For instance, Rosso and Fouts (1997) link environmental performance to economic performance based on the resource-based view of the firm. They suggest that improved environmental performance

will result in competitive advantage that is reflected by economic benefits. There are two categories of mechanisms for explaining the linkage between environmental and economic performance (Montabon et al., 2007). The first is “market gains”, which include experience-based scale economies and higher margins. With the development of a GSN, the overall container throughput in the PRD region can be increased. This implies that terminal throughput and profit can be used as performance indicators in the container terminal industry. The second is “cost savings” such as greater productivity or lower operating cost due to reduced energy and materials consumption. For instance, a vessel of 12,000 TEU on the Europe-Far East route would generate an 11% cost saving per container slot compared to an 8,000 TEU vessel and a 23% cost saving compared with a 4,000 TEU ship (Notteboom, 2004). Hence, lowering of the operating costs of shipping lines by using bigger ships in a GSN can be used as another performance indicator for liner shipping operations.

Although GSPs are essential to implementing a GSN, their levels of engagement vary among firms. GSPs involve a set of business processes that require firms to assess their environmental impacts, determine environmental goals, implement environmental operations, monitor goals attainment, and undergo management review. GSPs assist firms in scrutinizing their internal operations, engaging employees in environmental issues, continually monitoring for environmental improvement, and increasing their knowledge about their operations. These actions facilitate the improvement of firms’ internal operations and create opportunities to gain competitive advantage. GSPs also encourage firms to use more sophisticated environmental strategies that build on their basic environmental protection principles to eliminate environmentally hazardous operating processes and redesign existing operating systems. Developing a GSN through engaging in GSPs offers an excellent opportunity for firms to assess all aspects of their operations jointly to minimize the shift of environmental harms from one subsystem to another and achieve greater organizational efficiency. GSPs focus on identifying best practices that simultaneously reduce the negative impacts of firms’ activities on the natural environment and contribute to better firm performance. Unlike regulatory requirements that are derived from the outside, GSPs consist of operational processes that arise from within a firm. GSPs are a collection of internal efforts in business planning and implementation. GSPs consist of a business policy and a set of business processes that require firms to assess their environmental impacts, determine environmental goals, implement environmental operations, monitor goals attainment, and undergo management review. Through continual environmental and organizational improvement, firms may enjoy opportunities to enhance their performance.

CONCLUSIONS

Global economic development is supported by the commercial shipping industry. Shipping operations by maritime transport contributes to the growth of international trade activities, which heavily depends on ships to transport cargoes from places of production to places of consumption. Carriage by sea has increased by 50% in the past two decades and accounts for approximately 90% of the global trade volume. The movement of containerships emits CO₂ from fuel consumption during the voyage. Depending on ship size, ocean-going vessels emit between 15 and 21 grams of CO₂ per ton-km (International Chamber of Shipping, 2010), leading to concerns about the environmental damage caused by shipping activities. There are studies exploring the use of cleaner fuels and the development of emission control areas. Nevertheless, the fees charged for accessing emission control areas and the capital investment for adopting cleaner fuels will add costs to shipping operations, which lifts freight rates. Consequently, traders may bear higher freight rates for shipping cargoes between ports with emission control. Such development can be detrimental to the competitiveness of such ports as high freight rates discourage trade activities and consequently dampen shipping demand.

Hong Kong and Shenzhen are two of the top five global container ports servicing the same hinterland in the Pearl River Delta (PRD) region. Since the two cities are closely linked geographically and economically, port operations should be coordinated with strategic port policies. However, counter-productive competition exists between the two ports due to their unclear roles and a lack of shipping network development in the PRD region. This study contributes to port policy development in the PRD region by classifying ports in the region as feeder ports and hub ports. Such classification will provide policy insights for developing a green shipping network (GSN) that will emit lower CO₂ in the region. Feeder ports refer to ports that emit a higher level of CO₂ when they act as ports of loading for containerships. The total emissions can be substantially reduced if barges are used to transport containers to hub ports in the PRD region. Developing a GSN based on the port classification to be developed in this study will yield the following advantages: (1) selection of shipping routes by shipping firms that produce less air pollution, thus reducing the global warming effect, (2) reduction of double or triple calling of ports in the PRD region, so reducing CO₂ emissions, and (3) development of green shipping hubs (GSHs) in the PRD region, hence strengthening the competitiveness of the region. This timely study will provide insights for policy makers to “green” the pillar shipping industry, which services the vast manufacturing base in the PRD region, yielding enhanced productivity and efficiency.

Appendix 1: Formulas to determine the voyage distances of a direct voyage and alternative routes between the ports in the PRD region and their discharging ports

The environmental cost for container transport from a port of loading r to a port of discharge s can be written as:

$$EC_{rs} = \sum_i ec_1 d_{rs,i} s_{rs,i} \quad (1)$$

where ec_1 is the environmental cost for transport mode 1, which is defined in this study as containership transport. $d_{rs,i}$ and $s_{rs,i}$ are the demand and equivalent containership travel distance from the port of loading r to the port of discharge s through route i , respectively. Note that

$$s_{rs,i} = \sum_m (ec_m / ec_1) s_{rs,i}^m \quad (2)$$

where $s_{rs,i}^m$ represents the total distance travelled using mode m transport along route i from the port of loading r to the port of discharge s .

In order to minimize the environmental cost, all the demands between a particular port of loading r and a port of discharge s must use the shortest route. Therefore,

$$\min EC_{rs} = \min_i \sum_i ec_i d_{rs,i} s_{rs,i} = ec_i d_{rs} \min_i s_{rs,i} \quad (3)$$

Thus, once the equivalent containership travel distances have been calculated for all the possible routes from r to s , the minimum environmental cost for transporting containers from r to s can be determined using the shortest route.

The next step is to convert barge distance to an equivalent containership distance (ECD) by multiplying the barge distance with the ratio of the environmental cost for barge transport to that for containership transport. Therefore,

$$1 \text{ barge distance} = (3.3/6.3) = 0.53 \text{ ECD}$$

With the barge distances between the origin ports and the containership distances between origins and destinations, the ECD travelled on all the routes can be determined as:

$0.53 \times$ barge distance between ports in the PRD region + containership distance from port of loading to port of discharge

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Evaluations of port performances from a seaborne cargo supply chain perspective

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ABSTRACT

Previous research on port efficiency focuses primarily on the provider's perspective and assumes that maximizing the output is always desirable. This paper recognizes that maximizing the final output does not necessarily guarantee an efficient system and the notion of port efficiency and service effectiveness needs to be considered from the perspectives of both the provider and the consumer of the port service. The paper proposes a network-DEA model to evaluate the performances of 30 seaports worldwide. The concurrent consideration of efficiency scores from the network-DEA model and the traditional DEA-CCR model will offer valuable insights to port operators on how to improve port performances as part of a seaborne cargo supply chain.

Key words: Seaborne cargo supply chain; Port efficiencies; Freight transportation; Port service benchmarking

INTRODUCTION

Adams Smith (The Wealth of Nations, 1776), in his discussion of specialization and the extent of the market, stresses the relationship between wealth and trade between nations. Despite some lingering controversy, empirical studies show a positive relationship between trade and growth (Clark, Dollar and Micco, 2004). At a global level, more than 85% of international trade volume is conducted by maritime transport¹⁾. Compared to air and land modes, maritime transportation represents a viable and cost-effective way to transport a large amount of goods over long distance. Nagorski (1972), in his book *Port Problems in Developing Countries*, advocates that an efficient and well-organized seaport would attract trade volume, facilitate economic growth, provide excellent sources for employment and generate significant foreign exchange earnings. In the era of globalization, seaports play an ever-increasing important role in manufacturing and international business. Functioning as interfaces connecting the maritime and continental parts of the logistics chain, ports represent a growth pole with significant potential to trigger the economic prosperity of a nation. Conversely, a port can also become a major bottleneck and economic setback in the event of inferior performance.

Over the past four decades, the effectiveness of the maritime transport as a carrier of trade is further enhanced by containerization and advancements in logistics systems. While the port and maritime industry has grown significantly with trade, overlapping of the expanded port hinterlands, larger containerships and increased number of ports have also fueled competitions among ports. Port operators respond to the competition with an emphasis on the provision of services that matches to global competitiveness in terms of quality of services and overall efficiency of the port. These involve many aspects ranging from the reduction of the vessel turnaround time to the efficient handling of customers' trucks so as to utilize the internal resources. In some cases, an expansion of port facilities or the construction of a new port may be necessary. As port development projects absorb large amounts of investment, the industry witnesses a paradigm shift and institutional reform towards the private sector's participation in ports. Along with this, the issue of port efficiencies gains importance owing to its impact on the investment return and international competitiveness of the ports (Low 2010).

The issue of port efficiencies has been dealt with by numerous scholars. Inherent in the measurement of port efficiency is the notion that a framework should be formulated to ensure multiple factors (inputs) and multiple goals (outputs)

¹⁾ In fact, a 2009 United Nations study reported that ocean shipping accounted for 66.3% of the world's merchandise trade in dollar terms (UNCTAD 2009).

are adequately considered. A review of the literature showed that Data Envelopment Analysis (DEA) models dominate among the scientific methods of quantitative efficiency analysis that have been applied (see Table A-1). One of the major strengths of the DEA is that it enables the assessment of multi-factor productive efficiencies through an effective integration of multiple inputs and outputs factors within a single efficiency score. Particularly, DEA allows each decision making unit (DMU) to choose their own most favorable weights subject to the simultaneous consideration of other DMU's efficiency scores, relevant constraints and objectives instead of having a subjectively defined weight assigned a-priori in the computation of the efficiency score. Furthermore, this methodology neither imposes a parametric structure on data nor does it have heavy data requirements in terms of sample size. Data measured in different units can also be used simultaneously within a DEA model. Nonetheless, being an extreme point technique in which the efficiency frontier is formed by the actual performance of best performing observations, efficiency scores are highly sensitive to even small errors in measurement. Where sample size is small, it would result in a large proportion of observations having an efficiency score of 1. (Tone et al 2009 and Zhu 2009 provide a detailed theoretical discussion on the DEA methodology).

Apart from the DEA, econometric frontier analysis is another technique that has been used in the analysis of port efficiencies. For example, Coto Millán et al (2000) applied a translog function to 27 Spanish ports; Estache et al (2001) estimated a Cobb-Douglas and a translog production frontier for Mexican ports; Cullinane et al (2002) fitted a stochastic Cobb-Douglas production function to Asian ports among others. In comparison to the DEA methodology, econometric frontier analysis is disadvantaged in the sense that it requires a pre-specified functional form of the production or cost frontier (which may be ambiguous). As a statistical method, restrictive assumptions such as data normality, variable independences and residual randomness etc. also need to be satisfied when applying the econometric frontier analysis.

Despite the abundance of studies, application-related methodological improvements are relatively scant. More notably, most of the studies, if not all, share the common property that the efficiency of the system is evaluated as a whole. However, within a seaborne cargo supply chain, complexity arises from the fact that various factors and goals should be considered simultaneously. Particularly, there may be interactions among players with conflicting objectives that need to be addressed. It is not difficult to tell that the definitions for "efficient services" deviate, if not contradict, between the port service providers and the port users. From the viewpoint of the provider, efficiency is achieved when the port provides sufficient services at the least costs. Whereas according to the user, an efficient port is one which offers valued attributes such as shortest handling time or minimum damages to the containers. Service effectiveness can only be achieved if the service provided by a port is valued by the port users. Ships will call at their desired ports and the capacities provided by these ports are utilized by shippers and ocean liners, thereby generating cargo traffic in a port. To this end, it is meaningful to develop a method that is capable of measuring and evaluating the performance of port systems from the perspectives of the upstream and downstream players is necessary. The challenge remains on how to divide the system into the disaggregated processes, i.e., how to make sense of

the input-output relationship between entities (or nodes) and the entire system.

This paper aims to accomplish the performance evaluation of port systems in an integrated framework that reflects the views of the provider and the user. The integrated framework utilizes a network-DEA formulation where the performance of a system and those of its component processes can be simultaneously measured. Specifically, the service provided and consumed in a container port creates an association between the provider and the user perspectives and hence it is chosen as the unit of analysis²⁾. As oppose to the conventional treatment of having individual ports as the DMUs, an inter-linked network of supply and demand nodes is used to represent these DMUs. The computation of efficiency of DMUs can be equivalently viewed as the computation of service effectiveness within this network of nodes that takes into account of both viewpoints. To the best of our knowledge, there has been no precedent of such model being used in the context of ports. As the industry globalizes, it has become imperative for port operators know their standing in a global scale. Thus, the study will proceed to measure and compare port performances in a sample consisting of major ports from Asia, Middle East, Europe and America.

Port authorities, actual transportation planners and port engineers could potentially be the users of the modeling framework proposed in this paper. Through this model, the performance of port is decomposed into two stages, from which one can further identify the sources of poor performance. For instance, from a provider's point of view, resources expended on port services need to be minimized for purpose of economization while ensuring adequacy for a smooth operation; from a consumer's point of view the handling capacity should be maximized to avoid congestion. Hence, achieving a delicate balance will ensure a port to be truly efficient.

The rest of the paper is organized as follows: The next section introduces the network-DEA model as a proposed conceptual framework that deals with "disaggregate" performance measurement, followed by the justifications for considering the provision of services in a container port as a DMU, assumptions and a mathematical representation of the model. Section 3 conducts the empirical study and compares the results between the network-DEA model and the traditional DEA-CCR model. Section 5 discusses the implications of the results and Section 6 concludes.

THE MODEL

Conceptual Framework

Fig. 1 is a graphical presentation of the conceptual framework of the system. In the diagram, the provision of port services is represented as a network of inter-linked nodes that is a result of both the provider's and user's decisions. Similar to other studies in the field, scarce resources (such as berth capacity and terminal area) are used as inputs for the production unit and services provided as outputs. As the evaluation is based on the process of input-output transformation, this transformation is measured as an efficiency score relative to the performance frontier (as formed by the set of best performing inter-linked network of nodes). This is in contrast to the general treatment in existing DEA application studies where the production unit is often designated as the DMU in the efficiency evaluation.

²⁾ According to the literature, the definition of a decision making unit can be flexible. While, in most cases, the production unit under evaluation is designated as DMU, the decision maker is not always equivalent to a DMU. In this paper, the decision maker is the port operator but the DMU is the provision of the services in a port.

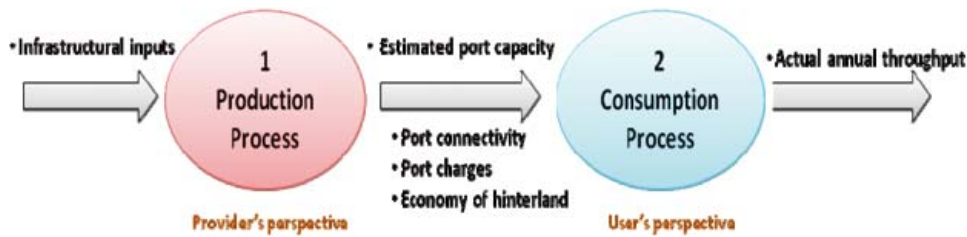


Fig. 1. Conceptual framework

Public transit is similar to liner shipping in its most basic form. As a mode of transportation, it facilitates the passenger movements (instead of cargos) from origin nodes to destination nodes along scheduled routes. Pratt and Lomax (1996), in their study on performance of public transit systems³⁾, highlighted that the performance measures should be in conformance with the objectives that the process is meant to achieve. From the provider's point of view, efficiency in port will be closely associated with achieving objectives such as maximizing the annual revenue or minimizing the total operational costs. The decision maker (the port authorities or port operators in this case) will decide how to vary the inputs to improve the system based on the efficiency score, which indicates of how well the transformation process has been done. Since the inputs considered are infrastructural and port traffic is treated as outputs, an estimated return on port capacity can be obtained. Meanwhile, the user of the port services is the shippers or ocean liners that transport or store containers via the port system. For a major user such as ocean liner, efficient service in a port will be the one that minimizes the vessel turnaround time and container damages. Node 2 represents this perspective in the model.

The proposed model (Fig. 1) links the production process (provider's perspective) and the consumption process (user's perspective) using some common variables being used for both perspectives. For instance, the output from the provider, namely, the "estimated port capacity" is used as inputs in

the case of users. From the provider's perspective, limited and costly resources should be used to build a port with facilities that maximize its handling capacity. Therefore, in the production process, the estimated port capacity (i.e., the theoretical throughput given the infrastructural and operational conditions), is used as the parameter for the intermediate output. Higher port capacity is assumed to correlate with higher user satisfaction. This is because low handling capacity will result in costly delay⁴⁾ for ship owners who can ill afford it.

A summary of the constructs and some of corresponding input variables are given in the graphical illustration in Fig. 2. Variables pertaining to port infrastructures and operations determine the physical capacity of the port; information regarding shipping lines and vessels reflects port network and connectivity; port charges and vessel turnaround time measures the service standards of a port; and institutional factors such port ownership and economic development can also affect port performance. In the recent years, port sustainability (quantified by the amount of emissions and pollution produced) has also become a crucial issue.

The actual annual throughput represents the output for port users, as well as, the final output for the entire system. This actual annual throughput usually differs from the estimated capacity because for the port users also consider other factors, besides handling capacity, when they decide whether to use a specific port or not. These factors include the port

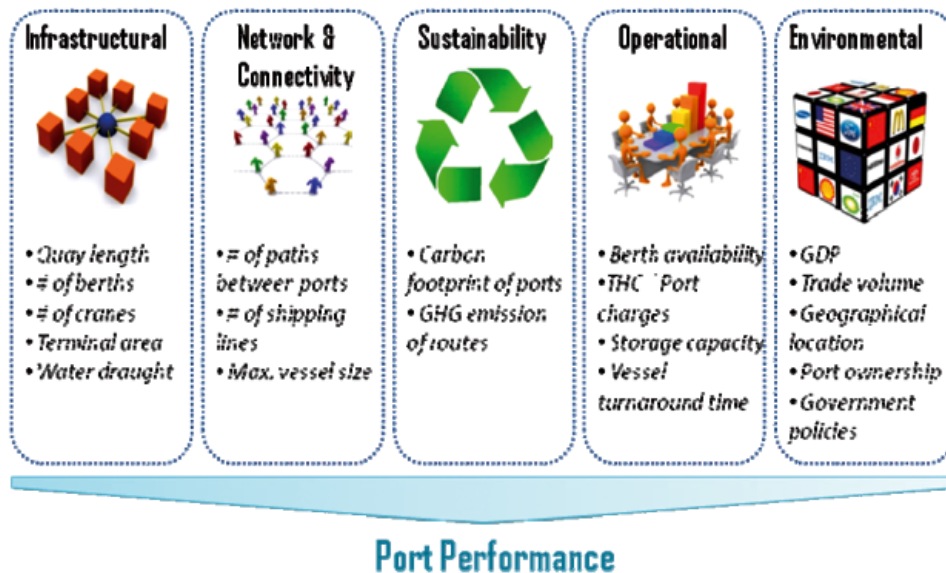


Fig. 2. Factors affecting port performances

³⁾ Prior to Pratt and Lomax, (1996), Fielding et al (1978) have proposed that three elements of transit operations, namely: resource input (labour; capital; fuel, etc.), service output (vehicle-hour; vehicle-km; capacity-km, etc.), and service consumption (passenger trip; passenger-km; operating revenue, etc.) constitute the three corners of a triangle. The three sides of this triangle represent resource-efficiency (measuring service output against resource input), resource-effectiveness (measuring service consumed against resource input), and service-effectiveness (measuring service consumed against service output), respectively.

⁴⁾ According to Talley (2006), port congestions arise when port users interfere with one another in the utilization of port resources, thereby increasing their time in port and lead to a longer turnaround time for ships.

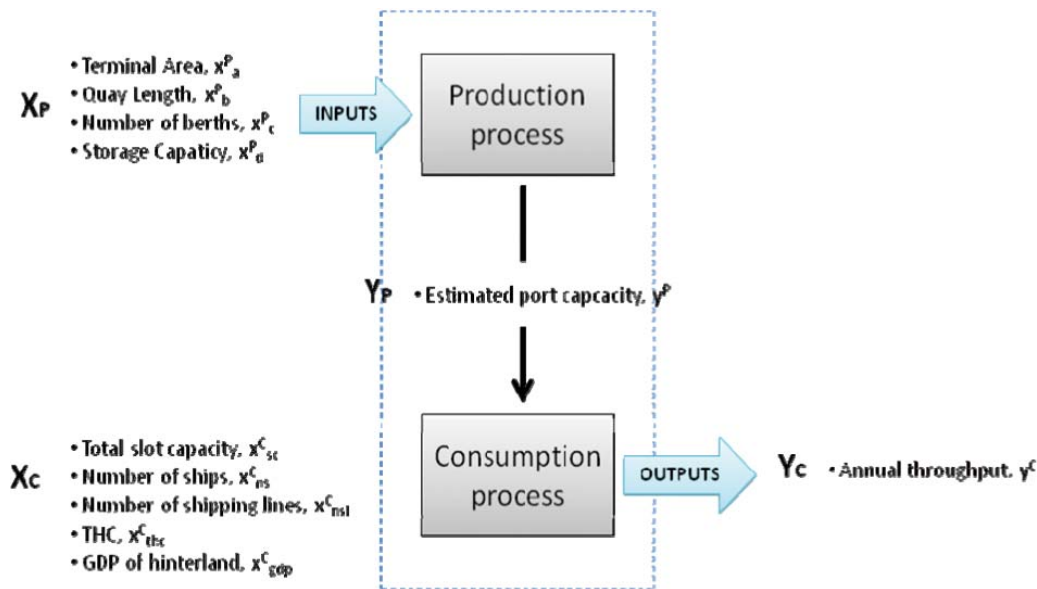


Fig. 3. Conceptual framework with detailed inputs and outputs

connectivity, charges, locations and economy of the hinterland, etc. As these variables are common influences on shippers' and liner shipping companies' port choice in any geographical locations, they can facilitate the comparison of port services. Hence this also ensures, to certain extent, the generalization of the analysis.

Mathematical Representation

The network-DEA model is based on three assumptions: first, ports are isolated entities engaging in similar activities and provide comparable range of services; second, container ships are similar in size in terms of transportation capacity; third, uncertainties in the data collected are ignored. Notations for analysis are shown in Fig. 3 together with the model below:

Inputs

- x_{ij}^p – inputs for the production process where i is the i^{th} type of input for production in the j^{th} port. For instance, x_{aj}^p represents “terminal area” as input for production process for port j
- x_{qj}^c – inputs for the consumption process where q is the q^{th} type of input for consumption in the j^{th} port and. For instance, x_{gdj}^c represents “GDP of hinterland” as input for consumption process for port j

Outputs

- y_j^p – outputs for the production process where j is the j^{th} port. For instance, y_j^p is the “estimated port capacity” for port j
- y_j^c – outputs for the consumption process where j is the j^{th} port. For instance, y_j^c is the “actual annual throughput” for port j

Weight Variables

- u_r – intensity vector associated with output type r
- v_i – intensity vector associated with input type i
- w_p – intensity vector associated with input for consumption process
- w_q – intensity vector associated with intermediate output

Mathematically, the model can be written as follows:

$$\text{Max } \sum_{r=1}^s u_r Y_{rk}$$

Subject to:

$$\sum_{i=1}^m v_i v_{ik}^p = 1$$

System:

$$\sum_{r=1}^s u_r y_{rj}^c - \sum_{i=1}^m v_i v_{ik}^p \leq 0 \quad i = \{a, b, c, d\}$$

Production process:

$$\sum_{r=1}^s w_p y_{pj}^p - \sum_{i=1}^m v_i x_{ij}^p \leq 0 \quad i = \{a, b, c, d\}$$

Consumption process:

$$\sum_{r=1}^s u_p y_{rj}^c - \sum_{i=1}^m w_q x_{qj}^c \leq 0 \quad i = \{sc, ns, nsl, thc, gpd, p\}$$

Non-negativity constraints:

$$u_r, v_i, w_p, w_q \geq 0$$

The efficiency score is between 0 and 1. DMUs with the efficiency score equal to 1 are efficient while a DMU with a score of less than 1 is relatively inefficient.

EMPIRICAL ANALYSIS

Data and Variable Descriptions

An empirical analysis is conducted on a sample of 30 major seaports world-wide. Based on data availability, the ports are listed below according to the regions where they are located:

- **Southeast Asia:** Tanjung Priok, Singapore, Port Klang, Port of Tanjung Pelapas, Laem chabang, Manila
- **Northeast Asia:**
 - **China** Hong Kong, Shenzhen, Ningbo, Guangzhou, Qingdao, Kaohsiung, Tianjin, Xiamen, Dalian, Shanghai
 - **Japan:** Yokohama, Nagoya, Tokyo
 - **Korea:** Busan
- **South Asia:** Jawarharlal Nehru, Colombo
- **Middle East:** Salalah, Dubai
- **Europe:** Antwerp, Rotterdam, Hamburg, Valencia
- **USA:** New York, Los Angeles

11 variables, pertaining to various aspects of a maritime logistics chain, are chosen to reflect the decisions of the port

operators and the users. While port annual throughput as the final output variable chosen coincides with that in the conventional studies (Cullinane and Wang 2007), the input variables are classified into two stages. In the stage of the production process (provider's perspective), infrastructural and operational factors such as number of berths, terminal area, storage capacity and quay length are selected as inputs. With these input variables representing port facilities at the waterside and landside, the provider is expecting the maximum handling capacity from the hardware of the port. On the other hand, in the stage of the consumption process (user's perspective), the actual throughput may differ from the port capacity estimated from the (previous) production process. For a given amount of throughput, a larger number of ships suggests higher frequencies while a smaller number of ships may render greater economies of scale and allows for competitive pricing. Other important aspects that will potentially exert an influence on the perceived attractiveness of a port include port network connectivity⁵⁾, economy of the region⁶⁾, port charges⁷⁾ and location⁸⁾ etc. Table 2 provides a brief description on the variables used in the analysis.

According to Raab and Lichty (2002), the minimum number of DMU observations should be three times greater than the total number of inputs and output. Since this empirical analysis is based on a network-DEA model, for each stage and for the entire system, the aforementioned condition is satisfied [Stage 1: $30 \geq 3(4+1)$; Stage 2: $30 \geq 3(6+1)$; Overall: $30 \geq 3(4+1)$]. A complete set of data on all 30 selected ports, sourced from Containerization International YearBook 2010 and Lloyd's World of Ports 2010, can be found in Appendix A.

DEA Results

The network-DEA model is programmed as a spreadsheet application using MS Excel VBA. Table 3 gives the efficiency

scores computed from the traditional DEA-CCR and network-DEA models, as well as, the relative rankings of the ports based on the respective scores.

The efficiency scores obtained from the network-DEA model are rather different from those computed using the traditional CCR model. The network-DEA model reports Hong Kong and Rotterdam as the only two ports that are fully efficient ports. Singapore and Hamburg ports rank the third and fourth, respectively. A number of Chinese ports (i.e., Ningbo, Shenzhen, Tianjin, Qingdao and Shanghai) are also found to be quite efficiency with efficiency scores greater than 0.7. However, Xiamen, Guangzhou and Dalian ports are significantly lagging behind. The efficiency scores in other ports in the Southeast Asia and South Asia region range from 0.25 to 0.57. Notably, the efficiency scores of 3 Japanese ports are among the lowest below 0.24 with Los Angeles port at the bottom of the list.

On the contrary, the efficiency scores from DEA-CCR model rank Singapore, Dubai and Antwerp as the three best performing ports. Hong Kong, Shanghai, Qingdao and Rotterdam ports are also highly efficient with efficiency scores above 0.9. Three other promising China ports (i.e., Ningbo, Tianjin and Shenzhen) dominate the next band by having efficiency scores between 0.8 and 0.9. While the most of the ports in the sample obtain reasonable efficiency scores above 0.5, Tokyo, Yokohama and Manila continue to report efficiency scores below 0.3

Comparing the port rankings under the two respective DEA models, it can be observed that the ports of Hamburg, Salalah, Guangzhou and Rotterdam have shown significant improvements in the network-DEA model. Other ports that exhibit similar tendency are Hong Kong, Shenzhen, Ningbo and Valencia. On the contrary, ports like Antwerp, Dubai, Kaohsiung and Shanghai are ranked better under the DEA-

Tab. 2. Input and output variables used for analysis

Variables	Description
Number of berths	Total number of berths of all terminals
Terminal area	Total terminal area in m ²
Storage capacity	Total storage capacity of all terminals in TEU
Quay length	Total quay length in m
Estimated port capacity	Expected annual throughput in TEU
Slot capacity	Total annual slot capacity deployed to/from port in TEU
Number of ships	Total number of ships deployed to/from port
Number of shipping lines	Number of shipping lines operating in the port
GDP	Gross Domestic Product (GDP) of the hinterland in 2008 in billion USD
THC	Terminal handling charge for a dry 20 feet container in USD
Annual throughput	Annual port throughput In TEU

* The numbers of ships and shipping lines, as well as, the GDP of the hinterland provide a rough representation of the locational advantage of the ports.

- 5) Wang and Cullinane (2006) stated that the accessibility of a container port reflects its competitiveness. Generally, a port is that is more accessible enjoys higher connectivity due to more port calls from major shipping lines.
- 6) Robinson (2002) and De and Ghosh (2003) remarked that ports that are natural gateway to rich hinterland could be at an advantage compared to ports in small island economies. Similarly, Fleming and Baird (1999) and Loo and Hook (2002) advocated that the presence of a large local market enhances the attractiveness of a port.
- 7) Chang et al (2008) found that the main haul shipping lines are more sensitive to port costs than feeder service providers. Prior to this, Lirn et al (2004) found handling cost of containers (THC) is the most important attribute under the control of port/terminal operators, which ports can compete on to attract transshipment cargo.
- 8) Stopford (2009) observed that the closure of centrally located ports, at major trading axes, will result in the route deviations that will increase the average haul. Following that, Low and Tang (2011) advocated that the centrality of a port conveys the degree of indispensability of the port within a liner shipping company's network.

Tab. 3. Efficiency scores and ranking of scores

Seaport	Country	DEA-CCR efficiency	Network DEA efficiency
Hong Kong	China	0.970 (4)	1.000 (1)
Rotterdam	Netherlands	0.902 (7)	1.000 (1)
Singapore	Singapore	1.000 (1)	0.979 (3)
Hamburg	Germany	0.408 (23)	0.946 (4)
Ningbo	China	0.891 (8)	0.906 (5)
Shenzhen	China	0.822 (10)	0.883 (6)
Tianjin	China	0.841 (9)	0.877 (7)
Dubai	UAE	1.000 (1)	0.841 (8)
Qingdao	China	0.930 (6)	0.742 (9)
Shanghai	China	0.950 (5)	0.736 (10)
New York	USA	0.612 (12)	0.733 (11)
Salalah	Oman	0.523 (19)	0.718 (12)
Antwerp	Belgium	1.000 (1)	0.645 (13)
Xiamen	China	0.604 (13)	0.607 (14)
Guangzhou	China	0.427 (22)	0.575 (15)
Klang	Malaysia	0.601 (14)	0.570 (16)
Busan	South Korea	0.592 (15)	0.554 (17)
Kaohsiung	Taiwan	0.656 (11)	0.543 (18)
Jawaharlal Nehru	India	0.556 (17)	0.536 (19)
Colombo	Sri Lanka	0.573 (16)	0.500 (20)
Tanjung Pelepas	Malaysia	0.538 (18)	0.400 (21)
Tanjung Priok	Indonesia	0.429 (21)	0.380 (22)
Dalian	China	0.432 (20)	0.368 (23)
Laem Chabang	Thailand	0.324 (27)	0.350 (24)
Valencia	Spain	0.333 (26)	0.323 (25)
Manila	Philippines	0.295 (28)	0.250 (26)
Nagoya	Japan	0.337 (25)	0.236 (27)
Yokohama	Japan	0.285 (29)	0.220 (28)
Tokyo	Japan	0.124 (30)	0.173 (29)
Los Angeles	USA	0.353 (24)	0.101 (30)

* Figures in the parenthesis indicate the ranking

CCR models. Some possible reasons behind these differences in efficiency performances are discussed in details in the next section.

DISCUSSIONS

Three interesting observations emerge from the DEA results in the preceding section. Firstly, there appears to be significant differences in performances among the seaports as illustrated from the efficiency scores ranging widely from 0.1 to 1. This finding is consistent with previous research on global seaports using DEA-CCR model (Tongzon 2001; Park and De 2004; Cullinane et al. 2002). Among the best three performers, the ports are each serving a different region. This points to the fact that port throughput are dependent on the traffic in the region, and capturing a large market share represents a key to efficient operation (possibly owing to the presence of scale economies).

Secondly, the set of fully efficient ports in the DEA-CCR model is different from that in the network DEA model: the ports of Singapore, Dubai and Antwerp are found to have an efficiency score of 1 when the traditional DEA-CCR model

is used for evaluation. However, none of these three ports is 100 percent efficient in the network DEA model. Several reasons can be used to explain these differences. When the traditional DEA-CCR model is applied, only the production process (provider's perspective) is considered. As a result, small infrastructural input value with large output value will result in relatively high efficiency scores. Meanwhile, additional factors come into play when the user's perspective is taken into account in the network-DEA model. Apart from port capacity, important considerations such as the accessibility of the port, port charges, geographical location of the port within the liner shipping network affect demand for the available port capacity and determine the utilization of the ports. In the case of Singapore and Antwerp ports, the aggressive strategy pursued by these ports has led to large investment in port capacity. With actual throughputs falling short of the planned port capacity, the Singapore and Antwerp ports report relatively lower efficiency scores in the network-DEA model against the traditional CCR model.

Under the network-DEA model, Hong Kong and Rotterdam are the only two ports deemed to be fully efficient. To some extent, the high port charges in Rotterdam and Hong Kong

may have ironically helped the ports to boost their efficiency score in the network-DEA model. Rotterdam and Hong Kong ports are gateway ports to the European and Northeast Asia regions. Shippers and liner companies that choose to use the ports perceive that value of port services is more than sufficient to offset the high port charges. Should the ports charge lower port dues, the demand for the port services may exceed the port capacity, leading to congestions and lower efficiency. Among all the ports in the sample, port of Hamburg is seen to increase its efficiency most tremendously under the network-DEA model. The port charges high port dues with a moderate level of GDP for its hinterland, which possibly indicates lower trade volume translating into lower throughput. As infrastructural prices are relatively high in Germany, restricting unwarranted port capacity provision may prove to be beneficial. Hence, the port of Hamburg received a higher efficiency score in the network-DEA model as compared to the DEA-CCR method (which emphasizes primarily on a large throughput).

More interestingly, it could be inferred that congestions in supply chains account for some of the differences observed in performance of ports. For instance, Antwerp port suffers quite a lot as the ring road is extremely congested when Rotterdam has developed a most beneficial strategy as regards the overcoming of this congestion. In other words, conditions of liner shipping 'sharing' the impact of 'number of shipping lines serving a port' is less significant in influencing port performance compared to the presence of congestions in supply chain.

Thirdly, ports reporting low efficiency scores under both the network-DEA and the DEA-CCR models generally fall into two categories. In the first category, the ports suffer from high infrastructural input prices and operating cost. The high cost that is passed onto the port users dampens the demand, and results in low actual throughput. As a consequence, the ports have been underutilized. Especially for the case of Tokyo port, the high port charges have driven users to other cheaper alternative ports. Given the suppressed demand, lower capacity may be more beneficial to the port. The second category consists of ports in developing countries (i.e., Laem Chabang in Thailand and Manila in Philippines). Technological hindrance may limit the handling capacity of the ports, and thus resulting in low efficiency scores.

In a nutshell, the network DEA model provides the port operators with an opportunity to find out the stage of the system where the inefficiency occurs. This can be done by calculating the efficiency of each stage of the system, in this case, the production process or the consumption process. If the former is inefficient, infrastructural and internal operational changes could be made to improve the corresponding process. Meanwhile, if the consumption process is inefficient, port operators should look at the factors influencing user's decisions on port selections and cater their port services to the needs of the users. However, this is likely to be more challenging as some factors may not modifiable, for instance, the location of the port.

CONCLUSIONS

Port operators and port users are partners for freight transportation in the maritime supply chain. As competitions in the port and maritime escalate, efficiency becomes a central issue to port operators and port users alike. However, definitions for "efficient services" often deviate, if not contradict, between these two parties. From the port operator's viewpoint, efficiency is achieved when the port is able to generate maximum service outputs at the least operating costs (Lee et al. 2005). Whereas according to the user, an efficient port is one that provides quality services such as

shortest handling time or minimum damages to the containers at reasonable charges (Murphy and Daley 1994). Therefore, an accurate assessment of port efficiency inexorably requires goals of the port operators and port users to be taken into consideration simultaneously.

This paper proposes a network-DEA model to evaluate the efficiencies of 30 major ports (spanning across Asia, Middle East, Europe and North America), which form an important pillar in global seaborne-freight transport. The proposed network DEA model is capable of capturing the intricate relationships between the provider and the consumer of the port services and integrating their goals in a single efficiency score for the evaluation of port services. The efficiency score will be high only if this relationship is adequately balanced: when the estimated port capacity (intermediate output) is greater than the actual throughput (final output), the port may be under-utilized due to factors adversely influencing the user's decisions; and when the estimated capacity is equal or smaller, the efficiency score may be still low and indicates that the demand for port services is higher than expected.

Our results show that the port of Hong Kong and Rotterdam are the most efficient port systems when the perspectives of both the providers and users are taken into account under the network DEA model. It is also meaningful to note that the network-DEA model and the traditional CCR-DEA model produce two sets of very different efficiency scores. While most of the CCR scores are higher than the corresponding network DEA efficiency, some ports such the ports of Salalah and Hamburg show significant increase in efficiency when using network-DEA model for evaluation. Hence, the concurrent consideration of efficiency scores from the network-DEA model and the traditional DEA-CCR model will offer valuable insights to port operators on how to improve the efficiency of the port (i.e., at which stage of the maritime supply chain that inefficiencies occur).

Admittedly, there have been some limitations in this study. Firstly, owing to the difficulty in accurate quantifications, technological supporting system that enhances the handling efficiency in ports to the same effect of larger infrastructural investment is not explicitly taken into account. Similarly, important measures of quality of port services such as vehicle loading and unloading service rates, vehicle turn-around time, berth and channel reliability (accessibility) are omitted due to the lack of data. Secondly, port charges are approximated using THC's (which is defined in Fung et al (2003) as fees charged by shipping lines and paid by shippers for moving containers between container terminals (or the shore) and ships). Such treatment is justified on the observation that the THC, in most cases, is proportional to the total port charge and thus it represents well this parameter. Thirdly, GDP of hinterland is used as a proxy for the trade volume in the region. This simplification is imposed because it is difficult to delineate the boundaries of the hinterlands, especially with the logistical developments that have led to their overlapping. Nonetheless, we recognize that trade volume of respective regions should be used instead.

For future research, it would be meaningful to extend this study to consider the negative externalities as an undesirable environmental output of the consumption process when measuring the performances of ports.

Acknowledgements

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Appendix A

Tab. A-1. Literature Taxonomy on Port Efficiency Studies

Reference	Sample	Method	Inputs	Outputs
Roll and Hayuth (1993)	20 hypothetical ports	DEA-CCR model	Manpower, capital, cargo uniformity	Cargo throughput, level of service, consumer satisfaction, ship calls
Liu (1995)	28 British port authorities, 1983-1990	Translog production function	Movement of freight	Turnover
Martinez Budria, Diaz Armas, Navarro Ibáñez and Ravello Mesa (1999)	26 Spanish ports, 1993-1997	DEA-BCC model	Labour costs, depreciation charges, other costs	Total cargo moved through docks, revenue obtained from rent of port facilities
Coto Millán, Baños Pino and Rodriguez Alvarez (2000)	27 Spanish ports, 1985-1989	Translog cost model	Cargo handled	Aggregate port output, including total goods moved and the passenger embarked and disembarked and the number of vehicles with passengers
Tongzon (2001)	4 Australian and 12 other international ports, 1996	DEA-CCR additive model	Number of cranes, container berths, tugs, terminal area, delay time, labour	Cargo throughput, ship working rate
Estache, Gonzalez and Trujillo (2001)	14 Mexican ports, 1996-1999	Translog and Cobb-Douglas production frontier model	Containers handled	Volume of merchandise handled
Cullinane, Song and Gray (2002)	15 Asian container ports, 1989-1998	Stochastic Cobb-Douglas production frontier: half normal, exponential, truncated models	Number of employees	Annual container throughput
Itoh (2002)	8 Japanese ports, 1990-1999	DEA-CCR and BCC with window application	Port infrastructure, port superstructure, labour	Total annual container throughput
Cullinane and Song (2003)	5 container terminals in Korea and UK, 1998	Stochastic Cobb-Douglas production frontier: half normal, exponential, truncated models	Fixed capital	Turnover derived from the provision of container terminal services, excluding property sales
Barros (2003a)	5 Portuguese ports, 1990-2000	DEA -allocative and Technical efficiency	Number of employees, book value of assets	Ships, movement of freight, gross tonnage, market share, break-bulk cargo, containerized cargo, dry bulk, liquid bulk, net income prices,
Barros (2003b)	10 Portuguese ports, 1990-2000	DEA-Malmquist index and a Tobit model	Number of employees, book value of assets	Ships, , movement of freight, break-bulk cargo, containerized cargo, dry bulk, liquid bulk
Park and De (2004)	11 Korean ports, 1999	DEA-CCR and BCC model	Berthing capacity and cargo handling	Cargo throughputs, number of ship calls, revenue and consumer satisfaction

Reference	Sample	Method	Inputs	Outputs
Barros and Athanassiou (2004)	2 Greek and 4 Portuguese ports	DEA-CCR and BCC model	Labour and capital	Number of ships, movement of freight, cargo handled, container handled
Bonilla, Casaus et al. (2004)	23 Spanish ports, 1995-1998	CCR, BCC and Imprecise DEA	General available equipment	Total liquid, breakbulk and general commodities cargo in Ktons
Turner, Windle et al. (2004)	36 continental US and Canadian container ports, 1984-1997	DEA-CCR with Tobit regression on industry structure, port authority conduct, ocean carrier conduct, situational factors and control variables	Total terminal area, number of quayside gantry cranes, berth length	Container throughput
Cullinane, Song and Wang (2005)	57 international container ports, 1999	DEA-CCR, DEA-BCC and DEA-FHD models	Terminal length, terminal area, quayside gantry, yard gantry and straddle carries	Container throughput
Tongzon and Heng (2005)	25 international container ports	Stochastic Cobb-Douglas model and a competitiveness regression, with restriction to the frontier equation	Terminal quay length, number of quay cranes, port size	Container throughput
Barros (2005)	10 Portuguese ports, 1990-2000	Stochastic translog cost frontier	Price of labour, price of capital, ships, cargo, trend	Total costs
Cuillinane, Wang, Song and Ji (2006)	28 international container ports, 1983-1990	Stochastic Cobb-Douglas and DEA model	Terminal length, terminal area, quayside gantry, yard gantry and straddle carries	Annual container throughput
Cuillinane and Wang (2006)	69 European container ports, 2002	Output oriented DEA-CCR and DEA-BCC	Quay length, terminal area, number of equipment	Annual container throughput
Cuillinane and Wang (2006)	104 European container ports	Output oriented DEA-CCR and DEA-BCC with Tobit regression	Quay length, terminal area and equipment cost	Annual container throughput
Fu, Song et al. (2007)	10 China ports	DEA based evaluation of Malmquist Productivity Index with PCA	Number of berths, quay length, yard area, number of gantry cranes, GDP of hinterland, value of second industry of hinterland	Annual container throughput, number of shipping lanes, number of liner ships calls
Liu (2008)	10 ports in Asia Pacific	DEA-CCR, DEA-BCC and 3-stage DEA model	Container lot size, number of bridge cranes, deepwater berths, length of berth	Annual container throughput, number of port calls
Herrera and Pang (2008)	82 international container ports	DEA-CCR, DEA-BCC and FDH model	Land, equipment	Annual container throughput

Reference	Sample	Method	Inputs	Outputs
Sharma and Yu (2009)	70 international container terminals	DEA-CCR and DEA-BCC with Kohonen's self-organizing maps for performance clustering	Quay length, terminal area, number of quay cranes, yard cranes, straddle carriers and stacker vehicles	Annual container throughput
Low (2010)	23 major Asian ports, 2008	CCR, BCC, Slack-based measure, congestion, measure specific	the number of gantry cranes, terminal area, quay length and draft	Annual container throughput, tons of bulk cargo and the number of ship calls
Chin and Low (2010)	13 Asian ports, 2009	CCR, BCC, Slack-based measure models	Frequency of shipping services, Bilateral trade flows	Annual container capacity flows between ports, nitrogen oxide, sulphur, carbon dioxide, and particulate emissions

Appendix B: Port Data

	Singapore	Shanghai	Hong Kong	Shenzhen	Busan	Dubai	Ningbo	Guangzhou	Qingdao	Kaohsiung
Terminal Area (m2)	3890000	8569837	2794500	3550800	2799300	1621050	1957000	4650000	836800	1821374
Quay length (m)	10754	8956	8841	8923	11835	6263	4138	5219	5449	6714
Storage Capacity (TEU)	300000	420084	255238	223217	230523	101876	127045	292805	117872	90584
Number of berths	44	30	25	12	11	10	19	16	26	19
Total Slot Capacity (TEU)	3495215	4882737	4606177	2219426	2426863	1437928	3677906	1395068	3868143	2143715
Total Ships Deployed	927	1123	1017	510	634	335	846	321	889	514
No. of Shipping Lines	88	77	80	35	81	13	58	22	61	58
Expected Port Capacity (TEU) 2008	35000000	34000000	19000000	20000000	15000000	15000000	11000000	11500000	15000000	10200000
THC Dry20' (\$)	133.8	58.6	270.3	150.0	90.4	175.6	58.6	150.0	58.6	166.7
GDP 2008 (\$bn)	215.0	233.0	320.0	114.3	121.0	80.0	58.1	143.0	65.0	45.0
Throughput (TEU) 2008	29918200	27980000	24248000	21413888	13425000	11827299	11226000	11001300	10320000	9676554

	Tianjin	Port Klang	anjung Pelepa	Laem Chabang	Xiamen	Dalian	Tanjung Priok	Jawaharlal Nehru	Colombo	Yokohama
Terminal Area (m2)	1292400	1736300	1200000	2445800	1065000	1648579	1656000	1208400	672300	2388922
Quay length (m)	3472	5279	5140	5600	2753	3536	3192	2437	2886	6000
Storage Capacity (TEU)	138350	120800	200000	161150	129387	124468	119140	93500	62320	124062
Number of berths	12	21	6	27	6	11	14	7	10	18
Total Slot Capacity (TEU)	1014595	2557643	557435	488257	1648716	3107196	179113	846573	980245	1766131
Total Ships Deployed	233	630	137	207	379	714	154	306	241	540
No. of Shipping Lines	16	78	17	48	26	49	41	46	53	68
Expected Port Capacity (TEU) 2008	8500000	7740000	8000000	11000000	5034600	4502700	3500000	4,400,000	5300000	3481485
THC Dry20' (\$)	54.2	101.8	66.9	78.3	58.6	60.1	120.0	88.6	151.0	324.2
GDP 2008 (\$bn)	74.0	361.2	361.2	273.0	22.9	56.5	92.0	164.0	39.6	271.0
Throughput (TEU) 2008	8500000	7970000	5,600,000	5133930	5034600	4502700	3984278	3,952,735	3687465	3481485

	Tokyo	Salalah	Manila	Nagoya	Rotterdam	Hamburg	Los Angeles	New York	Antwerp	Valencia
Terminal Area (m2)	1883150	765000	1821980	1511475	6881600	5384000	6477336	5566100	7434073	1612300
Quay length (m)	5179	2205	3556	4105	4900	5700	3302	3615	2000	3675
Storage Capacity (TEU)	285020	58090	59821	72922	81000	149600	104006	48323	196988	88046
Number of berths	13		54	13	25	35	25	36	33	5
Total Slot Capacity (TEU)	1298626	850173	117651	1480434	1580000	2200000	1397400	1146080	970000	780000
Total Ships Deployed	397	159	81	453	305	106	200	180	121	98
No. of Shipping Lines	50	16	30	57	32	90	76	24	30	19
Expected Port Capacity (TEU) 2008	3700000	6000000	1500000	2500000	13000000	12000000	8400000	5300000	15000000	3500000
THC Dry20' (\$)	324.2	75.0	110.0	324.2	219.6	260.8	198.0	198.0	178.4	206.6
GDP 2008 (\$bn)	1479.0	68.3	149.0	297.5	877.0	118.2	792.0	1144.0	390.5	141.1
Throughput (TEU) 2008	3083266	3068000	2977606	2816827	10783825	9737000	8081000	5300000	8663000	3042665

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Integrating truck arrival management into tactical operation planning at container terminals

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ABSTRACT

Truck arrival management (TAM) has been recognized as an effective solution to alleviate the gate congestion at container terminals. To further utilize TAM in improving the overall terminal performance, this study integrates TAM with the other terminal operations at a tactical level. An integrated planning model and a sequential planning model are presented to coordinate the major terminal planning activities, including quayside berth allocation, yard storage space allocation and TAM. A heuristic-based genetic algorithm is developed to solve the models. A range of numerical examinations are performed to compare two planning models. The result shows that: the integrated model can improve the terminal performance significantly from the sequential model alone, particularly when the gate capacity and the yard capacity are relatively low; whereas the sequential model is more efficient than the integrated model in terms of computational time.

Keywords: container terminal; integrated planning; truck arrival management; berth allocation; storage space allocation

INTRODUCTION

As an intermodal interface, marine container terminals serve vessels on the sea side and trucks/trains on the land side. Operating a container terminal involves many different decisions and they often interact with each other. Due to the multi-criteria nature, the complexity of operations, and the size of the operations management problem, it is extremely difficult to make the optimal decisions for the entire terminal system (Zhang *et al.*, 2003). Traditionally, the whole system is decomposed into a set of sub-planning problems of manageable complexity. The sub-problems may be solved in a sequential fashion, in which the output of one sub-problem is treated as the input of another sub-problem. This sequential solution enables a clear hierarchy of decision making, but on the other hand, ignores the interrelations between the sub-problems and often leads to plans of poor overall quality (Bierwirth and Meisel, 2010). In order to find better planning decisions, it is necessary to integrate some of the sub-planning problems and optimize them simultaneously at a reasonable planning level, as mentioned by Stahlbock and Voss (2008) that “improved terminal performance cannot necessarily be obtained by solving isolated problems but by an integration of various operations connected to each other.”

Many container terminals in Asia have a typical layout as shown in Fig. 1, which consists of three parts: the seaside

area, the yard storage area and the landside area. The seaside area is the place where vessels are berthed and operated by quay cranes. The landside area, also called gate house, is the entrance and exit place for external trucks (XTs). Between the seaside and the landside areas is the storage yard, which stores inbound (I/B) and outbound (O/B) containers temporarily because there are time differences between vessel arrivals and land-carrier arrivals (Meisel, 2009). Typically the yard is divided into several blocks, which are laid out in parallel to

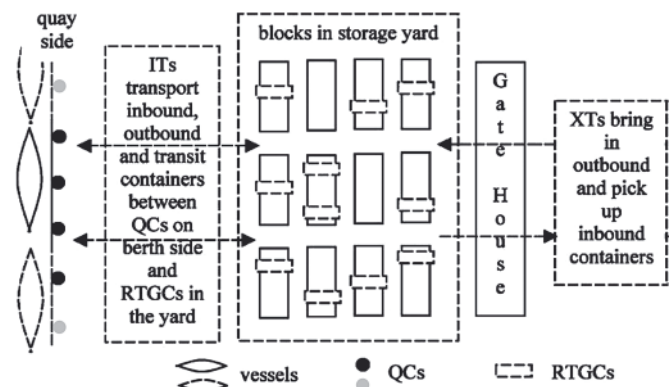


Fig. 1. A schematic diagram of a container terminal
(Source: Zhang *et al.*, 2003)

the quay. The blocks are usually separated into two parts: the one on the seaside is for O/B containers and the other on the landside is for I/B containers.

In a container terminal, all the operations are originally triggered by the vessel arrival process, including O/B container deliveries, vessel unloading/loading operations and I/B container pickups. Before a vessel arrives, the O/B containers are delivered into the terminal by XTs. An XT has to go through the gate check and then drives the container to the appointed block, where a yard crane (YCs) will unload the container from the truck and stack it onto the block. When the vessel is berthed, the quay cranes (QCs) discharge I/B containers from the vessel and load them on internal trucks (ITs). ITs provide transportation of containers between the QCs and the storage yard. After the unloading process, the QCs start to load the vessel with the O/B containers that have already been in the yard. When both unloading and loading operations are finished, the vessel departs and the storage space previously occupied by the O/B containers is released for future arriving O/B containers. Meanwhile XTs start to pick up the I/B containers and deliver to customers.

The above terminal operations give rise to a series of operation planning problems at different levels, including berth allocation problem (BAP), QCs assignment, QCs scheduling, storage space allocation problem (SSAP), container location planning, YCs assignment, YCs scheduling, horizontal transport scheduling in yard, workforce management and gate management. Among the above, BAP, SSAP and gate management are the major planning activities dealing with the space usage of a container terminal. BAP is to determine berthing location and time for arriving vessels, and SSAP is to allocate storage space to each vessel for future arriving containers, with an aim to utilize terminal space efficiently and to make loading/unloading operations more efficiently.

Gate management generally facilitates truck entries into a terminal. At the major seaports long XTs queues occur very often at gate, which generate heavy air pollution and limit the terminal efficiency. To alleviate the gate congestion, terminal operators try two measures: reducing truck service time and managing XTs arrivals. Truck service time mainly depends on gate capacity and the number of yard cranes. Due to the high cost of yard cranes and the scarce land for gate capacity extension, it is not always possible to effectively reduce truck service time. Therefore truck arrival management (TAM) is receiving more and more attention. TAM tries to match the demand with the supply of XTs service by managing the truck arrival rate. There are different ways to do TAM, for example terminal appointment system, tariff and vessel dependent time windows (VDTWs). In a gate appointment system, the terminal operator announces the gate opening hours and hourly entry quotas through a web-based information system, and then the XTs make entry appointments in the information system. Tariff is also an effective method to move some traffic to non-peak times by charging higher entrance fees for peak time entries. Chen *et al.* (2011a) propose a two phase approach to find a desirable pattern of time varying tolls that leads to optimal XTs arrival pattern, by combining a fluid based queuing model and a toll pricing model. VDTWs involve partitioning truck arrivals into groups and assigning different time windows to the groups. The XTs entries related to a same vessel are grouped to share one specified time window. VDTWs are implemented in some terminals in Northern China, especially those having limited storage space because VDTWs is originally used to speed up container turnover. This paper focuses on VDTWs and its integration with other major terminal operation planning activities.

In order to better manage the space usage of container terminals, it is important to conduct all the three major planning activities, BAP, SSAP and TAM, in an integrated way. Since TAM is a relatively new topic in terminal operation research, the following interesting research questions arise: 1) How to integrate TAM with the other planning activities? 2) How to solve the integrated planning model? 3) In what situations the integration is more beneficial or less beneficial? The third question is based on the fact that the integrated model is more complicated and more difficult to solve, e.g. it may require more data and computational effort. This study tries to address these questions by developing an integrated planning model at the tactical level, covering BAP, SSAP and TAM. The tactical level is chosen for two reasons. First, tactical planning focuses on the space usage of a terminal over a medium term planning horizon, which represents a roll-over dynamic interval and provides a scheduling guidance for short-term operational activities. Second, tactical planning involves only a few major sub-planning problems, so the complexity of integration is manageable. In this study, the proposed integrated planning model takes the terminals in northern China as a prototype, where VDTWs is implemented to do TAM. To solve the proposed model, we develop a heuristics-based Genetic Algorithm (GA). Numerical experiments are conducted to compare the integrated planning model with its corresponding sequential planning model, in which the tactical BAP, SSAP and TAM are solved in a sequential fashion.

Our main contributions include: (i) we propose two models to coordinate three major planning activities for container terminal management at the tactical level including BAP, SSAP, and TAM. The first model is an integrated planning model which considers the two-way interactions between these planning activities. The second model is a sequential planning model, which is a natural development from traditional separate models; (ii) we develop heuristics-based GA algorithm to seek the solutions to two models so that the problem can be solved fairly efficiently; (iii) in the range of our experiments, it is found that the integrated model performs significantly better than the sequential model alone especially when the gate capacity and the yard capacity are relatively low; whereas the sequential model may fail to find a feasible solution; however, the sequential model has the advantage of much less computational time; (iv) our model can also be used to identify the lower and upper bounds of the yard capacity and the gate capacity for a given scenario.

LITERATURE REVIEW

There is a rich literature in the area of marine container terminal modelling. A few comprehensive reviews on terminal related operations research have been conducted, e.g. Stahlbock and Voss (2008), Steenken *et al.* (2004) and Vis and Koster (2003). Here, we only review the existing studies related to BAP, SSAP, TAM and their integration at the tactical planning level.

BAP is one of the most frequently addressed topics in the literature on container terminals. There are two main categories of BAP: the discrete operational BAP (Imai *et al.*, 2001; 2003; Cordeau *et al.*, 2005), and the continuous operational BAP (Imai *et al.*, 2005; Guan and Cheung, 2004). Very few studies have been conducted on the tactical BAP problem. Moorthy and Teo (2006) address a continuous BAP problem at the tactical level, i.e. berth template design, which arises in transshipment container terminals. The problem concerns the allocation of favourite berthing locations (home berths) to vessels that call at the terminal based on a weekly schedule.

Two procedures are proposed to build good and robust templates, which are then evaluated via numerical simulations. Ganji *et al.* (2010) propose a GA-based algorithm to solve continuous BAP problem. Giallombardo *et al.* (2010) integrate the discrete BAP problem and the quay crane assignment problem in transshipment container terminals at a tactical level. The objective is to maximize the quay crane utilization and minimize the container housekeeping costs. The problem is solved by a heuristic algorithm which combines Tabu search methods and mathematical programming techniques. To solve the discrete BAP more efficiently, de Oliveira *et al.* (2012) propose a hybrid Clustering Search method, which is found faster than the existing methods in the literature.

SSAP is another well addressed terminal operation planning problem. Regarding the SSAP for O/B containers, Taleb-Ibrahimi *et al.* (1993) propose some methods to estimate the average space requirement and suggest a strategy of providing a temporary storage area for the containers that arrive before a designated storage space has been allocated for them. Zhang *et al.* (2003) consider the SSAP problem under the complex storage policy, which means I/B, O/B and transshipment containers are mixed at the block level. They attempt to balance the workload among different blocks to avoid possible bottlenecks in terminal operations. Kim and Park (2003) propose two heuristic algorithms to solve the SSAP for O/B containers based on the duration-of-stay of containers and the sub-gradient optimization, respectively. Lee *et al.* (2007) propose a yard space allocation method for a transshipment hub port. They present an algorithm for assigning parts of blocks (called sub-blocks) to containers that are to be loaded (discharged) onto (from) a same vessel so as to minimize the congestion during the vessel handling operations. Bazzazi *et al.* (2009) propose a GA algorithm for a SSAP problem that is similar to the one in Zhang *et al.* (2003), aiming to minimize the variation in the handling workload across various blocks. Woo and Kim (2011) develop a method to determine the size of the storage space for O/B containers in the initial stage of constructing container terminals. Chen and Lu (2010) propose a two stage method to solve the storage location assignment problem for O/B containers. Regarding the SSAP for I/B containers, Kim and Kim (1999) propose mathematical models and solution procedures to optimally allocate storage space in the segregation strategy, with the aim of minimizing the expected total number of rehandles.

As mentioned previously, there are three common ways to handle TAM, i.e. terminal appointment system, tariff, and VDTWs. Here we only review the studies related to the VDTWs method. These studies mainly focus on two problems: truck arrival estimation and queue length estimation. Regarding the truck arrival estimation problem, Yang *et al.* (2010) analyze empirical data from a Chinese port where VDTW is employed, and find that truck arrivals for O/B container drop-offs within a specific time window basically follow a Beta distribution. This finding makes it possible to predict truck arrivals at a terminal based on gate time window assignment for truck entries. Thereafter Chen and Yang (2010) address the time windows assignment problem to spread out the truck arrival peaks and develop a Genetic Algorithm to solve the problem. Regarding the queue length estimation problem, an empirical study, Guan and Liu (2009), finds that the gate service times follow an Erlang distribution with a parameter of four. Chen *et al.* (2011b) develop a non-stationary Exponential-Erlang queueing model to analyze a queueing system with Poisson arrival process and Erlang service process. Chen *et al.* (2011c) find that although the above queueing model may not theoretically match the VDTWs truck queueing system in terms of customer arrival

process, it is practically acceptable to use the model to analyze such a system under the VDTWs control.

There have been a few studies addressing the integration of planning activities in container terminals. According to Geoffrion (1999), integration can be done either by a deep integration or by a functional integration. A functional integration is realized by a computational agenda that defines a sequence of sub-problems and the feedback loops between the sub-problems. Deep integration merges two sub-problems into a partial monolithic problem formulation (Bierwirth and Meisel, 2010). Deep integration has been widely used to merge BAP and QCs assignment into an integrated planning model. It was firstly introduced by Park and Kim (2003) and further investigated by Meisel and Bierwirth (2005), Imai *et al.* (2008), Giallombardo *et al.* (2010), Han *et al.* (2010) and Chang *et al.* (2010). For a comprehensive survey on this topic, we refer to Bierwirth and Meisel (2010).

An increasing number of tactical planning researches on terminal operations appeared in the last several years. Tactical planning deals with medium-term planning issues and provides an input to the operational planning phase. Cordeau *et al.* (2007) address the service allocation problem, a tactical problem arising in the yard management of a container transshipment terminal. They define a service as the sequence of ports visited by a vessel, where shipping companies usually ask for a dedicated specific yard area and a specific berth from a terminal. The objective is to minimize the volume of container rehandling operations inside terminal yards by optimizing the home berth for each service. The above mentioned Giallombardo *et al.* (2010) and Moorthy and Teo (2006) are the other existing studies on tactical terminal planning.

From the above literature review, it can be seen that the existing studies of integrated terminal planning focus on the seaside operations, for example combining the BAP and the SSAP problems. Moreover, most of these existing integration studies are conducted at the operational level, and only a few are at the tactical level. Because TAM is a relatively new topic in terminal operation research, to the best of our knowledge, there is no published research on integrating the TAM problem with the other planning problems. This paper tries to fill this gap.

PROBLEM FORMULATION AND MATHEMATICAL MODEL

Problem Formulation

For the tactical terminal operation planning, vessel arrival times and handling volumes are known to terminal operators from the negotiation with shipping lines. To utilize terminal space and resources, a terminal operator makes tactical decisions on the following issues: BAP, SSAP and TAM. According to the classification in Bierwirth and Meisel (2010), the BAP problem in this study is a discrete and dynamic one. The berth handling efficiency is assumed to depend on berth location, rather than the number of assigned quay cranes. In the terminal yard, the storage blocks are separated into zones, with around six or eight blocks in one zone. Each berth has an O/B and an I/B container zones in equal size lying parallel to it. The SSAP for O/B container storage is solved at the storage zone level, following the 'nearest location principle' proposed by Woo and Kim (2011), which requires 'the spaces that are assigned to a container vessel should be located as near as possible to the berthing position of the corresponding vessel'. The TAM for O/B containers adopts the VDTWs mechanism. At the gate, XTs are served on the principle of 'first come, first served' (FCFS).

For simplicity, this study focuses on the O/B operations in these issues. The interaction between the O/B and the I/B operations is insignificant and can be neglected at the tactical operation planning level, because the two types of containers are operated either in separate spaces and/or during separate time periods. The objective of the tactical planning is to minimize of total vessel turn-around time in the planning horizon, which includes vessel waiting time for available berth, handling time and extra waiting time caused by gate congestion. There are some assumptions as below:

1. Both terminals and trucking companies provide 24×7 service, which is the case in China;
2. Each berth can service one vessel at a time without any physical or technical restrictions such as vessel draft and water depth;
3. Once moored, a vessel will remain in its location until all the handling is done, because it is costly to interrupt vessel handling process in practice;
4. Vessel handling time depends on the handling volume of the vessel and the handling efficiency of the assigned berth, as well as the distance between the vessel berthing location and the container storage location;
5. SSAP problem is solved at the storage zone level, and the container location problem is not under consideration in this tactical operation planning.
6. Yard equipments are sufficient and will not affect the gate capacity and the quay capacity. In other words, yard handlings are not considered in this model.

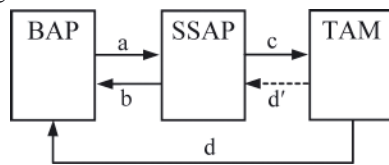


Fig. 2. The structure of the integrated tactical planning model

Based on the above description and assumptions, we develop an integrated tactical operation planning model by combining BAP, SSAP and TAM problems with the deep integration approach. A key issue of the deep integration approach is to identify the interrelations between the sub-problems. Fig. 2 shows the interrelations between BAP, SSAP and TAM in our integrated model. Interrelation ‘a’ represents that, when a vessel gets an assigned berthing time and location, SSAP is triggered to allocate storage space to the O/B containers. The output of BAP is the input of SSAP. Interrelation ‘b’ represents that, the distance between the container storage location and the vessel berthing location influences on vessel handling time and hence the BAP plan. Interrelation ‘c’ represents that, when a storage space is assigned to a vessel, TAM is triggered to find a suitable time window from the available period of the storage space for the XTs entries. Interrelation ‘d’ can be linked to either BAP or SSAP. If linking to BAP, it represents the case that a vessel departs only after all the handling is completed, meaning the gate congestion directly leads to vessel handling delay. If linking to SSAP, as shown by the dashed arrow ‘d’’, it represents the case that a vessel always departs on schedule leaving the late containers in the yard for future pickup by a vessel (usually at next week), which means the gate congestion leads to longer container storage time. Both cases could happen in reality; we study the first one in this paper.

Integrated planning VS sequential planning

In this section, we use a simple example to illustrate the benefit of the integrated planning versus the sequential planning. For simplicity, the example focuses on the interrelation between

BAP and TAM. Suppose at one berth in a container terminal, there are two ships arriving at the same time (at hour 20), which raise a question of the berthing sequence. The berth is free when the ships arrive. Ship A will load 2,000 TEU from the terminal, and ship B will load 1,500 TEU. The available gate capacity is shown in Fig. 3: it increases from 0 to 200 truck/hour at hour 10, and decreases to 75 truck/hour at hour 20. The gate operation is managed with the VDTWs method, in which the terminal operator uses time windows to control truck arrivals. To make this example as small as possible, we make the following assumptions:

- Both ships have no unloading operations, i.e. no I/B container operations.
- The berth handling efficiency is 100TEU per hour.
- There is sufficient storage space in the yard, so no need to consider SSAP problem.
- The O/B container arrivals will distribute evenly in a given time window, so the arrival process is not stochastic but deterministic. This means the truck queueing time can be estimated by simple fluid model, and there is no need for any queueing model.
- The time window for the trucks serving a ship will be closed when the ship arrives.

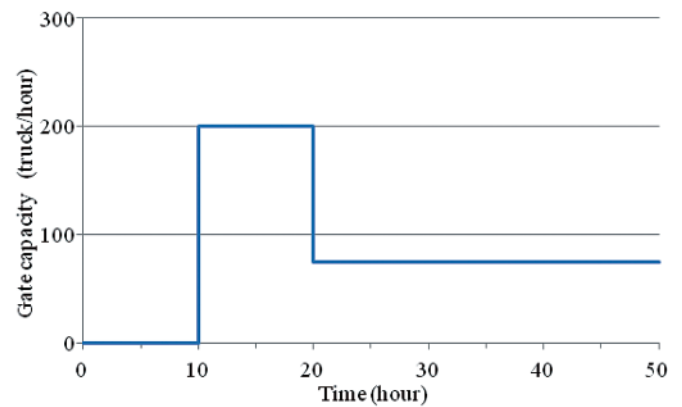


Fig. 3. The available gate capacity at the terminal

Since the SSAP is not considered, the solution for this example problem includes a berthing sequence and the starting points of the time windows for truck entries. This problem can be solved by either sequential planning or integrated planning. Sequential planning consist two steps, i.e. first, deciding on the berthing sequence, with the aim of minimizing the total ship waiting time, and second, deciding on the time window setting, with the aim of minimizing the total truck waiting time. The integrated planning solves the two problems simultaneously, aiming to minimize the total ship waiting time.

Sequential planning approach

The result of sequential planning is shown in Table 1. The procedure is described briefly here. The first step is to decide on the berthing sequence: obviously, putting ship B on berth before ship A, will lead to 15 hours ship waiting time, which is 5 hours less than putting ship A before ship B. Please note that this step does not consider the ship operation delay caused by gate congestion. The SSAP problem is skipped, because of sufficient storage space. Next step is to decide on the starting point of time windows: the best solution is to set both at hour 10, which means the time windows for ship A and B are [10, 35] and [10, 20] respectively. In such a solution, the total truck waiting time is 7,500 hours. The truck queue is presented in Fig. 4. Due to the delay of the last O/B container (which will cause the ship departure delay of the same time length), the ship

Tab. 1. The solutions of the sequential and the integrated planning

	Berthing sequence	Time windows	Total ship waiting	Total truck waiting
Sequential planning	B, A	[10, 35] for ship A [10, 20] for ship B	24 hours	7,500 hours
Integrated planning	A, B	[10, 20] for ship A [20, 40] for ship B	20 hours	0 hour

A will be delayed for 4 hours and the ship B will be delayed for 5 hours. So in total, the ship waiting time is 24 hours.

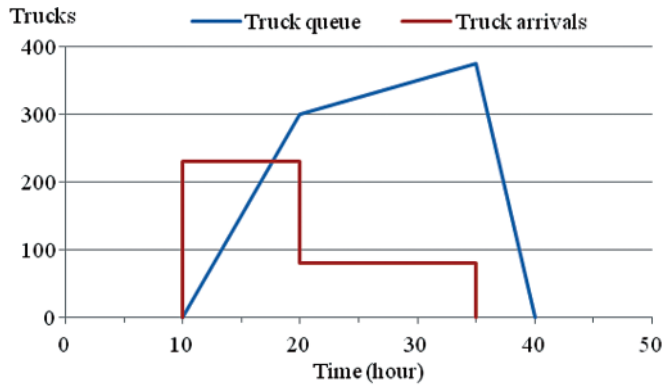


Fig. 4. The truck arrivals and queues at the terminal gate

Integrated planning approach

The result of integrated planning is also shown in Table 1. The best solution is: putting ship A on berth before ship B, and setting the time windows as [10, 20] and [20, 40] respectively. In this solution, the total ship waiting time is 20 hours, while the total truck waiting time is 0 because the gate capacity just fits with the truck arrival pattern.

Comparing the above results, we can see that the sequential planning misses the best solution due to the neglect of the interrelation between truck congestion and ship delay. While the integrated solution find the best solution, because it takes the interrelation into consideration.

Integrated Planning Model

In this section we present the integrated tactical planning model of terminal operations. All the input data, derived variables and decision variables are introduced first:

Input variables	
I	The set of vessels in the planning horizon (i.e. a week in this paper);
J	The set of berths;
K	The set of storage zones;
P	The maximum time step (e.g. in hours) in the planning horizon;
t	The time step in the planning horizon, $1 \leq t \leq P$;
A_i	The arrival time of vessel i ;
V_i	The handling volume of vessel i (TEU);
r_i	The ratio of loading volume over the total handling volume of vessel i ;
B_k	The storage space of storage zone k (TEU);
G	The total gate processing rate (trucks/hour);
H_j	The handling efficiency of berth j (TEU/hour);
β	The truck modal split for the container deliveries in the terminal;
fM_1	The average loading factor of a truck (TEU);
M_2	The average vessel mooring time;
d_{jk}	The minimum length of a time window;
Derived variables	The distance between berth j and storage zone k ;
T_i^C	
z_i^w	The handling completion time and the departure time of vessel i ;
z_i^h	
e_{ti}	The waiting time of vessel i (hour);
d_j	The handling time of vessel i (hour);
N_t	1 if the time step t is within the period $[T_i^S, T_i^C]$, otherwise 0;
p_{it}	The distance between berth j and the nearest storage zone, $d_j = \min(d_{jk})$;
q_t	The number of trucks that arrive at time step t ;
w_t	The probability of a truck related to vessel i arriving at time step t ;
T_i^E	The estimated queue length at the gate at time step t ;
	The estimated waiting time of the trucks arriving at time step t (hour);
Decision variables	
x_{ij}	The ending point of the time window assigned to vessel i for truck entries;
s_{mi}^j	
y_{ik}	1 if vessel i is assigned to berth j , otherwise 0;
T_i^S	1 if vessel i is scheduled as the successor of vessel m at berth j , otherwise 0;
	1 if the containers of vessel i are stored in zone k , otherwise 0;
	The starting point of the time window assigned to vessel i for truck entries.

The objective of the integrated planning problem is to minimize the total waiting and handling time of all vessels in the planning horizon as follows:

$$\min Z = \sum_{i \in I} (z_i^w + z_i^h) \quad (1)$$

Subject to:

$$z_i^h = \sum_{j \in J} \sum_{k \in K} x_{ij} y_{ik} \left(M_1 + \frac{d_{jk}}{d_j} \times \frac{V_i}{H_j} \right) \quad \forall i \in I \quad (2)$$

$$z_i^w = \max \left(0, \sum_{j \in J} \sum_{m \in I} x_{ij} s_{mi}^j T_m^C - A_i \right) + w_{T_i^E} \quad \forall i \in I \quad (3)$$

$$T_i^C = A_i + z_i^w + z_i^h \quad \forall i \in I \quad (4)$$

$$T_i^E = A_i + z_i^w - w_{T_i^E} \quad \forall i \in I \quad (5)$$

$$w_t = \frac{q_t + q_{t-1}}{2 \times G} \quad 1 \leq t \leq P \quad (6)$$

$$q_t = B - \text{PSFFA}(q_{t-1}, N_t, G) \quad 1 \leq t \leq P \quad (7)$$

$$N_t = \sum_{i \in I} \frac{p_{it} V_i r_i \beta}{f} \quad 1 \leq t \leq P \quad (8)$$

$$p_{it} = \begin{cases} \frac{\int_a^b u^{0.29} (1-u)^{2.25} du}{\int_b^l u^{0.29} (1-u)^{2.25} du} & \text{if } a < b < l \\ 0 & \text{otherwise} \end{cases}$$

where:

$$a = \frac{t - T_i^S}{T_i^E - T_i^S}, b = \frac{t - T_i^S + 1}{T_i^E - T_i^S} \quad (9)$$

if:

$$t \in [T_i^S, T_i^E] \quad \forall i \in I, 1 \leq t \leq P$$

others

$$\sum_{i \in I} x_{ij} z_i^h \leq P \quad \forall j \in J \quad (10)$$

$$\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I \quad (11)$$

$$\sum_{m \in I} s_{mi}^j \leq 1 \quad \forall i \in I, \forall j \in J \quad (12)$$

$$\sum_{m \in I} \sum_{i \in I} s_{mi}^j = \sum_{i \in I} x_{ij} - 1 \quad \forall j \in J \quad (13)$$

$$\sum_{t=1}^P e_{ti} = T_i^C - T_i^S \quad \forall i \in I \quad (14)$$

$$\sum_{i \in I} y_{ik} V_i r_i e_{ti} \leq B_k \quad \forall k \in K, 1 \leq t \leq P \quad (15)$$

$$\sum_{k \in K} y_{ik} = 1 \quad \forall i \in I \quad (16)$$

$$T_i^C - P \leq T_i^S \leq T_i^E - \max \left(M_2, \frac{V_i r_i}{fG} \right) \quad \forall i \in I \quad (17)$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in I, \forall j \in J \quad (18)$$

$$s_{mi}^j \in \{0, 1\} \quad \forall i \in I, \forall m \in I, \forall j \in J \quad (19)$$

$$y_{ik} \in \{0, 1\} \quad \forall i \in I, \forall k \in K \quad (20)$$

$$e_{ti} \in \{0, 1\} \quad \forall i \in I, 1 \leq t \leq P \quad (21)$$

Equation (2) calculates the handling time of vessel i at berth j when the containers are stored in the storage area k , here M_1 is the mooring time of a vessel. Equation (3) calculates the waiting time due to terminal gate congestion ($w_{T_i^E}$) and the waiting time of vessel i for the availability of the assigned berth. Equation (4) calculates the expected handling completion time of vessel i , considering the influence of yard operations and gate congestion. Equation (5) calculates the ending point of gate time window i . Note it is assumed that the time window assignment will not be influenced by the vessel delays caused by gate congestion; otherwise it will become a circular cause and consequence. Equation (6) calculates the average waiting time of the trucks arriving at time step t . Equation (7) calculates the queue length at gate at time step t with the non-stationary queueing model proposed by Chen et al. (2011b), for simplicity here we quote the queueing model with its name 'B-PSFFA' instead of its complicated equations. Equation (8) calculates the number of trucks arriving at terminal gate at time step t . Based on the Beta distribution from Yang et al. (2010), Equation (9) calculates the probability of a truck related to vessel i arriving at the terminal gate at time step t .

Constraint (10) ensures that the total handling workload (hours) of each berth will not exceed the berth service capacity. Constraint (11) ensures every vessel must be served at some berth. Constraints (12) and (13) represent that in the berth plan any vessel has at most one immediate successor, and the total number of such succession relations at one berth equals to the number of vessels minus one. Constraint (14) ensures that every vessel gets a storage space reserved for its containers from the beginning of the time window to the vessel handling completion. Constraint (15) ensures that, at any time step, the storage demand in any storage zone does not exceed the storage capacity. Constraint (16) ensures that the storage space reserved for a vessel must be in one storage zone. Constraint (17) means that each time window must be long enough for the related trucks to enter the gate and also not shorter than the minimum time window length, meanwhile the starting point should not be earlier than the vessel handling completion time in the previous planning period according to practical experience.

ALGORITHM SOLUTION

Solving the integrated planning problem in (1)~(21) is complicated and difficult, because four sets of decisions have to be optimized simultaneously, including berthing position of each vessel, the vessels' berthing sequence, yard storage space allocation to each vessel, and time window assignments for XT's entries. This optimization model is a nonlinear integer problem, which is NP-hard. To compromise the computational complexity with the solution quality, we propose a heuristic-based GA to solve the integrated planning model. The GA part in the algorithm is used to simultaneously optimize the vessel berthing positions and time window assignment for

XTs entries, i.e. x_{ij} and T_i^S . The heuristic part consists of two heuristic rules (denoted as A and B). Given a profile of x_{ij} from the GA part, Heuristic A is used to find the optimal vessel berthing sequences at each berth, i.e. s_{mi}^j ; and then Heuristic B is used to allocate yard storage space to the containers of each vessel, i.e. y_{ik} . The adopted GA is illustrated in Section 4.1, and two heuristics are explained in Section 4.2 and Section 4.3 respectively. Section 4.4 introduces the wrap-around effect of periodical operation plans, which is needed in every single solution generation.

GA Algorithm

The proposed GA algorithm is designed to optimize two sets of decision variables x_{ij} and T_i^S . However, instead of directly using them as a chromosome in the GA, we introduce another set of variables $\{b_i\}$, where b_i is the berthing position of vessel i . The chromosome of the GA consists of b_i and T_i^S , as shown in Fig. 5. Note that b_i can be converted into x_{ij} using Equation (22). Using b_i instead of x_{ij} can significantly simplify the solution representation and reduce the algorithm search space.

1	2	3	...	I	← Vessel index
b_1	b_2	b_3	...	b_I	← Berth number
T_1^S	T_1^S	T_1^S	...	T_1^S	← Starting point of time window

Fig. 5. The chromosome structure in the GA

$$x_{ij} = \begin{cases} 1, & \text{if } j = b_i \\ 0, & \text{others} \end{cases} \quad (22)$$

$$F_k = \frac{\max(Z)}{Z_k} \quad (23)$$

The outline of the entire GA procedure is as follows:

- Step.1 Initialization: generating an initial population in two ways:
 - 1) importing the obtained solutions from the sequential planning model if any;
 - 2) randomly generating a solution in the following rule: to generate each b_i , randomly select two berths and choose the one with fewer handling workload; convert b_i into x_{ij} using Equation (22); assign s_{mi}^j based on x_{ij} with Heuristic A; assign y_{ik} based on x_{ij} with Heuristic B; lastly randomly generate T_i^S under the constraint of Equation (17).
- Step.2 Evaluation: evaluate the initialized solutions and give higher probabilities to good solutions for survival with Equation (23), where F_k is the fitness value of individual k .
- Step.3 Selection: use the roulette wheel method to select some solutions out for later breeding.
- Step.4 Crossover: use the two-point crossover operator to produce an offspring.
- Step.5 Mutation: to increase the variability of the population, randomly change the gene value of b_i of each individual with the mutation ratio; convert b_i into x_{ij} using Equation (22); assign s_{mi}^j based on x_{ij} with Heuristic A; assign y_{ik} based on x_{ij} with Heuristic B; lastly randomly change the bits of T_i^S under the constraint of Equation (17) with the mutation ratio.
- Step.6 Evaluation: evaluate the objective values of the offspring solutions.
- Step.7 Reinsert: put two generations together and delete duplicate solutions if any, and give higher probabilities to good solutions for survival with Equation (23), where F_k is the fitness value of individual k . Select the top 20% solutions with Elitism Strategy and allow the others survive randomly.
- Step.8 Termination: stop, if the number of iteration reaches the pre-defined number; otherwise go to Step.3.

Fig. 6. The GA algorithm for the integrated planning model

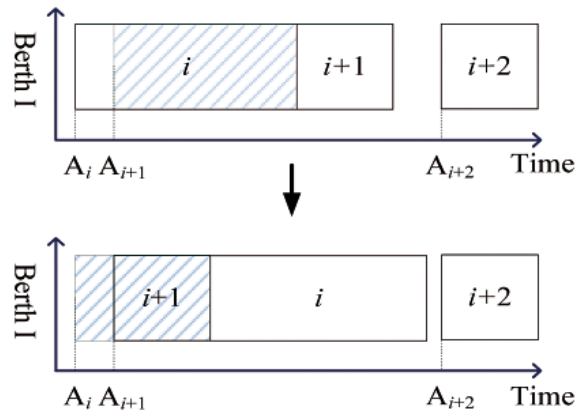


Fig. 7. Swapping berthing sequences in BAP planning

Heuristic A

Heuristic A is an iterative procedure designed to optimize s_{mi}^j based on x_{ij} . Given a profile of vessels at a specific berth, Heuristic A assigns s_{mi}^j preliminarily based on the FCFS principle. Since the FCFS rule does not promise an optimal sequence, Heuristic A modifies s_{mi}^j by swapping the berthing sequences of two neighbouring vessels, when a reduction of the total vessel waiting time can be realized. An example is shown in Fig. 7: the shadow area illustrates the vessel waiting time, which can be reduced by swapping the berthing sequences of vessel i and vessel $i+1$. The swapping operation is repeated following the rule shown in Fig. 8, which ensures that all pairs of neighbouring vessels are checked and the final sequence is optimal.

Case: Suppose I_k vessels have been assigned to berth k . Let s denote the vessel index based on FCFS rule.

Initialization: calculate the total waiting time W and start the swapping operation from the second vessel by setting $s = 2$

While $s \leq I_k$

Switch the vessels sequenced as s and $s-1$, and recalculate the total waiting time W'

If $W' < W$

Set $W = W'$ and $s = s-1$

Else

Switch the two vessels back, and set $s = s+1$.

End

If $s = 1$, set $s = 3$, End

End

Fig. 8. Heuristic A for assigning vessel berthing sequences

Heuristic B

Heuristic B is the procedure designed to optimize y_{ik} based on x_{ij} . Since locating containers far from the vessel berthing position will lead to long handling time, preliminarily the 'nearest location first' principle is used, i.e. allocate the closest storage space to a vessel (Woo and Kim, 2011). Then we use Equation (15) to check that whether the minimal storage demand in a storage zone exceeds the storage supply at any time step. Minimal storage demand refers to the demand whenever

T_i^S is set as its latest possible starting point $T_i^E - \max\left(M_2, \frac{V_i r_i}{fG}\right)$.

If the maximum of minimal storage demand exceeds the supply in any storage zone, Heuristic B is used to modify y_{ik} .

Wrap-around Effect

The wrap-around effect refers to the backward and forward effect of a periodical plan on the neighbouring periods, which

is equivalently wrapped around back to the current planning period. The wrap around effect was introduced to solve the tactical BAP problem by Moorthy and Teo (2006). Fig. 10 illustrates the basic idea to deal with this effect, taking the BAP planning as an example. In Fig. 10, a rectangle represents the berthing time and the berthing position of a vessel and a shadow area represents a vessel's waiting time before berthing. The

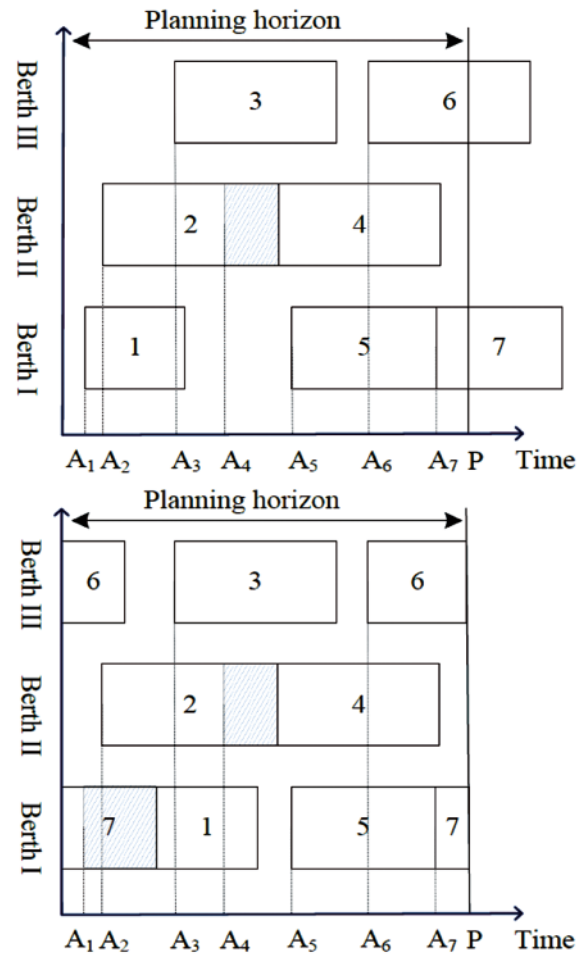


Fig. 10. Wrap around effect on BAP planning (the left is before wrapping and the right is after wrapping)

Initialization: assign y_{ik} according to the 'nearest location first' principle, calculate the minimal storage demand D_{kt} .

Run the following procedure for each storage zone;

While $\max \{D_{kt}: 1 \leq t \leq P\} > B_k$ in storage zone k

Find the time step t^* corresponding to the maximum D_{kt} ; select vessel i^* such that $V_i r_i$ is the smallest among those vessels, e_{i^*i} is equal to 1, and $V_i r_i$ is not smaller than $(D_{t^*} - B_k)$. (The selected vessel i^* will be re-scheduled to another storage zone.)

Calculate the remaining capacities R_{kt} of other storage zones.

If no storage zone can accommodate the selected vessel, i.e. $\min(R_{kt}) < V_{i^*} r_{i^*}, \forall k \in K, \forall t \in [T_{i^*}^S, T_{i^*}^C]$.

Stop Heuristic B and mark the solution as an infeasible one.

Else

Reallocate the containers of the vessel i^* to the zone k^* whose R_{kt} is the smallest among those zones satisfying $R_{kt} \geq V_{i^*} r_{i^*}$ for any $t \in [T_{i^*}^S, T_{i^*}^C]$.

Recalculate the minimal storage demand D_{kt} .

End

End

Fig. 9. Heuristic B for allocating yard storage space

handling operations of vessel 6 and vessel 7 go beyond the planning horizon, so they should be wrapped around back to the beginning of the planning horizon. As a consequence of wrapping vessel 7 around, the berthing time of vessel 1 is postponed causing a new shadow area. The idea shown in Fig. 10 can be realized by Equation (24) and (25): the first one can modify the time variables, for example time step t ; the second can modify the variables indexed by time step, for example p_{it} .

$$a' = \begin{cases} a - P & \text{if } a > P \\ a + P & \text{if } a \leq 0 \end{cases} \quad (24)$$

$$a'_t = a_t + a_{(t+P)} + a_{(t-P)} \quad (25)$$

The above two equations can handle most of the variables in our problem, except for some conditional variables, such as T_i^C and q_t . These conditional variables are often indexed by time or refer to time, and their values at a (time) point highly depend on the previous ones. Wrapping such a conditional variable back will make a calculation circle, which is hard to find the right starting/cut point. In order to solve this problem, we need to make a feasibility test before wrapping a variable. The feasibility test concerns the relationship between demand and supply. Taking T_i^C as example, if the total demand (vessel handling time) exceeds the total supply (quay service hours) within a planning horizon, it will be infeasible to wrap around the conditional variable (T_i^C). If the total demand (vessel handling time) does not exceed the total supply (quay service hours) within a planning horizon, the conditional variables (T_i^C) can be wrapped around. The wrap around operation can be done by running the wrapped loop only twice, starting from any (time) point with a hypothetical minimal value (mostly zero).

NUMERICAL EXPERIMENTS

The previous sections have addressed the questions ‘how to integrate tactical terminal operations planning’ and ‘how to solve the integrated model’. This section focuses on the third question ‘in what situations the integrated planning model should be used’. We will answer this question by comparing the integrated planning model with a sequential planning model through numerical experiments.

Sequential Planning Model

As mentioned in the literature review, there are adequate existing studies on each single part of the container terminal system, so it is relatively straightforward to construct a sequential planning model. The sequential model can be regarded as a simple way to handle the interaction between different terminal planning activities. However, as there is no feedback from one end to the other, the coordination may be limited. For the simplicity of article structure, the detailed sequential planning model is presented in Appendix A, and here we only introduce the model framework briefly. In the sequential model, the three sub-planning models are placed in the top-down direction, as shown in Fig. 11. These sub-planning models will be solved in a sequential fashion: the output of BAP is used as the input of SSAP, and the output of SSAP is used as the input of TAM.

The BAP sub-model here is similar to the one in Moorthy and Teo (2006) in terms of the wrap around effect and the tactical level of modelling. While the BAP model in Moorthy

and Teo (2006) is in a continuous case, our BAP sub-model is a discrete one. We solve the BAP sub-model with a GA algorithm combined with Heuristic A.

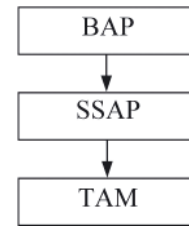


Fig. 11. The structure of the sequential tactical planning for terminal operations

The SSAP sub-model has two tasks: 1) allocating yard space to vessels for container storage and 2) defining a range of the starting point for each time window, which will be used as an input in the TAM sub-model in order to make sure the obtained time window assignment satisfying the storage space constraint. The first task can be completed with Heuristic B following the ‘nearest location first’ principle proposed by Woo and Kim (2011). After allocating storage space, the second task is to optimize the earliest possible starting points of the time windows aiming to maximize the yard utilization rate, i.e. the number of containers multiplied by their longest possible storage time. With respect to this objective, we find that the starting point of a time window must be a vessel’s handling completion time in the previous period, which releases some storage space. This means the size of the search space in the second task is I_k to the power of I_k , where I_k is the number of vessels whose containers are allocated to storage zone k . The second task can be solved with a search algorithm, for example GA or Tabu.

Given the range of each time window’s starting point, the TAM sub-model tries to find the optimal set of starting points to minimize the total truck waiting time, which may lead to vessel delays. A similar TAM sub-model with slightly different objective function is proposed by Chen and Yang (2010) and solved with a GA algorithm, so we adopt their algorithm solution to solve the TAM sub-model in this study.

After solving the three sub-models separately, it is necessary to evaluate the three obtained sub-plans as a whole. This is because the sequential planning model neglects some interrelations between the sub-models, for example truck congestion at the terminal gate may delay yard operations and vessel operations; storing containers far away from the berthing position of the correspondent vessel may increase handling time thereby delay the vessel departure. By introducing the interrelations into the combination of the obtained sub-plans, we will get a complete solution of the sequential planning model.

The obtained solution of the sequential planning model is later used as the input of the initialization operation for the integrated planning model in order to speed up the searching process.

Numerical Experiments

Suppose a hypothetical seaport terminal has five berths, ten yard zones and a gate house of four entries lanes. This hypothetical container terminal is proposed based on a real terminal. The analysis horizon for tactical operation planning is one week. Regarding the inputs, the vessel inter-arrivals are randomly generated following an Exponential distribution with an average interval of three hours, and the handling volumes of these vessels are generated following

a uniform distribution with an average of 1,100 TEU. The XT's arrivals are managed by the terminal operator with the VDTWs method, so a truck arrival time follows the Beta distribution within the corresponding time window. For simplicity, the handling efficiencies of the berths are assumed to be identical of 100 TEU/hour, and the average ratio of O/B handling volume is assumed as 50% for every vessel. The vessel mooring time and the shortest length of a time window are assumed as one hour and six hours respectively. In this hypothetical terminal, all the containers are delivered by XTs.

In the experiment, we conduct 130 instances with different yard capacities and gate capacities as shown in Table 2. The total yard capacity is evenly distributed over the yard zones, half of which are used for O/B container storage. The integrated and the sequential planning models are coded and solved using Matlab 7.8. The mutation ratio, the crossover ratio, the population, and the iteration number are set 0.02, 0.7, 100 and 5,000 in the GA for the integrated planning model, and as 0.05, 0.7, 100 and 1,000 in the GA for the sequential planning model. These GA parameters are selected based on some pilot experiments.

Result Analysis

Table 3 shows the total vessel turn time (in hours) of the sequential planning model in the instances. For each instance, the result is presented in a range covering the top 20 obtained

solutions. This is because the best solution obtained from the sequential planning model is not always the best overall plan, due to the neglect of the interrelations between the sub-models. So taking top-*n* solutions can better represent the sequential model performance than the 'nominal' best solution. The results of the top-*n* solutions in an instance form a result range. Across all the instances, the result range varies about 3.5 percent from the correspondent mean. Table 4 shows the total vessel turn time (in hours) of the integrated planning model in the instances.

It can be seen that the integrated planning model outperform the sequential model significantly when the gate capacity and the yard capacity are relatively low, although their difference diminishes as the gate or the yard capacity increases (compared to the lower bounds of the result ranges from the sequential model). The sequential planning model cannot find feasible solutions in the instances with low yard capacity, e.g. when the total yard capacity is less than 40,000 TEUs. However, the integrated planning model can handle all instances, except the ones with the lowest yard capacity of 16,000 TEU. This indicates that the bottleneck constraint of the yard capacity could be relaxed through the integrated planning. On the other hand, the results show that 20,000 TEU (corresponding to 24% of the total quay crane handling capacity, which is 84,000 TEU per week) is the minimal required yard capacity to serve the given demand in this experiment. Similarly, the minimal required gate capacity to serve the given demand in this experiment is 204 entries per hour.

Tab. 2. Parameters for the test instances

Parameter	Name	Value
I	Number of Vessels	56
V_i	Handling volume [min, max] (TEU)	[10, 2200]
ΣB_k	Total Yard capacity ($\times 10^3$ TEU)	16, 20, 24, 28, 32, 36, 40, 44, 48, 56, 64, 72, 84
G	Total Gate capacity (entries/hour)	200, 204, 208, 212, 220, 230, 240, 260, 300, 400
f	Truck loading factor (TEU/truck)	1.8

Tab. 3. The results of the sequential planning model

Gate (Entry/hour) \ Yard (10^3 TEU)	16	20 - 36	40	44	48	56	64	72	84
	200	— ^a	—	—	—	—	—	—	—
204	—	—	1059-1097	1053-1098	1031-1068	949-980	949-975	926-989	926-988
208	—	—	938-957	870-885	865-881	849-861	849-861	844-856	844-856
212	—	—	862-877	844-850	846-854	844-857	844-857	845-856	845-857
220	—	—	844-855	844-856	845-858	844-853	844-855	844-855	844-856
230	—	—	844-854	844-851	844-851	845-858	845-852	845-851	845-855
240	—	—	844-851	845-853	844-853	844-855	845-852	844-852	844-852
260	—	—	844-850	844-851	844-851	844-851	844-851	844-851	844-852
300	—	—	844-855	844-850	844-850	844-850	844-849	844-854	844-855
400	—	—	844-849	844-856	844-854	844-855	844-860	844-854	844-858

a – represents infeasible solution.

Tab. 4. The results of the integrated planning model

Gate (Entry/hour)	Yard (10 ³ TEU)												
	16	20	24	28	32	36	40	44	48	56	64	72	84
200	— ^a	—	—	—	—	—	—	—	—	—	—	—	—
204	—	1180	1099	1045	991	986	983	983	972	926	926	926	926
208	—	955	913	880	854	846	846	846	844	844	844	844	844
212	—	937	901	865	844	844	844	844	844	844	844	844	844
220	—	900	878	851	844	844	844	844	844	844	844	844	844
230	—	872	866	847	844	844	844	844	844	844	844	844	844
240	—	860	856	844	844	844	844	844	844	844	844	844	844
260	—	850	845	844	844	844	844	844	844	844	844	844	844
300	—	844	844	844	844	844	844	844	844	844	844	844	844
400	—	844	844	844	844	844	844	844	844	844	844	844	844

a – represents infeasible solution.

Tab. 5. The comparison of detailed results from two planning models

Instance		The Sequential Planning Model				The Integrated Planning Model			
Yard (10 ³ TEU)	Gate (entry/ hour)	z1'	z2'	z3'	Z'	z1	z2	z3	Z
40	200	844	0	— ^a	—	—	—	—	—
	204	844	0	68	1059	847	0	51	983
	208	844	0	32	938	844	0	1	846
	212	844	0	8	865	844	0	0	844
	220	844	0	0	844	844	0	0	844
	230	844	0	0	844	844	0	0	844
	240	844	0	0	844	844	0	0	844
	260	844	0	0	844	844	0	0	844
	300	844	0	0	844	844	0	0	844
	400	844	0	0	844	844	0	0	844

a – represents infeasible solution.

In Table 4, no improvement can be seen over the yard capacity of 56,000 TEU or over the gate capacity of 300 entries per hour, which correspond to 67% and 108% of the quay capacity respectively. This means, if the terminal is managed with the integrated model, there is no need to further invest on any yard capacity bigger than 56,000 TEU or any gate capacity bigger than 300 entries per hour. Therefore, from the practical perspective, our integrated model can be a useful tool to design a better tactical plan by coordinating BAP, SSAP and TAM. On the other hand, it is able to identify the lower and the upper bounds of the yard capacity and the gate capacity for a given demand scenario.

It is interesting to compare the components between the integrated model and the sequential model to understand the interaction between three sub-planning problems. Taking the instances with the yard capacity of 40,000 TEU as example, Table 5 gives more detailed results from two models. In Table 5, z1 is total vessel turn time (in hours) from the BAP sub-plan

in the integrated planning model; z2 is total vessel delay (in hours) caused by the SSAP sub-plan in the integrated planning model; z3 is total vessel delay (in hours) caused by the gate congestion from the TAM sub-plan in the integrated planning model; Z is total vessel turn time from the whole plan in the integrated planning model. While z1', z2', z3' and Z' are the correspondent results from the sequential planning model.

Table 5 compares the solutions from the integrated model and the corresponding 'nominal' best solution from the sequential model. The z1' column shows that the optimal berth plan obtained from the BAP sub-model in the sequential planning model contributes 844 hours to the total vessel turn time. From z2' column, we can see that the SSAP sub-model does not cause vessel delay in these instances, because the yard capacity is big enough to satisfy the storage requirements in the plan. The SSAP sub-model also defines a range for the starting point of each time window as an input of the next sub-model. Under this range constraint, the TAM sub-model

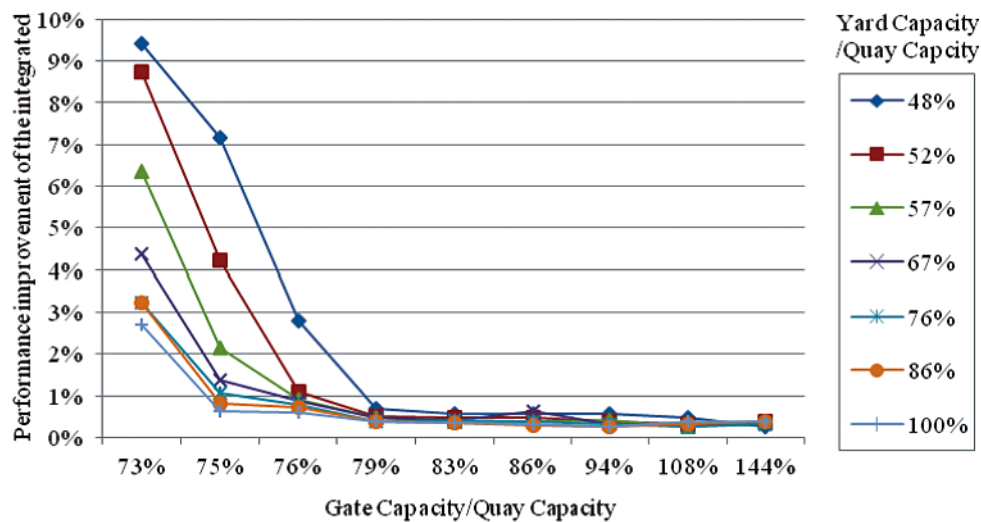


Fig. 12. Improvement percentage of the integrated model from the sequential model

tries to reduce the gate congestion, which sometimes leads to vessel delay as shown in z3' column. A vessel delay may also delay the following vessel if there is not sufficient gap between the handling operations of the two vessels. Too large vessel delay may lead to an infeasible overall solution, for example the instance with the gate capacity of 200 entries per hour. Comparing the columns of the integrated model with the ones of the sequential model, we can see that although the berth plan z1 may incur more berthing time than z1' in some instances, e.g. the instance with the gate capacity of 204 entries per hour, the total vessel turn time of the overall plan Z from the integrated model is smaller than Z'. In conclusion, the integrated planning model can balance the BAP plan and the TAM plan to reach a better overall plan.

The results in Table 3 and Table 4 indicate that the relative merits of the integrated planning model depend on the yard capacity and the gate capacity. In practice, it is quite often that the ratio of the yard capacity to the quayside handling capacity and the ratio of the gate capacity to the quayside handling capacity are of interest because terminal operators are seeking a reasonable balance between these processes. We therefore display the percentage of performance improvement achieved by the integrated model from the sequential model in Fig. 12, in which the horizontal axis represents the ratio of the gate capacity to the quayside capacity, and the vertical axis represents the performance improvement. The performance improvement in each instance is calculated based on the best solution from the integrated planning model and the average value of the top 20 solutions from the sequential planning model. Only the instances in which both the integrated and the sequential models find feasible solutions are shown in Fig. 12, and the instances with the same yard/quay capacity ratio are linked by a line.

Fig. 12 reveals that when the gate/quay ratio is less than 79%, the performance improvement of the integrated model from the sequential model is rather sensitive to both gate/quay ratio and yard/quay ratio, and the sensitivity increases as either gate/quay ratio or yard/quay ratio decreases. It is noted that when the yard/quay ratio is less than 48%, the sequential model is unable to find feasible solution while the integrated model can. When the gate/quay ratio reaches 79%, the integrated planning model is only marginally better than the sequential model (up to 1%). It should be pointed out that this finding is limited to the level of the assumed vessel operation demand, which is 73% of the quay capacity. Nevertheless, such demand/quay ratio is reasonable in many container terminals. Otherwise,

either the terminal operators may pursue more carriers (to avoid under-utilisation) or carriers may switch to alternative terminals (to avoid over-utilisation and congestion).

With respect to the computational efficiency, the sequential planning model is obviously more competitive against the integrated planning model. A 1,000 generation GA algorithm with 100 populations, taking around 10 minutes on a PC (Intel T7300 Core 2 Duo), is sufficient to find a near optimal solution for all the three sub-models separately in the sequential model. While the integrated model requires a 5,000 generation GA algorithm with 100 populations, which takes three times more computation time on the same PC. The disadvantage of the proposed GA for the integrated model is that if the initial population is poorly generated, the integrated model may not be able to find better solutions than the sequential model. So when the yard capacity and the gate capacity reach a certain level (50% and 80% respectively in the above experiment), the sequential model is preferable as it can yield solutions with similar quality with much less computational effort.

CONCLUSIONS

In marine terminal operations research, there is a growing interest in integration models that are able to find well balanced overall operation plans. This paper addresses an integration model covering the major planning activities at the tactical level, including BAP, SSAP and TAM. A heuristic based GA algorithm is proposed to solve the problem. Through the numerical experiments, it is observed that the integrated planning model performs much better than the sequential planning model alone especially when the yard capacity and the gate capacity are relative low. However, as the yard capacity or the gate capacity increases, the difference is decreasing. The sequential model has the advantage of less computational time.

The managerial implication of this study is that the terminal critical resources should be coordinated through the collaboration with other stakeholders including the seaside customers (e.g. shipping lines) and the landside customers (e.g. shippers) in order to achieve the terminal operation efficiency. The models developed in this study can serve as useful tools to design coordinated plans in terminal management and are able to identify the lower and the upper bounds of the yard capacity and the gate capacity at a container terminal.

This study has the following limitations. First, several practical constraints are not included into the model, including

the number and efficiency of quay cranes, the operations efficiency of yard cranes, the size of internal trucks and so on. Adding these factors into the model will enable the model to provide more managerial applications, if the problem complexity can be handled. Second, all the cost factors in this model are not analysed, including the cargo storage cost, the truck waiting time cost, the terminal operations cost and the vessel time cost. By including these cost factors, one can make some economic analysis on this topic. Third, the integrated model has only one objective, which is the total ship turn time. But actually there are some more objectives could be considered in this problem, for example the total truck waiting time. There may be some congestion at the gate, which only increases the waiting time of trucks and does not effect on the ship turn time yet. In order to take these related objectives into consideration, we could develop a multi-objective optimization model instead

of single objective model, so as to search for solutions with better overall quality.

For future research, we will apply the multi-objective optimization technique to cope with the multi-criteria nature of terminal operation planning. Moreover, investigating more efficient algorithms to improve the search speed for the integrated model is in need. Another research interest is to compare the performance of the integrated model under different assumption settings. In this study it is assumed that a vessel will depart after its handling activities are completed. An alternative in practice is that a vessel always departs on schedule and leaves the late arrived containers in the yard for next vessel to pick up (usually the next week). Considering both cases can produce a more comprehensive understanding of the integrated tactical planning for container terminal operations.

Appendix A: Sequential Planning Model

BAP Sub-model

$$\min Z = \sum_{i \in I} (z_i^w + z_i^h) \quad (A.1)$$

Subject to:

$$z_i^w = \max \left(0, \sum_{j \in J} \sum_{m \in I} x_{ij} s_{mi}^j T_m^c - A_i \right) + w_{T_i^E} \quad \forall i \in I \quad (A.2)$$

$$z_i^h = \sum_{j \in J} \sum_{k \in K} x_{ij} y_{ik} \left(M_1 + \frac{V_i}{H_j} \right) \quad \forall i \in I \quad (A.3)$$

$$T_i^c = A_i + z_i^w + z_i^h \quad \forall i \in I \quad (A.4)$$

$$\sum_{i \in I} x_{ij} z_i^h \leq P \quad \forall j \in J \quad (A.5)$$

$$\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I \quad (A.6)$$

$$\sum_{m \in I} s_{mi}^j \leq 1 \quad \forall i \in I, \forall j \in J \quad (A.7)$$

$$\sum_{m \in I} \sum_{i \in I} s_{mi}^j = \sum_{i \in I} x_{ij} - 1 \quad \forall j \in J \quad (A.8)$$

$$x_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in J \quad (A.9)$$

$$s_{mi}^j \in \{0,1\} \quad \forall i \in I, \forall m \in I, \forall j \in J \quad (A.10)$$

The decision variables of BAP sub-model are x_{ij} and s_{mi}^j . The objective in Equation (A.1) is the minimization of total vessel turn time. Equation (A.2) calculates the waiting time of each vessel before berthing. Equation (A.3) calculates the expected handling time of each vessel assuming that the related containers are stored in the closest storage zone. Equation (A.4) calculates the expected completion time of each vessel, which is also the expected departure time. Equation (A.5) ensures that the handling workload (hours) of each berth is not over its handling capacity. Equation (A.6) ensures every vessel must be served at some berth. Equation (A.7) and (A.8) ensure that every vessel is scheduled to follow another ship at the same berth, except the first ship.

SSAP Sub-model

$$\min \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{ij} y_{ik} d_{jk} V_i r_i \quad (A.11)$$

Subject to:

$$T_i^{LS} = A_i + z_i^w - \max \left(M_2, \frac{V_i r_i}{fG} \right) \quad \forall i \in I \quad (A.12)$$

$$e_{ti} = \begin{cases} 1, & \text{if } t \in [T_i^{LS}, T_i^c] \\ 0, & \text{others} \end{cases} \quad \forall i \in I, 1 \leq t \leq P \quad (A.13)$$

$$\sum_{k \in K} y_{ik} = 1 \quad \forall i \in I \quad (A.14)$$

$$\sum_{i \in I} y_{ik} V_i r_i e_{ti} \leq B_k \quad \forall k \in K, 1 \leq t \leq P \quad (A.15)$$

$$y_{ik} \in \{0,1\} \quad \forall i \in I, \forall k \in K \quad (A.16)$$

The SSAP sub-model has two tasks. The first task is to minimize the total container transport distances between vessel berthing locations and the correspondent container storage locations, as shown in Equation (A.11). The decision variable of the first task is y_{ik} and one of the inputs x_{ij} is obtained from the BAP sub-model. Equation (A.12) calculates the latest starting point of each time window, i.e. T_i^{LS} , based on the information from the BAP sub-model. Equation (A.13) is used to mark the time points that are covered by a time window. Equation (A.14) ensures every vessel must be allocated a storage space. Equation (A.15) ensures at any time step, the total storage demand in a storage zone does not exceed the storage capacity.

$$\max \sum_{i \in I} (T_i^c - T_i^{ES}) V_i r_i \quad (A.17)$$

Subject to:

$$T_i^{ES} \in [T_1^c - P, T_2^c - P, \dots, T_1^c - P] \quad \forall i \in I \quad (A.18)$$

$$\lambda_{ti} = \begin{cases} 1, & \text{if } t \in (T_i^{ES}, T_i^c) \\ 0, & \text{others} \end{cases} \quad \forall i \in I, 1 \leq t \leq P \quad (A.19)$$

$$\sum_{i \in I} y_{ik} V_i r_i \lambda_{ti} \leq B_k \quad \forall k \in K, 1 \leq t \leq P \quad (A.20)$$

When the storage spaces allocation is done, the second task is to maximize the yard utilization rate, i.e. the number of

containers multiplied by their longest possible storage time, as shown in Equation (A.17). The decision variable of the second task is the earliest starting point of each time window T_i^{ES} . Equation (A.18) shows that a T_i^{ES} must be set as one of the vessel's handling completion times in the previous period. Equation (A.19) is used to mark the time points when a storage space is occupied by a vessel. Equation (A.20) ensures at any time step, the total storage demand in a storage zone does not exceed the storage capacity.

TAM Sub-Model

$$\min \sum_{1 \leq t \leq P} q_t \tag{A.21}$$

Subject to:

$$p_{it} = \begin{cases} \frac{\int_a^b u^{0.29} (1-u)^{2.25} du}{\int_0^1 u^{0.29} (1-u)^{2.25} du} & \text{if } t \in [T_i^S, T_i^E] \\ 0 & \text{others} \end{cases}$$

where: (A.22)

$$a = \frac{t - T_i^S}{T_i^E - T_i^S}, b = \frac{t - T_i^S + 1}{T_i^E - T_i^S}$$

if:

$$t \in [T_i^S, T_i^E] \quad \forall i \in I, 1 \leq t \leq P$$

others

$$N_t = \sum_{i \in I} \frac{p_{it} V_i r_i \beta}{f} \quad 1 \leq t \leq P \tag{A.23}$$

$$q_t = B - \text{PSFFA}(q_{t-1}, N_t, G) \quad 1 \leq t \leq P \tag{A.24}$$

$$T_i^{ES} \leq T_i^S \leq T_i^{LS} \quad \forall i \in I \tag{A.25}$$

The decision variable is T_i^S , and the inputs T_i^E , T_i^{LS} and T_i^{ES} are obtained from the above sub-models. The objective is to minimize the total truck waiting time, as shown in Equation (A.21). Given a set of T_i^S , Equation (A.22) calculates the probability of a truck related to vessel i arriving at the terminal gate at time step t . Based on p_{it} , Equation (A.23) calculates the number of trucks arriving at terminal gate at time step t . Equation (A.24) estimates the queue length at time step t with the fluid-based B-PSFFA approximation method proposed by Chen et al. (2011c). Equation (A.25) ensures that the actual starting point of a time window must be between its earliest and the latest possible starting points.

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Seaport network performance measurement in the context of global freight supply chains

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ABSTRACT

A global distribution channel with a reliable freight transport system is essential in the contemporary world economy. Acting as trade facilitators, seaports are important players in the system. The study of the role of ports in supply chain management has recently drawn increasing attention from researchers and industry professionals alike. However, prior works mainly gathered the views from ports and terminals. To the authors' knowledge, no attempt by previous empirical studies has been made to cover the perspective from shippers and logistics providers, who are obviously taking a serious role in the process of global freight movements as major stakeholders. It becomes thus imperative to assess a port's supply chain orientation and performance from the perspective of the port users in the supply chain. Studying ports in the network context would be even more beneficial to capture the complexity needed to understand port performance and its interaction with various stakeholders. Drawing reference from multi-disciplinary fields, this paper aims to fill in the gap by developing a so-called unified framework for analysing port's integration in global freight supply chains including shipping line networks, hinterland and intermodal transport network, and even urban network. The framework embraces a wider group of stakeholders involved, for example, terminal operators, port authorities, shippers, shipping companies, inland transport providers, freight forwarders/logistics service providers, cities and other ports in the networks. A port that is a key node in these networks simultaneously would be able to create and sustain value for port stakeholders. Port authorities and operators can refer to the framework as their network performance indicators so as to obtain a better understanding of the various considerations in a port's network performance and to assist in positioning the port within the complex dynamics in the context of global freight supply chains. Finally, the framework developed in the paper can serve as a guide to empirical examinations of an emerging theme – a network-oriented performance by seaports along global freight supply chains – leading to various possible channels in future research.

Keywords: seaport; network performance; supply chain; sustainability; stakeholder

INTRODUCTION

A global distribution channel with a reliable transport system becomes ever more essential in the contemporary world economy, which is closely interlinked, for example, among manufacturers, consumers and assemblers. From a macroeconomic point of view, the increasing number of countries adopting market economies has brought about a change in how countries view the potential of international commerce and trade. The diversification and specialisation of markets, and the potential and impact of emerging or changing patterns of globalisation have added a new dimension to freight transport and affected the structure and operation of the transport industry as a whole (OECD, 2011). With globalisation and the increasing pressure to remain competitive, a country's capability to reduce transaction costs through the provision of adequate and efficient freight transport systems is more critical

than ever. From a microeconomic perspective, on the other hand, due to competitive pressures brought by consolidation in the manufacturing sector, firms tend to produce in places where resources are less expensive. Finding sources in lowering production cost has led to a situation where companies spread their production units across continents. These developments in the world economy have been accelerated owing to factors like the importance of economies of scale, geographical expansion and trade liberalisation, which in turn lead to increasingly globalised enterprise activities. Consequently, the manufacturing industry in global supply chains becomes more dependent upon shipping and ports in inbound as well as outbound logistics.

Having acted as trade facilitators, seaports^{*)} are important players in the freight transport system. The era of globalisation and global supply chain management (SCM) has led to the evolving roles of ports and port operators which are shaping

^{*)} Seaport or port will be used in an interchangeable manner throughout this paper.

an emerging academic discipline. The critical nature of a seaport is a connection point. It is a platform linking sea and inland transportation, the local hinterland and overseas foreland, various shipping and transport service providers as well as trade and the urban system where the port is located. Drawing references from multiple disciplines, this paper aims to develop a so-called unified framework for analysing port's integration in global freight supply chains including shipping line networks, hinterland and intermodal transport network, and urban network. A port that is a key node in these networks simultaneously would be able to create and sustain value for port stakeholders. In this paper, sustainability is viewed from the overall performance perspective and sustainable value refers to the benefit brought to stakeholders which is strategic and not easily to be imitated (Ketchen et al., 2008). The framework ultimately aims to contribute to the research domain by devising an original and systematic reference to network performance measurement for the benefit of charting future research efforts and industry applications.

After the introduction, this article is organized as follows. A literature review is given in the next section, while the third section presents the research methodology. Conceptual development is then discussed in detail, followed by the section in which a hierarchical structure of port's network performance evaluation indicators is illustrated. The sixth section discusses the practical and research implications drawn from the conceptual framework. Finally, the concluding remarks are made.

LITERATURE REVIEW

The study of the role of ports in SCM has drawn increasing attention from researchers and industry professionals alike. Seaports have become a key node in supply chains and global distribution channels (Robinson, 2002). A study on European ports called for a change of mindset from "port-to-port" to "door-to-door" operations and management (Perez-Labajos and Blanco, 2004). Global terminal operators are increasingly aware of the trend that the supply chain is regarded as a total integrated system. Vertical integration strategies would help to extend the terminal operators' control over the chain, thus making them more attractive to be the chosen operator (De Souza et al., 2003). Paixao and Marlow (2003) claimed that ports have indeed become more integrated in supply chains. They introduced the logistics concepts of 'lean' and 'agile' operations as key indicators of port performance in supply chains, and suggested that a port's performance and competitiveness increasingly depend on logistics attributes in determining cost and responsiveness. Hall and Robbins (2007) and Mangan and Lalwani (2008) also stated that ports have become increasingly responsive to major customers' supply chains. It has been illustrated by some studies that concepts of supply chain when incorporated into port planning and management can enhance port performance (Carbone and Martino, 2003; Almotairi and Lumsden, 2009; Lam and Yap, 2011).

Scholarly work in this field is gradually emerging but still quite limited in terms of breath and depth. Particularly, empirical work on the integration of ports in the supply chain is relatively scant. Table 1 summarises those empirical studies on ports in the supply chain context. To critically assess the state of the literature on this topic in focus, those papers just mentioning ports' connection with the supply chain without fulfilling the objective to understand ports' role/ relationship/ integration with the supply chain are not included in table 1. Focusing on the role of ports in the automotive supply chain, Carbone and Martino (2003) conducted surveys with various operators in the

port of Le Havre to analyse how they are involved in the supply chain. The study found that generally port competitiveness is increasingly dependent on external coordination and control of the whole supply chain. However, the authors admitted that the research findings cannot be generalisable as the work lacks wider field testing. In another attempt having claimed that ports are logistics centres playing a vital nodal role in the changing patterns of maritime and intermodal transport, Bichou and Gray (2004) suggested and tested a framework of port performance measurement from a logistics and supply chain management approach. It was found that the model is generally supported suggesting that there is a need to expand the scope of the inquiry beyond seaports to other supply chain members in order to investigate their perceptions and potential contribution to a shared management of international supply channels. Carbone and Gouvenal (2007) performed a survey with selected experts and confirmed the increasing awareness of the role of effective relationship management for a port's competitiveness.

In a recent work, Song and Panayides (2008) conducted a survey to collect the views from container port/terminal managers worldwide. Certain parameters of supply chain integration such as use of technology, value added services and user relationships are positively related to the parameters of port competitiveness. The authors suggested that these parameters form a basis for the exact attributes that contribute to port competitiveness in the supply chain. Panayides and Song (2008) extended the previous work by developing a measurement instrument that can be used by researchers to measure the extent to which a port or container terminal is supply chain oriented. Via a survey of container terminal operators in Europe and East Asia, the constructs were validated using confirmatory factor analysis. Tongzon et al. (2009) studied the port of Incheon as a case in point and measured the degree of its supply chain orientation based on the indicators developed by Panayides and Song (2008). The study found that ports or terminals in practice may not be supply chain oriented as theories predict. There is also a major gap on shipping companies' requirements perceived by port operators according to Woo et al. (2011). Based on a survey with various sectors in South Korea, port operators asserted that low price rather than high service quality is the most strongly required by shipping companies. But shipping companies indicated that service quality is the most important requirement on port performance in logistics environments.

Robinson (2002) suggested that ports are parts of a value-driven chain system and it is important for the port and its service providers to offer sustainable value to its users against other competing value-driven chain systems. Freight moves only when shippers and customers derive value and competitive advantage. Port users including shipping companies, shippers, consignees and freight forwarders/ logistics service providers are the ones who perceive such value. However, except for Tongzon et al. (2009) and Woo et al. (2011), the prior works mainly gathered the views from ports and terminals. Tongzon et al. (2009)'s survey included container lines, yet it studied only the port of Incheon. As for Woo et al. (2011), shipping companies' view was also restricted to 13 responses from South Korea. To the authors' knowledge, no attempt has been made by previous empirical studies to cover the perspective from shippers and logistics providers in the topic of port's integration in the supply chain, who are obviously taking a serious role in the process of global freight movements. It becomes thus important to assess a port's supply chain orientation and performance from the perspective of the port users in the supply chain. According to Ketchen et al. (2008), best value

Tab. 1. Summary of empirical studies on ports in the supply chain

No.	References	Perspectives of	Geographical coverage	Major findings
1.	Carbone and Martino (2003)	Various port operators	Port of Le Havre	<ul style="list-style-type: none"> When a port has gained the status of a crossroad between the production and distribution spheres, higher integration with the port operators' major customers is called for
2.	Bichou and Gray (2004)	Ports, international institutions and experts	Global	<ul style="list-style-type: none"> Ports are logistics centres playing a vital nodal role in the changing patterns of maritime and intermodal transport Supply chain approach in port performance measurement is supported
3.	Carbone and Gouvelal (2007)	Experts largely from the maritime field	Global	<ul style="list-style-type: none"> A main global trend on maritime supply chain is the increasing control of ports by international terminal operators Stable relationships with other actors in supply chain is a very important factor in port competitiveness
4.	Song and Panayides (2008)	Container ports and terminals	Global	<ul style="list-style-type: none"> Value added services, use of technology and relationship with shipping lines are positively related to port competitiveness
5.	Panayides and Song (2008)	Container terminals	Europe and East Asia	<ul style="list-style-type: none"> Validated constructs: (1) information and communication systems, (2) value added services, (3) multimodal systems and operations, (4) supply chain integration practices
6.	Tongzon et al. (2009)	Container terminals and liners	Incheon	<ul style="list-style-type: none"> There is a significant gap in perceptions between terminal operators and shipping lines with the widest gap observed in the provision of value-added services.
7.	Woo et al. (2011)	Port operators, shipping companies, public sector and academics	South Korea	<ul style="list-style-type: none"> Port operators assert that low price rather than high service quality is the most strongly required by shipping companies. But shipping companies indicate that service quality is the most important on requirement port performance.

supply chains go beyond traditional logistics requirements by stressing a holistic logistical value proposition which finds the ideal balance of the key competitive priorities, namely speed, quality, cost, and flexibility. Hence, for ports to contribute to the best value approach, they should also find the right balance of these key competitive priorities. It will be interesting to investigate what the right balance is. Furthermore, mainly inland transport connectivity was included as one of the constructs in existing measurement instruments. It appears that the prior studies neglected ports' seaward connectivity with other ports. Without assessing port-to-port connectivity, the performance measures only cover part of the supply chain, i.e. between port and hinterland, but not from the point of origin to the point of destination.

RESEARCH METHODOLOGY

Noting the various gaps in the literature, this study addresses the various issues by developing a comprehensive conceptual framework based on literature research, observation from the port industry and six semi-structured interviews conducted with maritime industry professionals and academic. Drawing reference from multiple disciplines, a detailed literature review has been performed to broaden the perspective on how to investigate into port research. Also, various sources such as trade journals, market reports, databases and credible internet references were consulted for collecting data and information. Six in-depth interviews were carried out from mid 2011 to mid 2012 to gain more insights from the industry practitioners and experts. Five interviews were targeted at the management personnel of a shipper, a logistics service provider,

a terminal operator, a shipping line and a maritime consulting firm respectively. As such, both port operator's and port user's views were represented, whereas the professional from the maritime consulting firm offered a neutral perspective since it is a third party which is neither a port operator nor a port user. As the research topic is in the context of global freight supply chains, the sample was selected from Fairplay's World Shipping Directory to include those international entities serving a wide coverage of the global market. Then a management executive in charge of supply chain solutions from the Asia headquarter or regional offices in each company was randomly selected from the sample companies and approached for an interview. To include the viewpoint from the scientific research community, an academic in the maritime field was also interviewed. The six interviewees have given information and opinion on the proposed framework and performance indicators in analysing port's integration with various networks which will be discussed in the next sections. The research design is to achieve the benefits from triangulation, whereby multiple data collection methods can mitigate biases and lead to stronger substantiation of research constructs (Eisenhardt, 1989). This study utilizes qualitative approach involving compilation, summary, comparison, classification and analysis of the data, information and opinion.

CONCEPTUAL DEVELOPMENT

Port's integration in supply chain network

The literature emphasised the importance of logistics integration into marketing channels in supply chains (Langley

and Holcomb, 1992; Alvarado and Kotzab, 2001). In the new paradigm seeing port as an element in supply chains, ports play a role in this logistics integration in delivering a value to their main customers (e.g., shipping companies), then to shippers and consignees, and accessorially to transport and logistics service providers (Robinson, 2002). These players do not choose a port per se, but a supply chain comprising a bundle of logistics services and a pathway to markets (Magala and Sammons, 2008). The rising demand from global customers in the competitive market creates a need for fourth generation ports, which are nodal points in supply chains and integrate with other supply chain members to form networks (UNCTAD, 1999). Lean and agile logistics would improve on efficiency and enhance integration of ports in supply chains to meet today's market requirements (Paixao and Marlow, 2003; Pettit and Beresford, 2009). This development supports the demand from global production networks whose interconnected nodes and links extend spatially across national boundaries and, in so doing, integrate parts of disparate national and subnational territories (Coe et al., 2008). Paixao and Marlow (2003), Bichou and Gray (2004) and Panayides and Song (2008) all have observed that ports are increasingly integrated in supply chains and the port performance evaluation framework should be built from the supply chain perspective. When different supply chains pass through the same seaport, the port authority could use benchmarking to identify the proper management model for the specific port and could utilize this approach to make decision about infrastructure investments and related hinterland connections (Carbone and Martino, 2003). The idea can be extended to include terminal operator for assessing port operations and management.

Port's integration in hinterland/intermodal transport network

As an interface between the water side and the shore, ports should be well connected with maritime transport on one hand and inland transport on the other hand. We firstly discuss inland transport connections. Hinterland is the backyard of cargo source for gateway ports. Ports strive to capture and expand their hinterland to the best they can and thus intensify land-based port competition (Starr and Slack, 1995). In the process, the emergence of inland ports, also known as dry ports, from the hinterland and regional development perspective can be explained by "port regionalization" (Notteboom and Rodrigue, 2005). Its characteristic is port functional integration and even joint development with hinterland logistics platforms in order to shape a regional transportation network to meet requirements from global freight distribution channels and chains. There is higher demand for port expansion due to increasing port traffic. However, local opposite voices owing to environment concerns present a paradoxical phenomenon in port development. Inland ports and other logistics platforms together with gateway seaports would form regional transportation network to mitigate this acute problem and achieve another optimised pattern of port expansion and externalization. The development of inland ports and freight corridors could be considered as port regionalization process involving integration between maritime and inland freight transportation (Notteboom and Rodrigue, 2005; Roso, 2007; Roso et al, 2009). The degree to which a port is integrated in the hinterland network is increasingly regarded as strategic and contributes to sustainability, thus represents an indicator of port performance.

Port's integration in liner shipping network

This section then discusses maritime connections. Ports having good geographical location along with major artery of maritime traffic are naturally advantageous. Singapore, Port Klang and Tanjung Pelepas situated along the Straits of Malacca and the ports of Hong Kong and Shenzhen as the gateway of South China, one of the world's largest manufacturing bases, are good examples. Ports are strategically important to shipping companies' and shippers' system (Hayuth and Fleming, 1994). The presence, extent and development of port competition and relationships can be determined by the levels and changes of shipping lines and slot capacity connected (Lam and Yap, 2011). Port centrality in liner shipping networks is a key determinant of port hierarchy (Ducruet et al., 2010; Doshi et al., 2012). Overall, seaward connectivity in terms of shipping services deployed is a performance indicator to analyse ports (as nodes) and routes and shipping lines (as links) that are embedded within the maritime supply chain (Lam, 2011). However, liner networks are ephemeral and dynamic since container shipping lines periodically restructure their networks to adjust to the demands from the market. Thus port connectivity is bound to change as well (Lam and Yap, 2011). Ports should keep themselves abreast of such dynamics and be proactive in attempting to sustain their position as a key node.

Port's integration in urban network

Ports are economic springboards for city and regional development. This has been sufficiently established by the fact that major cities and industries have developed in coastal locations to take advantage of maritime trade. In addition to facilitating trade and industries, ports contribute to economic development due to multiplier effects of port activities (Suykens, 1989). A port city is a hub in dense networks of maritime connections through which people, goods, ideas and meanings flow. Global port cities are powerful manifestations of global flows and trans-national integration (Driessen, 2005; Lee et al., 2008). A port city also plays key political and social roles in influencing its hinterland, including creating employment opportunities for residents. For example, Singapore is a global city-state with its port driving the international manufacturing, transport, communication and financial hub status (Tan, 2007; Lee et al., 2008). Nevertheless, optimising land use in view of increasingly stringent requirements from port users, competition for space from other sectors in the economy and increasing environmental concerns present concerns on port city development. Conflicts between the port and the city also exist due to urban traffic congestion and waterfront redevelopment (Hayuth, 2007). For instance, how to reconfigure Hamburg as a port city is a challenge (Grossmann, 2008). Port city research has attracted attention from geographers, economists, sociologists and historians (Tan, 2007). Thus the topic is multi-disciplinary, though it is reckoned that geography is a major direction in the literature so far. Hence, in terms of city and regional development, ports are important nodal points in urban networks. Ports should coordinate well with the city where it is located and generate sustainable values to it. This represents another indicator of port performance.

The concept of node and network

As revealed from the above discussion, a common concept which is important across various disciplines is centrality of a node and its integration with a comprehensive network. In

terms of spatial network in geography, centrality measures the level of concentration of a node. Intermediacy is to describe the closeness between origins and destinations (Fleming and Hayuth, 1994). These concepts have been widely applied to transportation and urban studies. In the field of strategic management, strategic networks and inter-firm collaboration have received considerable attention from researchers. Centrality measures the ability to access (or control) resources through direct and indirect links. Network centrality at the interpersonal (Brajkovich, 1994) and inter-organizational levels (Birley, 1985; Larson and Starr, 1993; Partanen and Möller, 2011) were studied. In sociology, particularly social network analysis, node centrality refers to the importance of a node due to its structural position in the network as a whole. A type of centrality is closeness, which is the sum of distances to or from all other nodes (Freeman, 1979). Another type of centrality is betweenness, which is a measure of the extent that a node lies along many shortest paths between pairs of others (Freeman, 1977). Social network analysis in the context of logistics and supply chain management is emerging (Carter et al., 2007; Borgatti and Li, 2009; Kim et al., 2011). In fact, there has been increasing interest in conducting supply chain research adopting a network perspective rather than merely a linear chain perspective.

The importance of port and terminal integration in supply chains has already been established in the literature. While studying ports from the supply chain perspective would be helpful, studying ports in the network context would be even more beneficial to capture the complexity needed to understand port's performance and its interaction with various stakeholders. Furthermore, we propose a holistic approach which considers not only one type of network, but a set of networks simultaneously, namely supply chain network, liner shipping network, hinterland/intermodal transport network and urban network, as illustrated in figure 1's unified framework. No matter whether we see port as a spatial, social or commercial entity, port's connectedness and integration with the networks are crucial qualities. There would also be trade-offs, conflicts and tensions that arise from trying to fulfill the needs of the four different stakeholder groups (De Langen, 2007; Coe et al., 2008). A port acting as a key node in these networks simultaneously and balancing the stakeholder groups' interests would be able to create and sustain value for port stakeholders including port users, hence the port possesses a competitive advantage which is difficult for rivals to replicate. The combined outcome is considered similar to the idea of agglomeration effect from development economics perspective put forth by Fujita and Mori (1996) who studied port cities. Our research approach is also able to unify the related research topics from various disciplines as discussed above, which is an original contribution.

SEAPORT'S NETWORK PERFORMANCE INDICATORS

This paper attempts to develop a framework for analysing a port's integration in various networks as discussed above. The framework is intended to be applicable to all container seaports. As such, based on Figure 1, we further develop a list of performance indicators and a systematic approach for the evaluation. The study proposes a hierarchical structure which categorises the performance indicators in three layers. The first layer is called evaluation determinants, which include three fundamental and encompassing indicators considering overall port performance – quality, timeliness and cost – with reference to logistics and supply chain performance analysis

conducted by Ketchen et al. (2008) and Garcia et al. (2012) as well as other scholars. Explanation on the network performance indicators will be given below.

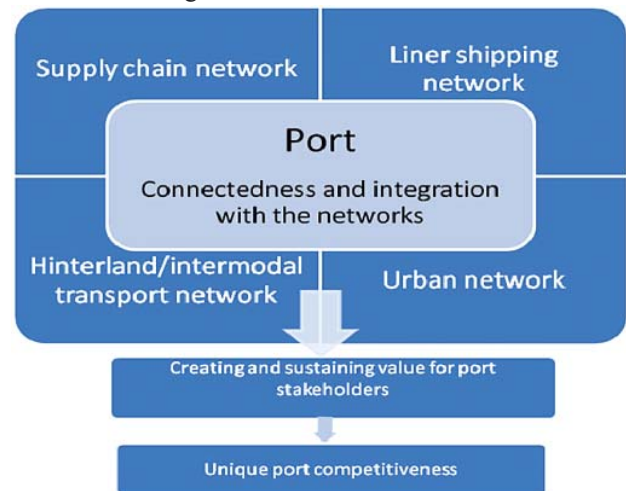


Fig. 1. A unified framework for a port's integration in associated networks.
Source: Drawn by the authors

Quality refers to the standard of the assets, service, process, planning, staff, shipment, documentation, safety, security, management and control in connection to a port's networks. It affects the productivity, effectiveness and reliability of the port's operations. Quality has become a major concern for shippers, and the primary value sought by many shippers has shifted from price to quality service performance (Lagoudis et al., 2006). From the total quality management's point of view, high quality operations and service would result in lower costs for users (Braglia and Petroni, 2000). *Timeliness* refers to time-related performance in terms of transit time, frequency, responsiveness, reliability and agility. Shipping is a vital component in global supply chain management, and at the same time, shipping appears a weak link due to its slow speed and low reliability (Saldanha et al., 2009). Shipping also faces more demanding customers and greater challenges as supply chains become longer and more complex. Time-related attributes are increasingly important due to the prevalence of just-in-time practice and are often found to be significant for shipping and ports (Cullinane et al. 2002; Carbone and Martino, 2003). *Cost* is another important performance indicator. It represents a total cost covering direct cost, indirect cost, logistics cost, shipment cost, ordering cost, fluctuation of cost and cost reduction performance. In general, suppliers offering cost effective solutions are highly valued (Chan and Kumar, 2007). Cost competitiveness can be translated to price attractiveness and lower user costs and thus is a crucial contributor to a port's competitive advantage (Lam and Yap, 2006; Yeo et al., 2011).

Thereafter, the second layer of the hierarchical structure is known as evaluation dimensions. As derived from the literature of various disciplines, port's connectedness and integration with other network members can be classified as three types: functional, information and communication, relationship. The dimensions specify the aspects of the upper-level evaluation determinants. First, *functional* integration is fundamental especially when physical movement of cargoes is concerned. This includes infrastructure and route connections among the various nodes in the intermodal transport network (Parola and Sciomachen, 2005). Smart management of container logistics system is also crucial for sustainable development, using systematic support (software) to offset the limitations in equipment (hardware) (Notteboom and Rodrigue, 2008).

Building upon the physical network and system, service offerings such as value-added service and compatibility with the port users/ stakeholders also determine the level of functional integration. Second, *information* flow is a major form of flow in supply chain management, which emphasizes the overall and long-term benefit of all parties in the chain through co-operation and information sharing (Srinivasan et al., 1994). Inter-organizational information system is one of the means to enhance information flow (Lu et al., 2006). Other than technology, the quality of communication between the organisations is also based on personnel’s competency (Paulraj, 2008). Third, effective inter-organizational *relationships* are important to SCM. Closer and long-term relationships based on trust within the supply chain would contribute to higher supply chain performance and better financial returns (Dyer and Singh, 1998; Fynes et al., 2005). There is also a positive link between a firm’s relational orientation and technological innovation (Hakansson and Ford, 2002). Wilding and Humphries (2006) demonstrated the importance of cooperation, coordination and collaboration in collaborative supply chain relationships. Hence, though relatively intangible, the relational dimension is crucial for port’s network performance.

Tab. 2. Hierarchical structure of a port’s network performance evaluation

Layers	Performance indicators
1: Evaluation determinants	Quality, timeliness, cost
2: Evaluation dimensions	Functional, information and communication, relationship
3: Evaluation elements	Shipping companies, other seaports, customs, inland transport corridors, freight forwarders/ logistics service providers, inland ports, shippers/ consignees and the city where a certain port is located

To further specify port’s network performance, the third-layer indicators contain eight evaluation elements based on the networks identified above which are shown in figure 1. The elements are shipping companies, other seaports, customs, inland transport corridors, freight forwarders/ logistics service providers, inland ports, shippers/ consignees and the city where a certain port is located. Shipping companies are port’s direct customers and have the closest relationship with a seaport’s maritime connectivity. This relates to a seaport’s connection with other seaports as these shipping companies operate the shipping routes calling at and linking with a set of ports. Considering trade facilitation, customs is included as an element since it functions in ports for import and export activities. Port’s integration in hinterland/intermodal transport network is another important aspect. Inland transport corridors are the links connected between the port and the hinterland, inland/dry ports are the nodes in the network, while freight forwarders/ logistics service providers are the operators. Finally, considering the urban network, how well a port is coordinated with its city should be included as an element. Altogether, these eight elements represent the nodes in various networks, port users as well as port stakeholders that formulate a port’s network contents. Table 2 summarises the port’s network performance evaluation indicators.

PRACTICAL AND RESEARCH IMPLICATIONS

This study makes a meaningful contribution to the existing literature by examining the topic of port’s supply chain

orientation and performance from the perspective of port users in the supply chain. An even more encompassing approach, which has yet been explored in the literature, is presented as a platform to investigate the subject from the wider perspectives of stakeholders engaged in the port businesses.

The concept of centrality for measuring the network performance of a node as discussed previously has been substantially extended in this research. The comprehensiveness of a port’s network is specified by the eight evaluation elements. A port’s integration level with these elements can be measured by three determinants from the angle of three dimensions. Thus the concepts of closeness and betweenness in centrality are embraced by our framework in terms of the quality measure in connectedness. In addition to spatial and social distances, a number of new considerations including process, planning, time, cost and information are incorporated into this multi-faceted framework. In future, measuring instrument can be employed to analyse the conflicts and interrelationships among the various network performance evaluation indicators of a port.

The framework for port’s network performance evaluation has proposed a hierarchical structure in organising the performance indicators. Port authorities and port operators can refer to the framework in order to obtain a better understanding of the various considerations in a port’s network performance and the complex dynamics within the context of global freight supply chains. This reference could assist them to better monitor and assess the port’s connectedness and integration with its associated networks, devise a new strategy for improvement, and work towards sustainable values to port users and stakeholders in the long term.

CONCLUDING REMARKS

This paper has provided a new insight into the framework for analysing port’s integration in global freight supply chains having shipping line networks, hinterland and intermodal transport network, and urban network in mind. The framework embraces a wider group of stakeholders involved, for example, terminal operators, port authorities, shippers, shipping companies, inland transport providers, freight forwarders/ logistics service providers, cities and other ports in the networks. This inclusion of extended stakeholders reflects the sophisticated and evolving role played by ports in practice. The study has also unified the related research topics from various disciplines in network performance and thereby creates a new perspective into a multi-disciplinary subject matter.

As an exploratory study in analysing port’s network performance within the context of global freight supply chain, this study has achieved the stated objectives. This paper, however, has a research limitation; that is, just a small number of interviews with industry professionals and academic were conducted as a pilot test for enhancing practicability and validity. The external validity of our proposed framework needs to be empirically tested with a much larger sample via survey as a potential method for further research. As demonstrated throughout the paper, the proposed framework has been thoroughly formulated through a comprehensive literature review and secondary research. Hence, collecting primary information and opinion from the maritime industry is regarded as a supplement in this stage of the research process.

As for other research areas that can be pursued in the future, a correlation analysis, for example, between a port’s network performance and cargo throughput, is helpful in deepening our understanding on the research topic. Furthermore, case studies with reference to the framework and network performance

indicators in question would be highly valuable for assessing and comparing the network performance of a port concerned. The research approach will be applicable to any container seaports in the world, regardless of port size and geographical location. A benchmarking study can be conducted for the benefit of identifying the port industry's best practices. As a whole, this line of study offers a theoretical exploration and specific performance indicators on a critical and topical research field, which could be extendable for an empirical examination.

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Peripheral challenge by Small and Medium Sized Ports (SMPs) in Multi-Port Gateway Regions: the case study of northeast of China

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ABSTRACT

This paper focuses on the role of small and medium-sized ports (SMPs) in enhancing the competitiveness and logistics performance of multi-port gateway regions and associated inland logistics systems. The concepts developed will be applied to the ports in the northeast of China, a multi-port gateway region around the Bohai Sea Economic Rim (BER). Port competition is analyzed by multi-variable methodology and generalized common characteristics of SMPs compared to gateway ports, and the similarities of SMPs and SMEs are also compared. Later in this paper, we analyze the role of a SMP in such region in different variables: (a) cargo volume and market share; (b) international connectivity; (c) relative cluster position; (d) port city and hinterland connection; and (e) logistics and distribution function. The five-dimension analysis combined with in-depth cases study of typical Yingkou port describes a profile of SMPs in the BER and provides future study possibility for more SMPs cases worldwide.

Key words: SMPs; BER; Small and medium sized enterprises (SMEs)

1. INTRODUCTION

The new economic background characterized by slower economic growth and highly volatile demand for international trade provides new opportunities for small and medium-sized ports (SMPs) that often are very responsive in dealing with supply chain dynamics and related logistics systems. However, there is no academic work on how SMPs grow and compete in multi-port gateway regions, a concept introduced by Notteboom (2009; 2010). This paper mainly deals with how SMPs can survive and become competitive in multi-port gateway regions by introducing the case study of the northeast of China.

Defining SMPs demands a multifaceted approach. Often, the scale or size of a port is measured by the single variable of the cargo throughput. Thus, small ports usually refer to ports with a total cargo throughput (volume) below a certain threshold value. Feng and Notteboom (2011) defined SMPs by proposing a seven-dimension method which takes into account the port's competitive position in its port cluster region, and the position is mainly reflected in the following seven aspects: (a) volume/market share, (b) international connectivity, (c) relative cluster position, (d) hinterland capture area, (e) Gross Domestic Product (GDP) of the port city, (f) GDP of the hinterland, and (g) logistics and distribution function. This definition will further apply into this paper in describing port competition mechanism in the northeast of China. But in this paper, we consolidate the variables into five perspectives to

avoid the overlapping of the indicators: (a) cargo volume and market share; (b) international connectivity; (c) relative cluster position; (d) port city and hinterland connection; (e) logistics and distribution function. This multi-variable method is to provide a complete picture how SMPs survive and compete in a multi-port gateway region. The deterrents of (a), (b) and (c) stress the SMPs' role in ports competition and the main focus is on the investigation of competition dynamics between SMPs and big ports. The variables of (d) and (e) will study how SMPs connect with and exert economic impact on the hinterland. The last variable is put SMPs in a logistics system to assess their potential and competitiveness, especially from the perspective of the inland port and intermodality. Veldman and Bückmann (2003) developed a model on container port competition and port choice in the Antwerp–Hamburg range. The study excluded the ports of Amsterdam and Zeebrugge due to their smaller market share. In recent models on port system development, SMPs are seen to be instrumental to the “peripheral port challenge” (and thus port system deconcentration, see e.g. Slack and Wang, 2002 and Notteboom, 2005). Moreover, SMPs also function more in “port regionalization” processes (Notteboom and Rodrigue, 2005) and are key to the formation of “multi-port gateway regions” (Notteboom, 2010) characterized by routing flexibility and inter-port competition and coordination. In contrast to bigger ports, small ports show a slightly larger variance in growth rate (Ding, 2005). SMPs develop in an independent way, which requires ports to find their specific competitive advantage, or in a cooperative way, which seeks

cooperation with neighboring bigger ports of the same multi-port gateway region. Firstly, SMPs' strategies can focus on the hinterland connections in competition with bigger ports. Feng and Notteboom (2011) studied the empirical case of Yingkou port in the logistics system of the Bohai Sea of China, which puts Yingkou port into a more competitive position in contrast to dominant ports in such area. Secondly, SMPs often look for a cost advantage in specific niche markets. Clark et al. (2001) demonstrated how small ports could compete with big ports in specialized markets. Thirdly, SMPs might also secure growth by serving the dominant ports in the multi-port gateway region. Such a strategy demands close cooperation between ports.

The dimensions for SMPs are similar to how we define SMEs. Although different countries have specific definitions on conceptualizing SMEs, certain criteria exist in the following aspects: SMEs by growth and motivation in more traditional categories such as size, market sector or business-to-business or business-to-consumer E-commerce proved to be appropriate for both firms in traditional industries and e-commerce.

- Employment: European Union categorizes companies with fewer than 10 employees as "micro", those with fewer than 50 employees as "small", and those with fewer than 250 as "medium". Successful SMEs place greater emphasis on soft issues (people) than hard issues (technology and structure). The management skills and concepts of the founders are deemed much more important than their technical skills. Employee skills are of crucial concern and can be most effectively developed in a nurturing working environment. Nevertheless the impact of business founders on organizational success remains the leading factor.
- Organizational structure: compared to large enterprises, most SMEs have simplified organization structure, even without clear labor division in order to decrease human cost and more flexible strategy adoption.
- Percentage of all production factors in total product cost (or product price): usually, production factors of SMEs are more localized with high marginal cost. Among the production factors, the weight of technology innovation is comparatively low while labor costs and marketing costs are high.
- Niche market: SMEs are in subordinating position of an industrial chain dominated by big firms and most SMEs engage in perfectly competitive market with low entry barrier. Some SMEs can be competitive in niche market.

When comparing SMEs and SMPs, the benchmarking ground should also be paid attention to. SMEs are defined more generally covering all industries and all forms of firms, thus it's similar to how we define SMPs. However, SMPs are specifically referred to ports industry. If we look at how a port is organized, we may find there are two forms; either a small port composed of small and big companies or a big port combined with small companies. Therefore, analyzing SMPs in a big port is more prone to referring to the SMEs cluster while SMPs of a small port are more like individual SME. Currently, globally SMEs account for 99% of business numbers and 40% to 50% of GDP, while in port industry, big ports contribute more to the global freight.

There are several reasons why the role of SMPs in multi-port gateway regions might be somewhat overlooked. First, most SMPs have a close connection with the local port city and the direct hinterland. This implies that the supply chain perspective of SMPs is often wrongly considered as only of local importance. Second, large ports are often facing a more visible array of local constraints that impair their growth and efficiency (Notteboom and Rodrigue, 2005). Most SMPs

typically have easier access to the (local) inland ports or relevant logistics system. The development issues in SMPs receive far less attention in the specialized press and therefore might seem less pressing. Traditionally, SMPs are regarded as being in a disadvantageous position compared to large ports in terms of the available resources supporting their development. However, we argue that most SMPs play an indispensable role in the development of multi-port gateway regions around the world. The development of SMPs depends on either location advantages or their contribution in improving the logistics network of the multi-port gateway region. As SMPs typically have a smaller scale, they are often more agile and flexible in dealing with new market-based challenges, e.g. by redefining the strategic mission of the port toward a specialized/niche port complementing the wider multi-port gateway region. There are several reasons why the role of SMPs in multi-port gateway regions might be somewhat overlooked. First, most SMPs have a close connection with the local port city and the direct hinterland. This implies that the supply chain perspective of SMPs is often wrongly considered as only of local importance. Second, large ports are often facing a more visible array of local constraints that impair their growth and efficiency (Notteboom and Rodrigue, 2005). Most SMPs typically have easier access to the (local) inland ports or relevant logistics system. The development issues in SMPs receive far less attention in the specialized press and even might be ignored. Traditionally, SMPs are regarded as ones in a disadvantageous position compared to large ports in terms of the available resources supporting their development. However, we argue that most SMPs play an indispensable role in the development of multi-port gateway regions around the world. The development of SMPs depends on either location advantages or their contribution in improving the logistics network of the multi-port gateway region. As SMPs typically have a smaller scale, they are often more agile and flexible in dealing with new market-based challenges. Thus, it is necessary to complement the wider multi-port gateway region by redefining the strategic mission of the port toward a specialized/niche port.

The above discussion suggests that the study of SMPs is not only relevant but also necessary in order to improve the competitiveness of multi-port gateway regions and to strengthen their role in facilitating network-based supply chain.

In August 2006, the Chinese State Council discussed and released the National Seaports Layout Plan, where Chinese seaports were classified into five port regions: the Bohai Sea Economic Rim (BER), Yangtze River Delta (YRD), Southeastern Coastal Ports Cluster, Pearl River Delta (PRD) and Southwestern Coastal Port Cluster. In all five port regions sharing some common characteristics, each one is composed of more than one gateway port (also conceived as hub ports or centrality) and most gateway ports in China serve high dependence on foreign trade. Within the same port region, gateway ports are usually considered to compete with each other directly owing to adjacent geographical locations. Other peripheral ports act as assisting ports and serve their gateway ports. However, this classification blurred port relationship within the same port region with more peripheral ports springing up. The anticipated networking between hubs and assisting ports didn't form, but fast increase of these "assisting" ports put new competition pressure on hub ports. Hence, we introduce the concept of SMPs in this paper to re-construct the competition mechanism in multi-port gateway region. To verify the application of SMPs, we assume this concept can only be employed to explain the port in the same port region, i.e. Yingkou port with 225.01 million tons of cargo volume in 2010, the 10th large seaport in China, ranks the sixth place in

the BER. In other words, a large port nationwide is measured as a medium sized port in the BER context. In current China port statistics, ports of “above Designated Size” are included but definition of “designated sized” is not specified. In this paper, we introduced definition of SMPs by classifying ports into three levels: big, medium-sized and small ports according to the five-dimension method discussed above. In Sections III, IV and IIV, we provide an in-depth description of ports with similar characteristics and draw more academic attention to SMPs. In this paper we mainly discuss the role of SMPs in enhancing the competitiveness and hinterland identification of multi-port gateway regions.

2. GENERAL PROFILE OF MULTI-PORT GATEWAY REGION IN THE BER

The multi-port gateway region in the northeast of China (defined as Bohai Sea Economic rim, BER) has seen a strong growth in recent years partly as a result of the efforts of the Chinese government to promote the region as a third major growth pole after PRD and YRD regions. The ports in the BER are becoming more important in the worldwide spoke-and-hub system as well. Major gateways of Dalian, Tianjin and Qingdao climbed in the world ranking and growth in Yingkou port even reached by 25% in 2009 (Table 1). Previous port competition analysis usually emphasized gateway port and the rest ports were conceived as assisting ports that couldn't form direct competition over these hub ports. With the rapid increase of SMPs, original port competition hierarchy has been blurred, and the periphery challenge by Yingkou ports, as well as other SMPs puts competitive pressure on the BER port system.

The BER is interpreted as the economic area around the Bohai Sea and a part of the coastal areas along the South Sea, which are also named as the Golden Coastline. The BER includes Beijing (Jing), Tianjin (Jin, Municipality), Liaoning (Liao), Hebei (Ji), Shanxi (Jin), Shandong (Lu) and eastern Inner Mongolia, covering 1.12 million square kilometers totally. More than 60 ports are dispersed along 5,319 kilometers of coastline in the BER. According to the data availability, we include 11 ports in this paper as our research objectives (Figure 1).

The BER is divided into three subordinate multi-port gateway regions in terms of geographical locations (Table 2): Liaoning, Jin-Ji and Shandong Bay. In contrast to other port clusters in China, the BER port group is more evenly distributed. Four ports of Dalian, Yingkou, Jinzhou and Dandong constitute the Liaoning port group, occupying 25.4% of total cargo volume in the BER in 2010. Comparatively, ports of Tianjin, Qinhuangdao, Tangshan and Huanghua are in the center of the BER, with 44.3% of market share, and the rest of ports serve Shandong bay.

Port competition in the BER can be re-identified if we include more ports, and the Pusan Port in the South Korea is exemplified as a typical case. The Pusan port deals with most transshipment importing from and exporting to China, Japan and other areas, and has formed direct competition over load centers (Dalian, Tianjin and Qingdao) of the BER. These gateway ports are mainly driven by foreland and compete with each other for international trade cargoes. The Pusan Port and three gateways ports of China have no cooperation and in between these ports direct competition exists. Direct competition in question covers two meanings: Above all

Tab. 1. Ports of BER in the world top container ports rank in 2009

Rank in 2008	Rank in 2009	Port	Throughput in 2008 (TEU)	Throughput in 2009 (TEU)	Change
59	41	Yingkou	2 036 400	2 537 000	25%
75	70	Yantai	1 510 000	1 401 100	-7%
24	22	Dalian	4 500 495	4 550 000	1%
14	11	Tianjin	8 500 000	8 700 000	2%
10	9	Qingdao	10 320 000	10 260 000	-1%

Source: author's elaboration on China port yearbook

Tab. 2. Multi-port gateway regions in the BER – key characteristics

Port region	Gateway port	Positioning of gateway port	Assisting ports	Cargo category	Hinterland
Liaoning	Dalian	Northeastern Asian International Shipping Center	Yingkou Jinzhou Dandong	Petroleum, grain, ore, steel	Liaoning\Jilin\Heilongjian Provinces, eastern Inner Mongolia
Shandong Bay	Qingdao	Northeastern Asian International Shipping Center	Yantai Rizhao Weihai	Coal, petroleum, ore, container	Shandong Bay, Henang Provinces
Jin-Ji	Tianjin	Northern Shipping and Logistics Center of China	Qinhuangdao Tangshan	coal and derivatives, steel, ore	Beijing, Tianjin, Hebei, Shanxi

Note: Positioning of gateway ports: the role and of these gateway ports outlined by central Chinese government



Fig. 1. Multi-port gateway regions in the BER

three Chinese hub ports face challenge from the Pusan Port due to cost factor, and it means cargos previously handled by these ports are now transported to the Pusan Port and then to other foreign ports, say Longbeach, etc. In the Pusan port, the Terminal Handling Charge (THC) is about \$ 40 per container in contrast to average \$ 88 in Chinese gateway ports in the BER. Besides, in between three Chinese gateways ports, competition also becomes intense because all these ports are driven by foreland and depend on international trade. The port competition in between one big transshipment port (Pusan) and three hub ports (Tianjin, Qingdao and Dalian) in the BER is similar to the PRD region in the south of China with existence of Hong Kong, Shenzhen and Guangzhou ports. In the PRD, the Hong Kong Port bears most transshipment, Shenzhen holds high percentage of international trade cargoes and Guangzhou serves more for domestic trade.

3. SMPS FEATURES AND PORT COMPETITION

3.1 Volume/market share

In order to identify port categories in the BER, we integrate data in total cargo volume, cargo traffic in the international trade and container traffic as measurement. All data are available exactly in the *China Port Yearbook*. Accordingly, we calculate the data of cargo traffic and container traffic and corresponding share (Table 3).

By two dimensions (X axis as total cargo volume, Y axis as container traffic), we classify ports in the BER into three categories: big, medium sized and small ports. Qingdao, Tianjin and Dalian are as big ports, with 46.25% of total market share.

Tab. 3. Port ranking, cargo volume and container traffic in the BER (2010)

Rank	Port (City/region)	Total cargo volume in million tons (A)	Container traffic TEUs in thousands (B)	Market share (A/total A)	Centralization degree
1	Tianjin	400.45	9439.92	17.44%	46.25%
2	Qingdao	360.42	11848.51	15.69%	
3	Dalian	301.31	5060.88	13.12%	
4	Qinhuangdao	257.14	340.04	11.20%	46.62%
5	Tangshan	250.62	244.52	10.91%	
6	Yingkou	225.01	2679.48	9.80%	
7	Rizhao	188.00	1061.01	8.19%	
8	Yantai	150.00	1527.31	6.53%	
9	Jinzhou	60.08	754.79	2.62%	7.13%
10	Dandong	55.05	319.72	2.40%	
11	Weihai	48.66	441.73	2.12%	
Total		2296.74	33717.90	100.00%	100.00%

Source: author's elaboration on China port year book 2011. Total cargo volumes include transshipment and transit volumes.

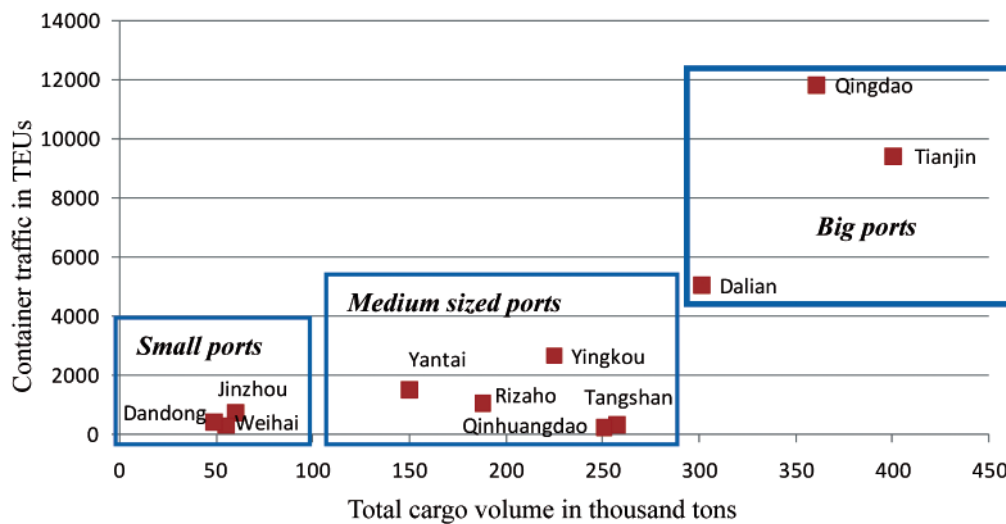


Fig. 2. Port hierarchy in terms of total cargo volume and container traffic

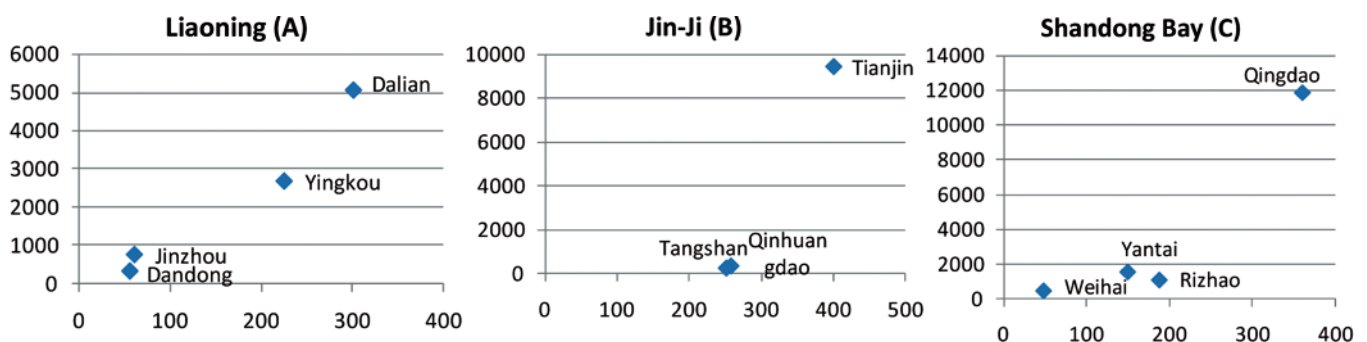


Fig. 3. Port hierarchy distribution in terms of total cargo volume.

Note: X axis in thousand tons and Y axis container traffic in TEU. Note different scales on the Y axis

Qinhuangdao, Tangshan, Yingkou, Rizhao and Yantai are medium sized ports, with 46.62% of total market share, while Jinzhou, Dandong and Weihai are defined as small ports, weighing 7.13% of total market shares (Figure 2). The fierce competition is present among medium sized ports.

If we have a deeper look at port competition mechanism in each separate port cluster, we'll find subtle difference (Figure 3). In the Liaoning port cluster, the gap between big port (Dalian ports) and medium sized one (Yingkou port) is narrowed to the hilt, so as for two small ports of Jinzhou and Dandong. Therefore, in Liaoning, ports competition exists between big port and medium sized ports, and the port "inbetweeness" competition phenomenon is obvious. In contrast, we get to know more competition in between medium sized ports in the Jin-Ji and the Shandong bay, while the difference between big ports and medium sized ports are too far to be defined as direct competition.

To better measure port competition and position of SMPs, we introduce Herfindahl–Hirschman Index (HHI index) to measure market concentration.

$$H = \sum_{i=1}^N s_i^2$$

Where s_i is the market share of port i in the market, and N is the number of ports.

$$H_{(A)} = 0.4412$$

$$H_{(B)} = 0.3567$$

$$H_{(C)} = 0.4007 \text{ (calculated from table 4)}$$

HHI index of the three regions are above 0.25, indicating a high concentration. The Liaoning with 0.4412 means the highest concentration degree in the BER. Market concentration

in BER shows a high degree, but HHI index can't measure the future uncertainty and to what extent the rise of SMPs can threaten dominance of hub port. Thus we introduce three definitions here: centralization degree (η), average centralization degree ($A\eta_{i,j}$) and variance (δ).

Tab. 4. Average centralization degree and variance of ports in the BER

Port/ $A\eta_{i,j}$, $\delta_{i,j}$	$A\eta_{i,j}$	$\delta_{i,j}$
Liaoning (A)		
Dalian	60.30%	0.0952
Yingkou	25.88%	0.0337
Jinzhou	9.22%	0.0006
Dandong	4.60%	0.0167
Jin-Ji (B)		
Tianjin	45.54%	0.0093
Qinhuangdao	35.11%	0.0549
Tangshan	10.54%	0.0453
Huanghua	8.80%	0.0281
Shandong Bay (C)		
Qingdao	56.78%	0.0428
Rizhao	22.65%	0.0155
Yantai	15.67%	0.0089
Weihai	4.90%	0.0007

$\eta_{i,j}$ = cargo volume of port i /cargo volume of port cluster j . Measures the market share of a port in corresponding port cluster. We adopt this figure to analyze port competition intensity. (2.1)

$$A\eta_{i,j} = \frac{\sum \eta_{i,j}}{10} \quad (i,j=1\dots n) \quad (2.2)$$

Average market share in 10 years.

$$\delta_{i,j} = \sum (\eta_{i,j} - A\eta_{i,j})^2, \quad (i,j = 1 \dots 10) \quad (2.3)$$

Measure what extent the position of a port will be changed, the higher value of δ , the high risk that a port's position could be changed.

If we compare $\eta_{i,j}$ and $A\eta_{i,j}$ values of Liaoning (A), we'll find more market shares are centralized among Dalian and Yingkou, and variance (δ) of Dalian is 0.0952, highest among all ports in the BER, which indicates the most possible peripheral challenge by medium-sized ports in Liaoning port competition structure. By contrast, variances (δ) in Tianjin and Qingdao are 0.0093

and 0.0428 respectively, illustrating a relatively stable port hierarchy. Decrease of the underlying change factors means the threat from SMPs in these two regions declines (Tables 2, 3 and 4). Therefore, the future port competition mechanism in Liaoning contains more uncertainties and changes while relations between hubs and SMPs in the other two regions keep relatively stable. The change factor involved in this paper has excluded the change possibility from external ports. If we include more adjacent ports in other nations, such stability may contain more changing factors.

3.2. International port connectivity in the BER

Beyond considering the size of ports to differentiate them, we classify ports into three categories depending on the cargo source only associated with container traffic (Table 7). Through

Tab. 5. Total cargo volume in the BER 2001-2010

Port/Volume	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Liaoning (A)	136.77	153.82	183.18	239.49	291.25	368.80	406.46	476.46	544.15	641.45
Dalian	100.47	108.51	126.02	145.16	170.85	200.46	222.86	245.88	272.03	301.31
Yingkou	25.20	31.27	40.09	59.78	75.37	94.77	122.07	150.85	176.03	225.01
Jinzhou	11.10	14.04	17.07	24.55	30.03	31.57	35.15	47.23	52.59	60.08
Dandong				10.00	15.00	42.00	26.38	32.50	43.50	55.05
Jingji (B)	238.29	255.72	339.77	428.57	510.97	595.65	707.51	796.58	889.86	1004.21
Tianji	113.69	129.06	161.82	206.19	240.69	257.60	309.46	355.93	381.11	400.45
Qinhuangdao	113.02	111.67	125.62	150.37	169.00	204.89	248.93	252.31	249.42	257.14
Tangshan	11.02	14.65	20.83	26.02	33.65	51.71	65.79	108.54	175.59	250.62
Huanghua	0.56	0.34	31.50	45.99	67.63	81.45	83.33	79.80	83.74	96.00
Shandong Bay (C)	162.48	189.84	226.64	261.46	331.37	413.01	517.89	585.26	661.46	747.08
Qingdao	103.98	122.13	140.90	162.65	186.78	224.15	265.02	300.29	315.46	360.42
Rizhao	29.33	31.36	45.07	51.08	84.21	110.07	130.63	151.02	181.31	188.00
Yantai	21.90	26.89	29.36	34.31	45.06	60.76	101.29	111.89	123.51	150.00
Weihai	7.27	9.46	11.31	13.42	15.32	18.03	20.95	22.06	41.18	48.66
Total (A+B+C)	537.54	599.38	749.59	929.52	1133.59	1377.46	1631.86	1858.30	2095.47	2392.74

Note: million tons except noted. Since 2007, the data for Yantai includes Yantai port and Longkou port.

Source: author's elaboration on year book 2001-2010.

Tab. 6. Centralization degree of the ports in the BER

Port/ $\eta_{i,j}$	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Liaoning (A)										
Dalian	73.46%	70.54%	68.80%	60.61%	58.66%	54.35%	54.83%	51.61%	49.99%	46.97%
Yingkou	18.43%	20.33%	21.89%	24.96%	25.88%	25.70%	30.03%	31.66%	32.35%	35.08%
Jinzhou	8.12%	9.13%	9.32%	10.25%	10.31%	8.56%	8.65%	9.91%	9.66%	9.37%
Dandong	0.00%	0.00%	0.00%	4.18%	5.15%	11.39%	6.49%	6.82%	7.99%	8.58%
Jin-Ji (B)										
Tianjin	47.71%	50.47%	47.63%	48.11%	47.10%	43.25%	43.74%	44.68%	42.83%	39.88%
Qinhuangdao	47.43%	43.67%	36.97%	35.09%	33.07%	34.40%	35.18%	31.67%	28.03%	25.61%
Tangshan	4.62%	5.73%	6.13%	6.07%	6.59%	8.68%	9.30%	13.63%	19.73%	24.96%
Huanghua	0.24%	0.13%	9.27%	10.73%	13.24%	13.67%	11.78%	10.02%	9.41%	9.56%
Shandong Bay (C)										
Qingdao	64.00%	64.33%	62.17%	62.21%	56.37%	54.27%	51.17%	51.31%	47.69%	48.24%
Rizhao	18.05%	16.52%	19.89%	19.54%	25.41%	26.65%	25.22%	25.80%	27.41%	25.16%
Yantai	13.48%	14.16%	12.95%	13.12%	13.60%	14.71%	19.56%	19.12%	18.67%	20.08%
Weihai	4.47%	4.98%	4.99%	5.13%	4.62%	4.37%	4.05%	3.77%	6.23%	6.51%

Source: author's elaboration on China port year book 2011.

Tab. 7. International connectivity of the ports in the BER 2010

Rank	Port (City/region)	Container cargo traffic TEUs in thousands (B+C)	Container Cargo traffic in international trade TEUs in thousands (B)	Share of int. trade traffic (B/(B+C)*100%)	Container Cargo traffic in domestic trade TEUs in thousands (C)	Share of domestic trade traffic (C/(B+C)*100%)
1	Qingdao	11848.51	10046.05	84.79%	1802.46	15.21%
2	Dalian	5060.88	4065.79	80.34%	995.09	19.66%
3	Tianjin	9439.92	5422.86	57.45%	4003.42	42.41%
4	Weihai	441.73	221.07	50.05%	222.30	50.33%
5	Qinhuangdao	340.04	122.83	36.12%	217.21	63.88%
6	Yantai	1527.31	366.39	23.99%	1160.91	76.01%
7	Dandong	319.72	54.94	17.18%	264.79	82.82%
8	Tangshan	244.52	23.09	9.44%	221.43	90.56%
9	Rizhao	1061.01	29.39	2.77%	1031.62	97.23%
10	Yingkou	2679.48	48.08	1.79%	2631.41	98.21%
11	Jinzhou	754.79	10.98	1.45%	743.81	98.55%

Source: author's elaboration on China port yearbook 2010.

assessment of international trade cargo percentage, Tianjin, Qingdao, Dalian and Weihai are of high degree of connection with international trade, i.e., highest of Qingdao with 84.79% and comparatively low of Weihai 50.05%. However, we need to draw attention that the Weihai port in this category is a special case because its small total volume and part of volume derives from transshipment of Qingdao. Therefore, even with high degree of international connectivity, Weihai can't be defined as a hub port. Port competition in the Shandong Bay is decentralized in terms of international port connectivity. We consider the second category of ports as domestic trade driven ports with medium degree of international connectivity. Three ports in this category, Qinhuangdao, Yantai and Dandong are located in three different port clusters. Furthermore in the third category, Yingkou, Tangshan, Rizhao and Jinzhou ports are domestic trade driven ports with comparatively low degree of international connectivity (Figure 4).

By analysis in port size and cargo classification, we therefore define hub ports in the BER as the ports of Qingdao,

Tianjin and Dalian. Port competition in the BER has the following characteristics: first, hub port competition is more intense as all three ports are similarly highly international trade driven. Second, Hub port and SMPs competition has reduced in Liaoning and Jin-Ji port cluster because Dalian and Yingkou are driven by international trade and domestic trade respectively, and similar to Tianjin and Qinhuangdao. Even closely located, SMPs and hub ports serve prominent roles. In comparison, the port competition in the Shandong Bay is more fierce, and the ports of Qingdao, Weihai and Yantai share high degree international trade dependence. In general, competition in between SMPs and central ports in the BER confines to regional area. For instance, Yingkou port's growth can challenge dominant position of Dalian port but there is no evidence that it has threat over Tianjin or Qingdao port. Some medium-sized ports in the BER are becoming regional centers as most SMPs in this region are hinterland-driven that requires more for accessibility to hinterland. The process of strengthening consecutiveness to hinterland speeds up their increasing role as

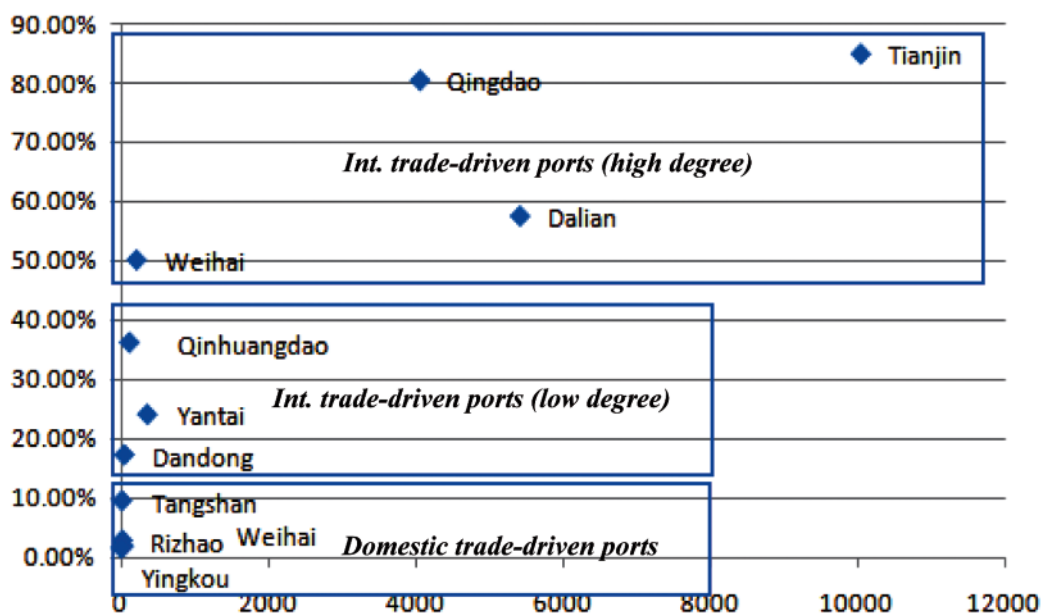


Fig. 4. Port category according to foreign trade cargo traffic

a regional center that requires more sophisticated functions in logistics system. Third, there is no clue that SMPs in different port clusters have direct competition. The fourth analysis on the port competition is developed among small and medium-sized ports in the BER. In contrast to direct competition between medium-sized and hub ports, this category contains more cooperation, and merger & acquisition cases are more prevalent among these ports. For example, in 2005, Yingkou port acquired Jinzhou port by taking its advantage of oil transportation, and in 2012 Yingkou was negotiating with Dandong port for further merger. Similar to the third category, competition among these ports is also restricted to the same region.

3.3. The role of SMPs in the relative port cluster

The role of SMPs in a multi-port gateway region varies in the whole supply chain. Some ports transship cargoes from hub ports and function as complements or assisting ports, while in contrast, other ports challenge the dominant position of centrality ports as substitutes with their rapid expansion in market competition. In the BER, “substituting” SMPs can be found in Liaoning and Jin-Ji ports region, and relationship between Dalian and Yingkou (Liaoning) as well as Tianjin and Qinhuangdao (Jin-Ji) is described as direct competition between incumbent hub ports and new emerging sub-hub ports. The possibility of dual-hub ports in specific regions receives attention from academic concerns (Wang, 2012). Though dual-hub ports can attract more cargoes and enhance overall competitiveness of such region, new risks may undermine this plausible blooming picture. On the one hand, the rise of sub-hub ports, conceived as medium-sized ports in this paper, will put more competition on hub ports. On the other hand, hub ports

need to either expand port size or improve efficiency to maintain port attractiveness. Some hub ports choose to construct new berth in a location near those sub-hub ports or accelerate pace in acquiring more small ports to enhance their competitive positions, i.e. in 2010 Dalian port acquired Lvshun ports which is closer to Yingkou and inland port of Shenyang in order to compete with adjacent Yingkou port. Counter measures of Yingkou port was taken such as expanding scale and acquiring the Dandong Port in 2012. This round of escalating ports consolidation restructured Liaoning ports cluster and dual-hub ports pattern in this region is going to emerge. However, expanding port size does not guarantee increasing attractiveness and in the background of volatile economy, both ports are facing problem of over capacity.

However, not all SMPs choose to expand port size when competing with hub ports. for the purpose of competitive advantage, most SMPs remain in their niche market in dealing with specific cargoes to “avoid” direct competition with those centrality ports. This competition system, to a large extent, keeps the multi-port gateway regions comparatively stable. In the BER, all three hub ports mainly deal with international trade cargoes and containership, while the rest of SMPs handle more bulk cargoes and domestic trade cargoes, and most SMPs find specific transportation cargoes in spite of overlapping hinterland (Table 8).

Another way to analyze SMPs’ role in relative port cluster and economic region is how they contribute to the overall port networking. We compare the transshipment of SMPs because this indicator can measure the frequency that SMPs can connect with other ports. Five SMPs serve high degree of domestic trade container transshipment different from big ports (Table 9).

Tab. 8. Cargo classification of SMPs in the BER

Port cluster	Ports	Cargo classification
Liaoning	Yingkou	Mineral, Iron and Timber
	Jinzhou	Timber, Textile products and Iron
Shandong	Yantai	Agricultural products and Iron
	Rizhao	Petroleum and Mineral
	Weihai	Mine construction materials, Coal and Rubber
Jin-Ji	Qinhuangdao	Coal
	Tangshan	Coal and agricultural products

Tab. 9. Transshipment volume of SMPs in the BER (TEU)

Port Region	Port	Total Container Transshipment Volume (A+B+C)		Foreign Trade Container transshipment				Domestic Trade Container transshipment (C)	
				international Container transshipment (A)		Export and Import Trade transshipment (B)			
		2010	2009	2010	2009	2010	2009	2010	2009
Liaoning	Dalian	581169*	388397*	99186	32813	269940	286198	-	-
	Yingkou	389785	232197	-	-	-	-	389785	232197
	Jinzhou	115	1721	-	-	-	-	115	1721
Jin-Ji	Tianjin	193368	44049	79180	9878	81027	1823	33161	32348
	Qinhuangdao	79	18397	27	-	-	-	52	18397
Shandong Bay	Qingdao	730393	631132	132696	49250	591118	572174	6579	9708
	Yantai	715601	682897	-	-	-	-	715601	682897
	Rizhao	13187	1535	-	-	-	-	13187	1535

Note: all transshipment volumes refer seaborne transshipment in between seaports. Data of river-sea transshipment are not available except for Dalian. In 2010 and 2009, 212043 and 102199 TEU were transported between river and sea respectively. **Source:** China port year book 2011. International container transshipment (A): containers loading by the ports in the BER through foreign ports then to export. Export and import trade transshipment (B): containers loading by the ports in the BER through other Chinese ports then to export.

Their role in connecting domestic transshipments within a multi-port gateway region is more prominent compared to international connectivity. SMPs in the regions of Liaoning and Shandong undertake high ratio of transshipment compared to their adjacent hub ports. While in contrast, in the Jin-Ji region, the gateway port of Tianjin undertakes more than 90% of total transshipment volumes. In other words, SMPs in Liaoning and Shandong are more dynamic in the relative port clusters. Their role in transiting domestic containers compensates the shortcoming of adjacent gateways ports; in a result, less intense competition in transshipment market promotes SMPs for the fast growth. The “complement relations” between SMPs and gateway ports in the transshipment market reinforce.

In general, most SMPs in the BER are competitive in niche segment markets and function as a “complement” to hub ports, and the rise of SMPs also makes a port networking complex in such regions. Some SMPs choose to cooperate with the hub ports, for example, in Shandong Bay, a new port system is planned by positioning Qingdao as a gateway port, Yantai and Rizhao as assisting ports (medium sized ports) and Weihai as feeding ports (small ports). Assisting ports will develop more international shipping lines while feeding ports engage in domestic markets. Some SMPs with the rapid increases can form direct competition over the big ports and relations between these ports are more like “substitutes”, such as the port of Dalian and Yingkou. The new emerging SMPs, like Yingkou ports, will implement more mergers and acquisitions for port expansion to gain more competitive advantage in competing with ports much larger than its size.

4. PORT CITY AND HINTERLAND CHARACTERISTICS OF SMPs

In this section, we analyze the interactions between SMPs and their hinterland capture. A distinction is made between the direct hinterland of the port and the more distant/extended hinterland. Hinterland access is one of the important factors that influence the competitiveness of a seaport when it competes with other ones.

The direct hinterland refers to the port city region and the extended hinterland is the coverage of a port where cargoes are transported from and to. Port cities were settlements, where cargoes were interfaced between land and ocean and where related businesses emerged about fifty years ago. However, correlation between ports and cities has changed a lot, i.e., a large city does not necessarily have a large port (e.g., London)

and vice versa (Talley 2009). Some big cities may have a small port (e.g., the U.S. cities San Diego, Philadelphia, Boston, etc.). The rationale is that the case for the cities can emerge “through agglomeration forces generated by the interaction of increasing returns and transport costs” (Fujita and Mori 1996).

In the BER, all three gateways ports (big ports) are accompanied with big cities and GDPs from these port cities rank in a sequent order that accords with corresponding port cargo volumes (Table 10). This correlation has been enhanced through institutional and policy effects, Tianjin expands its city area to the Binhai new city and Dalian port benefits from an economic revitalization policy issued in 2006. However, ports have no too direct relation with cities in a group of the medium-sized ports. For instances, GDP of Yantai city ranked the sixth position with 435.85 billion Yuan in 2011, while the cargo volumes of Yantai port were the eighth in the BER, and is the smallest port among all medium-sized ports. The production output of port city seems to be no impact on port freight expansion. Similarly, large size of Yingkou port doesn’t generate quasi big city because the GDP of Yingkou city is the smallest of all eleven study samples. This inconsistency also applies into small ports, such as Jinzhou port.

From the perspective of port cities, the industrial distribution and transportation demand will affect port attractiveness for cargoes. Like Jinzhou, the city close to Beijing with convenient rail and road connection with the adjacent big cities and most generated transportation demand can be satisfied through land transportation. On the other side, the extended hinterland yields more crucial effect on SMPs’ freight, and next, we’ll take the Yingkou Port for example for an in-depth analysis on how the extended hinterland affects SMPs.

We collect data from the inside of the Yingkou Port that is classified in terms of two dimensions: inbound and outbound cargo volumes through Yingkou port. Connecting ports and cargoes with few volumes are ignored in this paper (Table 11). In composing of outbound cargo volume, the Yingkou port exerts a moderate effect on the BER economy, and cargo volume exported from Yingkou port to the rest BER ports accounts for 12.3% of total cargo volumes, in comparison, more cargoes are imported to Yingkou port through the BER ports and corresponding figure reaches to 27.5%. The main demand for the Yingkou port is distributed in the south of China, for example, two regions of Guangdong and Shanghai make up the largest proportion of Yingkou port cargo volumes. The extended hinterland supports Yingkou port’s freight more than the port city does. In other words, niche market for SMPs

Tab. 10. Port cargo volume and port city GDP rank in 2011

Port cargo volume rank in the BER	Port cargo volume rank Nation wide	Port (City/region)	Total cargo volume in million tons	Port City GDP in Billion Yuan (RMB)	Port city GDP Rank in the BER	Port city GDP rank Nation wide
1	3	Tianjin	451.00	910.88	1	6
2	5	Qingdao	375.00	566.62	2	10
3	6	Dalian	338.00	515.8	3	14
4	7	Qinhuangdao	287.00	93.05	9	127
5	8	Tangshan	308.00	446.9	4	19
6	9	Yingkou	261.00	100.24	8	119
7	10	Rizhao	250.00	102.51	7	115
8	12	Yantai	180.00	435.85	5	20
9	-	Jinzhou	72.00	90.26	10	133
10	-	Dandong	76.37	72.89	11	175
11	-	Weihai	55.01	194.47	6	60

Tab. 11. Inbound and outbound cargo volumes of Yingkou port 2010

Rank	Outbound		Inbound	
	Port	Total cargo volume	Port	Total cargo volume
1	Guangdong	24217.18	Guangdong	16453.11
2	Shanghai	17237.64	Shanghai	12540.21
3	Jiangsu	15900.89	Fujian	9440.32
4	Fujian	10346.64	<i>Jin-Ji</i>	<i>7891.28</i>
5	Zhejiang	5862.32	<i>Shandong Bay</i>	<i>7799.36</i>
6	<i>Shandong Bay</i>	<i>4109.32</i>	Zhejiang	6010.42
7	<i>Liaoning</i>	<i>3822.14</i>	Jiangsu	5347.51
8	<i>Jin-Ji</i>	<i>2570.53</i>	<i>Liaoning</i>	<i>3373.87</i>
9	Guangxi	829.38	Guangxi	273.52
10	Anhui	710.76	Anhui	90.42
11	Hainan	28.68	Hubei	85.13
12	Hubei	7.17	Hainan	20.02
13			Jiangxi	11.37
Total		85642.65		69336.53

Thousand tons except noted.

Source: authors' elaboration on Yingkou port annual report 2010.

not only refers to cargo classification as introduced above, but also their attractiveness to transport cargoes to further regions in order to avoid intense competition over overlapping hinterland. However, individual case can't represent all cases of SMPs and further research into more cases can justify how extensive hinterland can enhance the role of SMPs in multi-port gateway regions.

5. LOGISTICS AND DISTRIBUTION FUNCTION OF SMPS

A seaport is a logistic and industrial node in the global transport system with a strong maritime character and in which a functional and spatial clustering of activities takes place. Activities that are directly or indirectly linked to seamless transportation and transformation process within the logistic chains (OECD, 2000). But seaports are complex and dynamic entities, often dissimilar from each other, where various activities are carried out by and for the account of different actors and organizations. Such a multifaceted situation has led to a variety of operational, organizational and strategic management approaches to port systems (Bichou and Gray, 2005). The current logistics nodes overlap in terms of function resulting in weak scale economies, so as to the role of SMPs and gateway ports in the same logistics system. A variety of methods in evaluating ports logistics and distribution functions have been applied, such as DEA (data envelopment analysis) method. Qi and Han (2006) assessed port logistics function efficiency by using DEA and drew a conclusion that Dalian port is more efficient than Yingkou, Dandong and Jinzhou. However, such conclusion is based on infrastructure as an input and cargo volumes as an output, such as yard area and berth length, while ignoring the inland port connection and multimodal transportation. The whole logistics industry in the BER is characterized by small scale businesses which offer basic logistics services such as warehousing and transportation. The inland port facilities and optimized logistics nodes should conform to three criteria: direct link to a seaport; high capacity transport link(s) and availability of services found in a seaport

(Roso and Léveque, 2002). To enhance ports' role in logistics system, gateways ports of Tianjin, Qingdao and Dalian chose to establish logistics parks and container logistics center that are located close to ports by providing warehousing and other value added services. For instances, three logistics centers were set up in the Dalian port, and Shenyang and Harbin serving for containers pick-up and loading business. Compared to self-established logistics infrastructures, SMPs seek to cooperate with inland cities by co-setting up inland ports to attract more cargoes from inland areas. Yingkou port utilizes inland port in Shenyang to expand its intermodal transportation and function in the whole logistics system. Whereas, inland connection among SMPs is less stressed in the Jin-Ji region and the Shandong Bay, and the main reason is that in these two regions, SMPs haven't formed direct competition over gateways ports. As a result, the logistics function of SMPs has been ignored. The dominant difference between logistics park and inland port in the BER lies in governance. Logistics parks are usually solely invested by port authority, where inland ports usually are launched by inland city governments and port authorities by agreement to invest or take share in part of infrastructures. Therefore, in the BER region the logistics system lacks the scale and the sophistication in order to cope with the increasing demand for modern logistics concepts. The role of SMPs in the whole logistics system or vice versa hasn't been improved in accord with their throughput growth.

Besides, intermodal transportation is another indicator in assessing the SMPs' logistics function. Intermodal connectivity and landside access to Chinese ports are not approached differently or in a more sophisticated way than in the United States or European Union. Many new built port facilities are located in large urban areas, and the access to and from these ports involves traversing mixed-use roadways (ITSP, 2008). In China, rail access to seaborne port hasn't gained enough investment, and railroad-sea (mainly containers) shipment accounts for more than 95% of total intermodal transportation. However, due to the increasing pressure from volatile oil price and demand for less emission, the intermodal transportation for rail-sea containers (RSC) receives more attention from

policymakers and practitioners. From international port experience, such transportation methods with high efficiency occupy high weight in a mature port, for example, about 13% of cargoes are transported from RSC in the port of Rotterdam and 11% in the New Jersey port respectively. While in contrast, the ratio is relatively low to average 2% in China, 84% of cargoes are transported through road-sea, and 14% are in between waterway and even lower in SMPs. In the BER, medium-sized ports bear less RSC transportation shares except for Yingkou port, and it came to 170,000 TEU containers through RSC, accounting for 7.6% of total container freight in 2009. The rest of SMPs only take up less than 0.5% of RSC cargoes. In contrast, in the adjacent gateway ports, the Dalian port has transported 250,000 TEU containers through RSC, accounting for more than 5% of total container freight. Tianjin and Qingdao are next to these ports, making up 2% and 0.8% respectively. SMPs in the BER are in a low ratio in terms of RSC transportation. One reason is that most SMPs in the BER handle much less containers compared to their bulk cargo volumes. The other reason is that most cargoes now are manufactured in coastal areas that are close to ports, with less need for long distance of railway transportation. However, with increasing labor and land costs, parts of manufacturing factories are transferred to more inland areas. RSC transportation could be another niche market for SMPs. Some SMPs in the BER are already committed to exploring this market to develop containerhips. For example, in Yingkou, three newly-developed sea-rail express routes with two days a shift are operated by COSCO, while the neighboring gateway ports of Dalian manage two routes and one of them is in a daily shift. Besides, Rizhao port also tries to develop such intermodal transportation to seek a more competitive position in logistics system of the BER.

Overall, we can conclude some typical characteristics in describing the profile of SMPs in the BER, and ports with annual cargo volume of less than 150 million tons are defined as SMPs (Table 12). Most SMPs in the BER are driven by domestic trade cargoes and competitive in bulk cargo market. Consequently, the less dependence on the world spoke & hub system retains SMPs to niche markets. Compared to the gateway ports, the market shares of those SMPs are increasing rapidly, and in specific regions, this fast market expansion even challenges the dominant position of neighboring gateway ports. To enhance or maintain the competitive position, some SMPs may choose agglomerations that contribute to port networking in such regions and we found more cooperation in between SMPs. When studying correlations between SMPs and port city/hinterland, we found less connection between ports city GDP growth and throughput, and the freight of SMPs may depend more on extensive hinterland and connection with inland ports.

However, the medium-sized ports differ from small ports. The peripheral challenge by SMPs refers to medium-sized ports only as there is no evidence that small ports can form direct competition on medium-sized port or gateway ports.

6. CONCLUSION

Difference between SMPs and gateway ports concerns not only the size of a port but endogenous heterogeneity. Every big port has experienced the start-up stage and evolves into the centrality position but not all the SMPs can grow into large ports. The main reason is how SMPs survive and maintain their competitive advantage in the highly competitive multi-port gateway regions. Some SMPs retain their capacity in specific niche markets or undertake transshipment to avoid competition from the hub ports. While other SMPs that intend to challenge the dominant position of gateway ports demonstrate the similarities. Firstly, port classification regarding part of SMPs and gateway ports is of clear divisional function. And they are either international trade or domestic commerce driven. In other words, relation between SMPs and gateway ports is more like "complements". Moreover, this relationship contributes to the relatively stable status in a multi-port gateway region and leaves enough space for development of SMPs. Secondly, with the rise of individual SMPs, this "complements" relation evolves into "substitutes", and gateway ports capture cargoes previously predominated by SMPs. This competition, to some extent, may result in vicious circle and overcapacity as both competitors are expanding port sizes rapidly when they seek the economies of scale. The other risk is that this escalating competition will undermine the complete logistics system and reduce the whole region's competitiveness in terms of logistics efficiency in confronting with the external challenges. The rest SMPs will choose to either maintain in their niche markets or cooperate with leading ports that will trigger the port consolidation and bring synergy effect. Therefore, the competition system in such multi-port gateway regions will evolve into a more dynamic and growing port cluster, in which, SMPs act like nodes connecting relevant stakeholders.

The three-level port classification by employing multi-dimension variable methods provides an in-depth analysis into the ports categories, and can be employed to describe the profile of SMPs, mainly from the role of SMPs in a competitive context. The further research will focus more on internal operation management of SMPs, for example, how to evaluate SMPs' performance, institutional factor on their developments, SMPs' role on enhancing multi-port gateway region's competitiveness, etc. The purpose is to find a compound research method to assess SMPs. Another issue concerned is

Tab. 12. Characteristics of SMPs and hub ports in the BER

Characteristics	SMPs	gateway ports
Port size	Medium size: cargo volume of 150-300 million tons Small size: cargo volume of less than 150 million tons	Cargo volume of over 300 million tons
Port classification	Domestic trade driven	International trade driven
Cargo	Bulk	Container
Market share	Increasing	Stable to decreasing
World spoke & hub system	Less connected	Connected
Port-city	Less correlated	Correlated
logistics system	Inland port connection	Logistics park
Port networking	Co-petition	Competition
Intermodality	Less connected	connected

the generalized application study on more SMPs worldwide that needs exploring more cases studies, especially in more extremely different regions.

The above characteristics for SMPs in the BER may change because of two factors: decrease of international trade due to volatile global economy and future free trade zone between Korea, Japan and China. The decline of international trade may force hub ports to switch to domestic trade and competition between hub ports and SMPs will change as well. The other factor is the proceeding of the free trade zone (FTZ) between neighboring three countries of China, South Korea and Japan. If FTZ is established, on the one hand, all ports will receive more cargoes and benefit from more convenient cargoes transferring. In other words, the overall throughput and port attractiveness in the north of Asia will improve, but both SMPs and hub ports in the north of China will face competition from Korea and Japan so that the previous port relations will be broken and the competition will surpass the current boundary restriction.

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A new planning model to support logistics service providers in selecting mode, route, and terminal location

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ABSTRACT

In this paper, we address the freight network design problem. A mixed integer linear program is formulated to help logistics service providers jointly select the best terminal locations among a set of candidate locations, shipping modes, and route for shipping different types of commodities. The developed model is applied to two different networks to show its applicability. Results obtained from CPLEX for the case studies are presented, and the benefit of the proposed model is discussed.

Key words: Intermodal transport; Freight logistics; Network design; Facility location; Routing; Mode choice

INTRODUCTION

Over the last 50 years, international trade in manufactured goods grew 100 fold, straining global supply chains and the underlying support infrastructure (IBM, whitepaper). Consequently, shippers and receivers are forced to look for more efficient ways to move their products. The process of moving products (i.e. freight) from one point to another is known as freight transportation. Typically, when freight is transported over long distances, more than one mode is used due to limited access at the receiving end (e.g. no rail access at distribution center or warehouse). Other reasons for considering more than one mode in transporting freight include (Eberts, 1998): (1) lowering overall transportation costs by allowing each mode to be used for the portion of the trip to which it is best suited, (2) reducing congestion and the burden on overstressed infrastructure components, and (3) reducing energy consumption and contributing to improved air quality and environmental conditions. When there are more than one mode involved in delivering freight (known as intermodal freight transportation), the cost of each mode, the trip time on each mode, the time that it takes to transfer to another mode, and the location of that transfer play a critical role in the overall efficiency of the process. One of the reasons for the inefficiencies in intermodal freight transportation is the lack of planning on where to locate intermodal facilities in the transportation network and to expand the surrounding infrastructure to accommodate newly generated traffic. This paper addresses this need by proposing a model that considers the intermodal terminal location jointly with other criteria.

Figure 1 illustrates a simple intermodal freight transportation network that consists of shipping origins and destinations, highway network that connects all origins and all destinations, limited number of intermodal terminals, and rail, air, or barge networks that connect the various intermodal terminals; an intermodal terminal is the location where freight is transferred between different modes. In this illustration, it can be seen that freight can be shipped directly from an origin to a destination using only the highway mode. Alternatively, freight can be shipped first to a nearby intermodal terminal, then shipped to another intermodal terminal near the destination using another mode such as rail, air, or barge, and finally delivered to the destination using the highway mode. It is evident that the optimal method of shipping will depend on the distance between the origin and destination, the proximity of intermodal terminals to the origin and destination, the type of intermodal terminal available (i.e. rail, air, or barge), and the transport and transfer cost. This paper takes the perspective of logistics service providers who are tasked to serve a multiregional customer base (Ishfaq, 2010). Of particular interest to these decision makers is the management of shipments between origins and destination through the use of different modes, routes, as well as logistic hubs. At a strategic planning level, these service providers need to develop long-term policies on terminal locations, modes, and routes to lower costs.

To assist these logistics service providers with their decision making, this paper proposes a new model that jointly considers a number of factors: establishing a predefined number of intermodal terminals at strategic locations, type of intermodal terminals that should be created, shipping mode, and route for

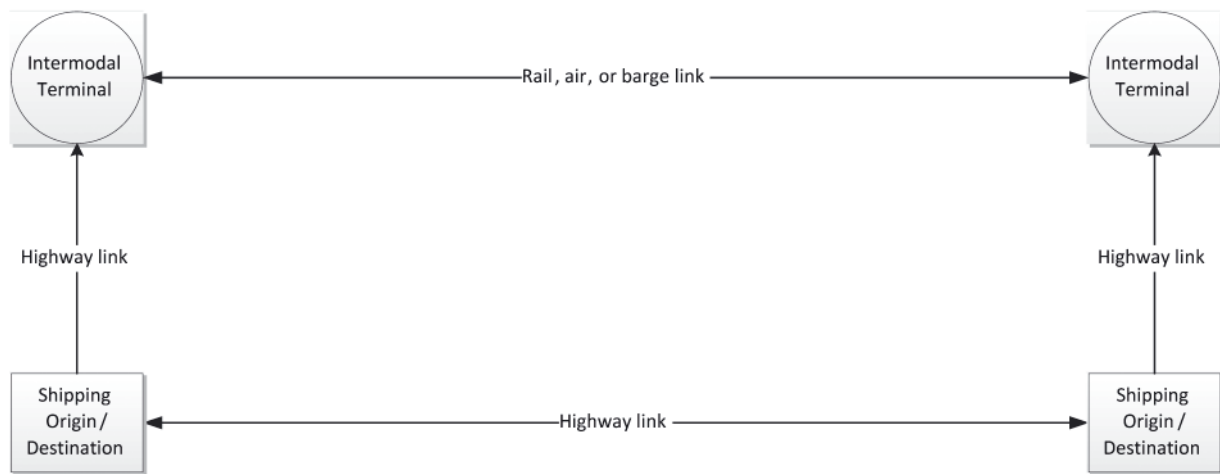


Fig. 1. Illustration of an intermodal freight network

shipping commodities. Additionally, it is envisioned that the proposed model could be used by the decision maker to estimate how many intermodal terminals are needed to maximize return on investment. To our knowledge, this is the first model that addresses multiple decisions jointly in the design of the intermodal freight network.

The remainder of this paper is organized as follows. Section 2 provides a review of related research, followed by the formulation of the proposed mixed integer linear programming model in Section 3. Section 4 discusses the computational results. Lastly, Section 5 provides concluding remarks and plans for future research.

PRIOR RESEARCH

The following summarizes previous studies on two related topics: identifying optimal location for intermodal terminals, and selecting optimal mode and route for shipping freight.

Rutten (1995) was the first to study where to locate new intermodal terminals with and without existing intermodal terminals. In his research, terminals were selected according to their attraction for freight movement so the network could have daily trains between terminals. He evaluated the impact of locating a new terminal on existing terminals' performance. Meinert et al.'s work (1998) involved locating a rail intermodal terminal among several potential sites in a network using simulation. Macharis et al. (1999) used multi criteria decision making to find where to build a new barge terminal in Belgium. They defined a hierarchy of criteria for four candidate locations and then used PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) to find the best candidate. Similarly, Arnold et al. (2001) proposed a mixed integer model to design a rail/road network in Belgium. In their model, two decisions were taken simultaneously. The first decision involved determining which terminals should be opened among a set of potential candidates. The other decision involved allocating the demand between each origin-destination (OD) to either use an intermodal terminal or a direct shipment (hence using just one mode). Groothedde et al. (2005) compared a road/barge intermodal option with a unimodal road network in a consumer goods market. Their heuristic found the best location for intermodal hubs. They concluded that using a hub-based intermodal network is more efficient than a unimodal road network. More recently, Limbourge et al. (2009) developed a model based on the traditional p-hub median problem to find the best location for intermodal terminals on a rail/road network. In addition to considering transportation cost, they

considered a variable transshipment cost in their objective function. The unit transshipment cost relates to volume of flow passes over each intermodal hub. Ishfaq et al. (2010) improved the previously studied intermodal distribution networks by considering a larger intermodal network of road, rail, and air. They integrated service time requirements into a hub location and allocation of demands to selected hubs. They also considered three different types of costs: fixed cost of opening an intermodal hub, modal connectivity cost, and transportation cost.

In freight logistics, the tactical decisions typically involve deciding which mode to use and what route to take to minimize trip time and to ensure reliable delivery (Crainic 2002). Barnhart et al. (1993) discussed methods to compare intermodal routing of rail/road freight network versus unimodal road transport. Least cost routes were selected based on the transportation cost per trailer and per flatcar, respectively. Boardman et al. (1997) proposed a decision support system to help decision makers find the best combination of mode and least cost route for transporting goods. Bookbinder et al. (1998) used simulation to find the best route for moving containers from Canada to Mexico. Boussejra et al. (2004) found the least cost travel path between each origin-destination pair in an intermodal transportation network considering time constraints. Song et al. (2007) developed a model to find the least cost path between each OD pair while minimizing total transportation, transshipment, and holding costs. They considered a time constraint on delivering shipments to their destinations. To make the problem more realistic, Grasman (2006) proposed a dynamic programming approach to find the least cost path considering both delivery time constraint and total transportation cost. Chang (2008) improved the traditional intermodal freight routing problem by considering more than one commodity in his model. He proposed a multi-objective model for his multi-commodity network to find the best route for each OD pair. His model simultaneously minimized total transportation cost and travel time. In the most recent study, Ayar et al. (2012) developed a mixed integer model for an intermodal multi-commodity road/maritime network to find the best route for each OD pair. Their model considered time-window constraints to deliver each commodity to its final destination and total transportation and stocking costs.

Table 1 provides a comparison of previous research's scope vs. our proposed model's scope. As shown, the work by Ishfaq et al. (2010) and Ayar et al. (2012) are the two closest related studies. Our model's contribution to the literature is the ability to deal with different combinations of modes (truck,

Tab. 1. Comparison of previous research's scope vs. proposed model's scope

Research	Decisions			Type of mode	Direct shipping option
	Terminal location	Mode choice	routing		
Arnold et.al (2001)	*			Road/rail	*
Groothedde et al. (2005)	*			Road/barge	*
Chang (2008)			*	Air/rail/truck/barge	
Limbourge et.al (2009)	*			Road/rail	*
Ishfaq et.al (2010)	*	*		Road/rail/air	*
Ayar et.al (2012)			*	Road/maritime	
Proposed model	*	*	*	Any combination of modes	*

rail, air, barge). This feature provides more options for the decision makers and subsequently a more robust intermodal freight network. Though Ishfaq et al. (2010) considered three modes in their work, their model will not allow for different combination of modes. Another contribution of our model is the integration of terminal location, terminal type, mode, and route jointly. In Ishfaq et al.'s work (2010), they did not consider route. The key difference between our model and that of Ayar et al. (2012) is that our model allows decision makers to identify the location and type of new intermodal terminals to establish in the network.

MATHEMATICAL FORMULATION

Within the context of this research, an intermodal freight network location-routing problem (IFNLRP) is considered. This network is represented by a graph $G(N, A)$ where $N = \{C, D\}$ represents the set of nodes and A represents the set of edges. The node set consists of these two subsets: C and D where C represents the cities and D represents the candidate intermodal terminal locations in the network. A set of commodities in containers is to be routed according to known demands f_w between each Origin-Destination (OD) pair $w \in W$. Among a set of D candidate intermodal terminal locations, at most $p \in D$ terminals will be located in the network. Binary decision variables O_d^t are used to identify the mode t is to be served at terminal d (i.e. rail terminal or air terminal). Each commodity can be delivered to its destination directly using trucks (single mode) or via intermodal facilities (multi modes). Thus, multiple modes T are considered, with $t \in T$ denoting the mode to be used ($t = 0$ is highway, $t = 1$ is rail, $t = 2$ is air, and $t = 3$ is barge). The fixed cost of opening a terminal, transfer cost and transportation cost are the three types of costs considered in the IFNLRP. The transfer cost is the cost of moving a container through a terminal and the exact cost is dependent on the terminal type. In this work, the transfer cost is considered as a different percentage of the fixed cost for each mode. The transportation cost is the cost of moving a container along the rail or truck links and is based on travel distance. This cost differs for different modes, with barge being the cheapest and air the costliest. For each OD pair that has demands, all available connecting routes are considered, with and without going through an intermodal facility. The model finds the least cost routes. Therefore, our proposed model consists of determining jointly the mode, route, and location to site and type of intermodal facility to operate to satisfy demands at minimum cost. The model is formulated as follows:

Sets:

- T – set of modes
- C – set of cities
- D – set of candidate intermodal terminal locations
- A – set of Arcs
- W – set of OD pairs

Parameters:

- p – Number of intermodal terminals to be opened
- f_w – Quantity of demand for OD pair w
- C^{t} – Transportation rate per container for mode t
- L^t – Capacity of a container for mode t
- MC_d^t – transfer cost of changing to a different mode t at terminal d
- F_d – fixed cost of opening and operating terminal d
- CL_{ij}^t – Total commodity flow over link (i, j) using mode t
- d_{ij} – total distance for link (i, j)

Decision Variables:

- $y_d = \begin{cases} 1, & \text{If terminal } d \text{ is to be sited} \\ 0, & \text{else} \end{cases}$
- $O_d^t = \begin{cases} 1, & \text{If mode } t \text{ is served by terminal } d \\ 0, & \text{else} \end{cases}$
- x_{ijw}^t – Proportion of demand of OD pair w shipped over link (i, j) using mode t

Model formulation:

$$\min \sum_{d \in D} F_d y_d + \sum_d \sum_t MC_d^t O_d^t + \sum_{(i,j), t \in T} C(i, j, t) \quad (1)$$

$$\text{s.t.} : \sum_d y_d \leq p \quad (2)$$

$$O_d^t \leq y_d, \quad \forall (d, t) \quad (3)$$

$$\sum_{d' \in D} \sum_w x_{d'dw}^t \leq |N|^2 O_d^t, \quad \forall (t, d) \quad (4)$$

$$f_{ij}^t = \sum_w x_{ijw}^t f_w, \quad \forall (w, t) \quad (5)$$

$$\sum_j x_{ijw}^t - \sum_j x_{jiw}^t = \begin{cases} 1, & \text{If } i \text{ is the origin for OD pair } w \\ -1, & \text{If } i \text{ is the destination for OD pair } w \\ 0, & \text{else} \end{cases} \quad (6)$$

$$\sum_t \sum_{d'} x_{dd'w}^t + \sum_i x_{idw}^t - \sum_t \sum_{d'} x_{d'dw}^t - \sum_j x_{d'jw}^t = 0 \quad (7)$$

$$\sum_t \sum_{d'} x_{dd'}^t - \sum_t \sum_{d'} x_{d'd}^t = 0, \forall d \in D \quad (8)$$

$$CL_{ij}^t = \sum_w x_{ijw}^t f_w, \forall (i, j) \in A, t \in T \quad (9)$$

$$C(i, j, t) = \frac{CL_{ij}^t}{L^t} C^t d_{ij}, \forall (i, j) \in A, t \in T \quad (10)$$

$$y_d, o_d^t \in \{0,1\}, 0 \leq x_{ijw}^t \leq 1 \quad (11)$$

The first term in objective function (1) is the fixed cost of siting and operating an intermodal terminal d , the second term is the transfer cost of changing to a different mode t at terminal d , and the third term is the transportation cost of transporting containers over each link of the network using mode t . Constraint 2 requires that not more than p intermodal terminals are to be opened. It should be noted that at least two terminals needed to be opened. That is, the intermodal shipping option (e.g. via truck/rail) requires at least two rail terminals because only trucks can access the node and origin nodes. Constraint (3) ensures operation of mode t at terminal d if the terminal is selected to be opened. Constraint (4) allows links terminated or originated from terminal d to be selected for a shipment using mode t if mode t is selected to be operated at terminal d . Total flow over link (i, j) for mode t is calculated using Constraint (5). Constraint (6) ensures flow conservation at each node. Regarding the flow conservation condition, the flow-in should equal to flow-out for all nodes that are not an origin or destination node of any of OD pairs. For the origin node, all flow should emanate from it, and for the destination node all flow should terminate into it. Similarly, Constraints (7) and (8) deal with the flow conservation at each terminal. Constraint (9) computes the flow between two intermodal terminals. Finally, Constraint (10) determines the transportation cost of moving containers between each pair of cities/terminals.

COMPUTATIONAL RESULTS

To demonstrate the applicability of the developed model, two case studies were conducted. The first case study uses a small hypothetical network with 7 nodes and 3 candidate locations for intermodal terminals. Highway, rail, and air are the three available modes on this network. Data for this case study were randomly generated. The second case study uses a larger network with 47 nodes and 14 candidate locations for intermodal terminals. This network includes major U.S. cities and key interstate highways that connect them. Highway and rail are the two modes considered for this network. For both case studies, the experiments were designed to investigate the effect of number, location, and type of intermodal terminals and costs on the performance of the intermodal freight network (i.e. total cost). Results were obtained using CPLEX.

Case study 1

Figure 2 shows the network for this case study. The numbers next to each link denote the distance of that link. Nodes A, B and C are the candidate intermodal terminal locations with fixed opening cost of \$700, \$800 and \$600, respectively. As done in Ishfaq et al's work, (2010), we considered the transfer cost for highway, rail and air to be 10%, 20% and 30% of a terminal's fixed cost. The commodities are considered to be shipped between 10 OD pairs. Table 2 shows the shipping data for these OD pairs. Demands are shipped using containers

that have capacity of 80,000 lbs. We considered \$0.2 and \$2 as the transportation rate per container per mile for rail and road, respectively (Luo et al. 2003). The shipping rate for air is \$3 per container per mile. To assess the efficiency of using intermodal transport, 2 scenarios are considered for this case study. In the first scenario, we considered the possibility of opening at most 2 intermodal terminals in the network. In this scenario, we assumed that the decision maker has a budget that limits the maximum number of terminals he can build. In the second scenario (the base case), all containers are to be transported using only the highway mode.

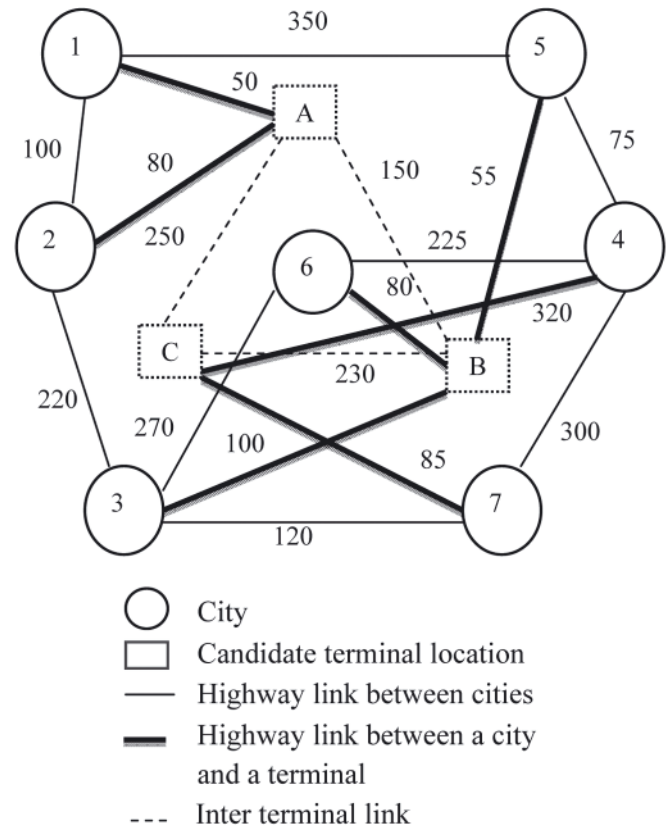


Fig. 2. Network for Case Study 1

Tab. 2. Shipping data for Case Study 1

Index	Origin	Destination	Demand (lbs)
1	1	4	132,000
2	1	3	125,000
3	2	6	130,000
4	2	7	120,000
5	3	2	140,000
6	3	7	130,000
7	4	1	80,000
8	4	5	110,000
9	5	7	120,000
10	6	1	90,000

The results of case study 1 are shown in Table 3. Since the network used for this case study is relatively small, all results were obtained in about 1 second from CPLEX. There is only one optimal route for each OD pair for both scenarios. Terminals A and B are selected as rail terminals. The network cost (i.e. optimal objective function value) for scenario 1 is \$21,991, whereas the network cost for scenario 2 is \$25,177. These results suggest that it would be more cost effective to

ship freight if the network were to have two rail intermodal terminals at nodes A and B and that freight are shipped via these terminals. In some cases, where there is a direct highway link between a pair of cities that are in close proximity, using just highway mode is more cost effective.

Tab. 3. Results of case study 1

OD Index	Optimal route for scenario 1	Optimal route for scenario 2
1	1-A-B-5-4	1-5-4
2	1-A-B-3	1-2-3
3	2-A-B-6	2-3-6
4	2-3-7	2-3-7
5	3-2	3-2
6	3-7	3-7
7	4-5-B-A-1	4-5-1
8	4-5	4-5
9	5-B-3-7	5-4-7
10	6-B-A-1	6-3-2-1

Selected terminals for scenario 1: A and B selected as rail terminals.
 Total cost for scenario 1: \$21,991
 Total cost for scenario 2: \$25,177

Case study 2

Figure 3 shows the network for this case study. As mentioned, this network considered 47 major U.S. cities and 14 of these 47 cities are considered as candidate locations for intermodal terminals. A total of 118 highway and rail links connect these cities to each other. Google Maps was used to find the distances between these cities. Transfer and transportation costs for rail and highway are the same as case study 1. The other data required for the model include the demand between OD pairs, and fixed costs of opening a terminal were generated randomly.

In contrast with case study 1, there is no predefined number of candidate terminals. Twenty (20) scenarios were conducted to find the optimal number of intermodal terminals, type, and locations, as well as routes for the different OD pairs. For case study 2, the experiment design involves finding the optimal number of terminals to open to reduce the total cost. The results of case study 2 are shown in Table 4 (an asterisk denotes the scenario with the optimal cost). For example, with 5 OD pairs, scenario 1 yields the lowest cost. The results shown in Table 4 provide some important insights: (1) increasing number of OD pairs that have shipments between them increase the optimal number of intermodal terminals; (2) the higher the number of intermodal terminals the lower the total cost, but only up to a certain threshold, beyond which yield no reduction in cost (e.g. with 50 OD pairs, it is best to have 5 rail terminals rather than 4, but there is no benefit to having 6); and (3) intermodal terminals are more likely needed for shipments going from the Southeast region of the U.S. to the Northwest than Southeast to Northeast. An example of the optimal route for the scenario with 5 OD pairs is as follows:

1. (NY,NO): NY-BLT-PIT-CIN-NSH-MEM-NO
2. (TMP,HOU): TMP-ORL-ATL-MEM-NO-HOU
3. (BOS,CLT): BOS-NY-BLT-CLT
4. (BUF,DEN): BUF-CLV-COL-IND-SLT-KC-OM-BL-DEN
5. (LV, PIT): LV-BL-OM-KC-SLT-IND-COL-CLV-PIT

The first 3 OD pairs uses truck for their shipments while the last two use the rail/road combination. These results indicate that the intermodal option is more cost effective when shipping cargo over longer distances.

As expected, the execution times increase as the number of OD pairs increases, with a maximum execution time of 30 seconds for 100 OD pairs. Since the IFNLRP is NP-hard, the execution times are expected to grow exponentially with the problem size. Thus, in order to solve large-sized problems, heuristics will be needed and will be the focus of our subsequent work. In this paper, our focus is in developing the model formulation and gaining insight into the problem through small-scale problems.

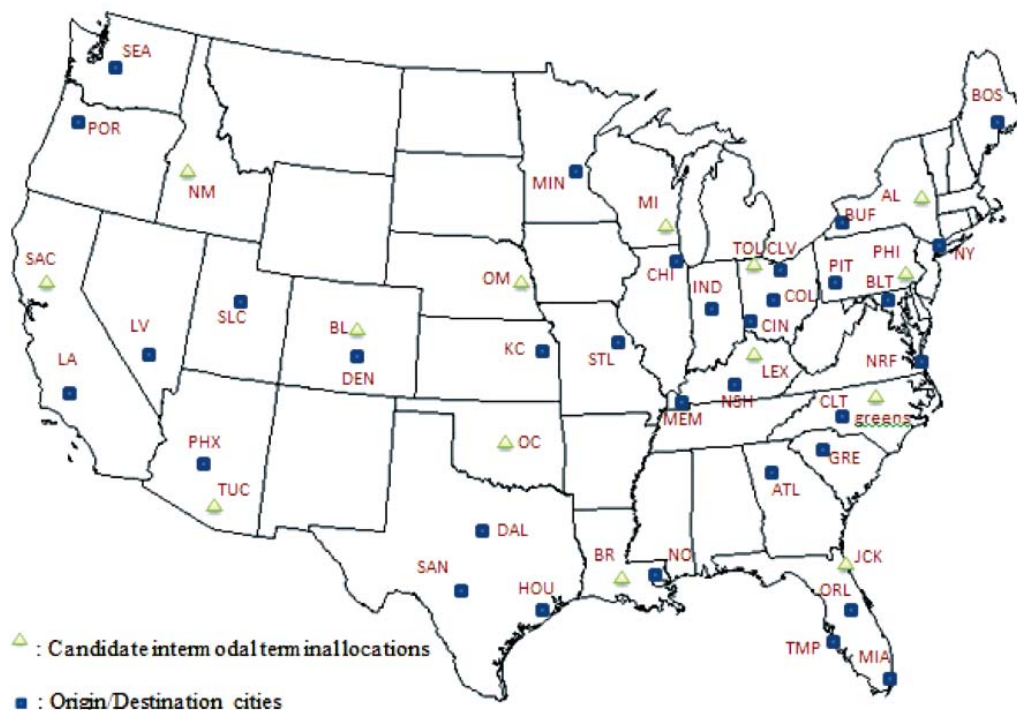


Fig. 3. Network for Case Study 2

Tab. 4. Results of Case Study 2

Scenario	# of OD pairs	Maximum Number of rail terminals to be opened	Total cost [\$]	Execution time [sec]
1	5	2	30875*	1:37
2	5	3	30875	2:30
3	10	2	61982	5:18
4	10	3	61139	6.24
5	10	4	53952*	6.96
6	10	5	53952	6.30
7	15	2	106186	6.15
8	15	3	96525	6.78
9	15	4	84503*	6.89
10	15	5	84503	6.9
11	30	4	184077	6.85
12	30	5	182129*	10.38
13	30	6	182129	12.74
14	50	4	301325	15.48
15	50	5	295243*	15.58
16	50	6	295243	14.33
17	70	5	389167*	23.71
18	70	6	389167	22.34
19	100	5	550101*	26.82
20	100	6	550101	30
*Optimal for specified OD pairs				

SUMMARY AND CONCLUSION

This study has developed a location-routing intermodal freight network design model that can simultaneously optimize the number, location, and type of intermodal terminals, as well as shipping modes and routes while satisfying demands at minimum cost. The model is formulated as a mixed integer linear program and can be solved using the CPLEX solver. The model was tested using two case studies. The results of the two case studies corroborated previous findings that shipping freight using the intermodal option is more cost effective than using the unimodal option (i.e. highway only). An interesting insight gained from the results is that as the number of shipments between OD pairs increase, more intermodal terminals are needed; however, only up to a certain number. The contribution of the developed model is that it could be used by logistics service providers to determine the number, location, and type of intermodal terminals needed to expedite shipping and minimize costs. It could also be used to predict the shipping mode and route (assuming shippers will seek to minimize cost) so that the necessary infrastructure could be upgraded to accommodate expected new traffic. In future work, the authors intend to improve upon this study by considering delivery time constraint and the impact of congestion.

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