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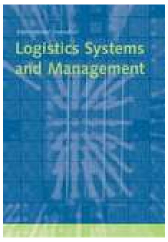

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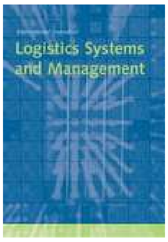

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Collaborative capacity sharing in liner shipping operations

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Abstract: This paper studies collaborative capacity sharing between two liner shipping companies by investigating the impacts of collaboration on the sharing of fuel-consumption. The proposed model is extended from the vehicle routing problem with time windows (VRPTW) through the inclusion of slow-steaming decision variables and constraints to manage the sharing of fuel consumption. Two cases differing in size are developed using Indonesian archipelago for the data background and three policies on fuel-consumption sharing are investigated: open policy, proportionate-sharing policy, and equal-sharing policy. The application of the collaborative model in Indonesian archipelago contributes to the scant literature in maritime logistics collaboration. The optimisation results from generated instances show that the open policy leads to minimum total fuel consumption but the unclear pattern in fuel-consumption sharing between carriers makes it impractical for planning purposes. Moreover, the fuel consumptions of the proportionate-sharing and equal-sharing policies are not significantly different but the smaller variance in the results of the proportionate-sharing policy indicates more predictability. The proportionate-sharing policy is therefore considered the most suitable for route planning.

Keywords: capacity sharing; liner shipping; fuel consumption; slow steaming; vehicle routing problems; VRP; time windows; maritime logistics; collaboration; Indonesia.

Reference to this paper should be made as follows: Wibisono, E. and Jittamai, P. (2015) 'Collaborative capacity sharing in liner shipping operations', *Int. J. Logistics Systems and Management*, Vol. 22, No. 4, pp.520–539.

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1 Introduction

Maritime logistics is the bloodline of international trade and a major driving force of globalisation. It is estimated that the share of weight borne by sea in international trade is in the range of 65% to 85% (Christiansen et al., 2007). Ships can carry large volume and high variety of cargoes across oceans and continents which give them advantage over the other modes of transportation. Land logistics such as trains, trucks, and buses, despite being the dominant source of worldwide mode of transportation, are limited not just because they can only travel over land, but also in terms of efficiency, i.e., the amount of cargo they can carry per trip and the distance they can cover. As with aircrafts, they mainly transport passengers or packaged goods but are limited in sizes and weights, not to mention their higher costs. In countries comprising of thousands of islands such as Indonesia, the Philippines, Greece, and Norway, the role of maritime logistics for domestic transportation is even more critical.

The 2008 economic crisis that was followed by debt crisis in several major European countries have brought distinct challenges for international shipping. The depressing market caused by these crises has reduced the global trade demand. Interestingly, however, this reduction is not mirrored on the supply side. The world merchant fleet recorded a continuous growth of capacity from 1.28 billion deadweight tons (dwt), 1.4 billion dwt, and 1.5 billion dwt in January 2010, 2011, and 2012, respectively; an increase of over 37% in just four years. This mismatch is the result of shipbuilding orders placed prior to the crises, where major shipbuilders such as China, Japan, and the Republic of Korea were reluctant to cancel or postpone orders (UNCTAD, 2010, 2011, 2012).

The current norms of supply-demand imbalance and rising oil prices have forced shipping companies to seek more efficient ways for transporting goods. One possible approach is via collaboration with other companies in capacity sharing where a company with low demand in a particular city can use the capacity of another company going to that city, and in return offer its capacity in a similar situation faced by the partner company. This strategy enables companies to avoid operating their under-utilised fleet and therefore improve their utilisation. Such collaboration is aimed at optimising the available fleet, thus avoiding further increase in the supply side.

The objectives and contributions of this paper are:

1 to introduce the concept of fuel-consumption sharing policies as the result of capacity sharing in liner shipping collaboration

2 to analyse the impacts of these policies in optimisation

3 to indicate which policy is the best for route planning.

The policies to be investigated are open policy, proportionate-sharing policy, and equal-sharing policy. The mathematical model extends the vehicle routing problems (VRP) with time windows (VRPTW) through the inclusion of slow-steaming decision variables and constraints to manage the sharing of fuel consumption. To the best of our knowledge, such an extension has never been proposed. This extension enriches the VRP application domain that has been studied extensively in land logistics but less in maritime logistics. A case study is developed based on Indonesian archipelago. Despite being the largest archipelago in the world with over than 17,500 islands, the country is yet to receive more attention in maritime logistics research. Therefore, this paper also contributes to that area.

The remainder of this paper is organised as follows: Section 2 reviews the related literature; Section 3 details the methodology including the mathematical model and the methods of data setup; Section 4 discusses optimisation results and highlights; and finally Section 5 summarises the findings and discusses future directions of the research.

2 Literature review

Shipping services can be grouped into three types: liner, tramp, and industrial (Christiansen et al., 2007). Liner shipping is akin to bus operations where it has fixed and published schedules; tramp shipping is like taxis where ships are contracted by specific buyers (cargo owners) to ship their cargo in a rather exclusive setting; industrial shipping is similar to owning private cars, i.e., both the ships and cargoes are owned by the same party. In Christiansen et al. (2013), tramp and industrial shipping are considered similar in certain aspects thus merged as one class. Pantuso et al. (2014) add to these reviews a specific topic on maritime fleet size and mix. The volume of research doubles every decade and over a hundred new papers have been published during the last decade. In addition to the types of service, ships can also be classified based on their physical attributes (Lindstad et al., 2011): bulk vessels for dry (iron ore, coal) or wet (oil) bulk cargoes; container vessels for a wide range of products that can be containerised; and roll-on roll-off (RoRo) vessels for rolling objects such as vehicles. Today, container shipping constitutes the major segment of liner shipping. Since 2006, the maximum ship size carrying capacity has surpassed the 10,000 TEUs (20-foot equivalent unit) milestone

(Imai et al., 2006). Given the fast growth of the containership fleet, liner shipping therefore has attracted a considerable attention in research especially on liner network design and its related topics. However, research dealing with partnership and collaboration in maritime logistics is very few compared to the same topic in land logistics.

The practice of liner shipping collaboration stretched back to 1875 with the formation of the UK-Calcutta Conference. Other conferences then followed and these were the primary form for liner companies to fix route allocation, cargo rates and members' quotas. In Europe, the industry had been sheltered by the Council Regulation 4056/86 that exempted conference practices from competition law, until the regulation was repealed in 2008. In the USA, The Ocean Shipping Reform Act of 1998 changed the treatment of conferences under American antitrust law by mandating secret and independent action to the members. In the absence of these immunities, evidence shows that conferences are gradually being displaced by alliances (Sjostrom, 2009). Different from conferences, alliances do not fix rates, but they enlarge service coverage by taking advantage of the economies of scale. Perhaps, being a new trend, studies concerning liner alliances are still scant in the literature. Agarwal and Ergun (2010) argued that only a few references on qualitative study on liner shipping alliances are available and a rigorous quantitative study is missing. Panayides and Wiedmer (2011) developed taxonomy for liner alliance literature and found that of the 17 papers surveyed between 1999 to 2010, only five papers (29%) can be considered as quantitative studies. This suggests that this area is still a vast research ground to be explored.

Partner selection and alliance alignment have been identified by Bhattacharjee and Mohanty (2012) as the critical early stages in supply chain collaboration. In the shipping industry, 'partner' can refer to other carrier(s) or ports-of-call and their selection is a key prerequisite to any collaborative activity. Lam (2013) constructed a normative model for managing container shipping supply chains and categorised carrier and port selection as a strategic level. Norbis et al. (2013) looked at the aspect of supply chain security in the selection of carrier and port and argued that such selection must be carried out in concert to augment an integrated and synergistic supply chain process. Other studies involving the ports as important stakeholder in maritime collaboration include: Boros et al. (2008) who optimised the cycle time between a shipping company and a port operator to satisfy the conflicting preferences of both parties; Rathnayake and Wijeratne (2012) who demonstrated the use of a game-theory approach in a case study of port location selection; Álvarez-SanJaime et al. (2013) who investigated the partnership between a shipping line and a terminal operator, particularly in determining whether it is strategically profitable for a shipping line to own a dedicated terminal; and Asgari et al. (2013) who compared the competition and cooperation strategies among three parties: two major container hub-ports and the shipping companies. The last authors studied three scenarios:

1. perfect competition between the hub-ports
2. perfect cooperation between the hub-ports
3. cooperation among all as a whole.

The above section highlights that most studies on maritime collaboration involve port operators, whereas collaboration between two or more carriers is rarely researched. Two examples in this area are the following. Lei et al. (2008) compared three management policies between shipping companies: the non-collaborative policy, the slot-sharing policy, and the total-sharing (the total collaboration) policy. In each policy, a mixed integer programming model was employed and the results were compared to arrive at a conclusion that the sharing policies have lots of potential to offer. Hsu and Hsieh (2007) studied the routing, ship size, and sailing frequency under hub-and-spoke environment. Their approach was multi-objective optimisation and two objectives being traded off were shipping costs and inventory costs in order to obtain Pareto optimal solutions. In their formulation, minimising shipping costs is the objective pursued by a shipping company, whereas minimising inventory costs is the shipper's objective.

Another perspective in maritime logistics is related to energy efficiency in shipping industry which is an attractive research topic nowadays as summarised in a survey by Psaraftis and Kontovas (2013). Different from road transport that cannot avoid traffic congestion, a ship can travel on seas and oceans relatively uncontested and it is limited only by its speed design and, to some extent, weather conditions. Faster speed burns more fuel in a quadratic (Fagerholt et al., 2010) or cubical (Corbett et al., 2009) relationship and increases gas emissions. Corbett et al. (2009) suggested that compared to bulk shipping, crude oil tankers, and general cargo ships, CO_2 emissions from containerships are 1.3, 2.2 and 2.5 times greater, respectively. In light of the above, speed reduction has been a strategic theme in shipping operations, not just from the perspective of vessels' owners, but also port authorities.

Dantzig and Ramser (1959) first introduced 'The Truck Dispatching Problem' that was since more popularly referred to as the VRP. The problem generalises the travelling salesman problem (TSP) and is therefore NP-hard, thus it follows that more complex variants such as VRP with pickups and deliveries (VRPPD) (Wassan and Nagy, 2014) or VRP with time windows (VRPTW) (Cordeau et al., 2007) are also NP-hard. Due to the complexity, heuristics and meta-heuristics are often proposed to deal with large instances in this domain. For example, Prins (2004) presented a simple and effective hybrid genetic algorithm (GA) and reported that it is able to outperform most published tabu search (TS) heuristics on some well-known instances; Pisinger and Ropke (2007) suggested a general heuristic to solve several different variants of VRP; Silva and Leal (2011) used multiple ant colony system to solve a VRPTW problem with multiple objectives (MACS-VRPTW); Baños et al. (2013) proposed a hybrid meta-heuristic for VRPTW in a multi-objective setting; and Melián-Batista et al. (2014) developed a scatter search metaheuristic for a bi-objective VRPTW. The VRP literature grows in an almost perfectly annual exponential rate at 6.09% between 1956 and 2005 (Eksioglu et al., 2009) and it would be impossible to cite all progresses unless in a dedicated review. However, several review papers are worth mentioning in case the readers are interested to trace back the latest advances to their origins. In addition to the general reviews by Cordeau et al. (2007) and Eksioglu et al. (2009), specific reviews can be found in El-Sherbeny (2010) for VRPTW; Vidal et al. (2013) for heuristics for multi-attribute VRP; and Lin et al. (2013) for a survey of trends in green VRP.

Despite its increasing popularity, VRP models in maritime logistics are rarely applied. Hoff et al. (2010) argued that one possible reason is the assumption of homogenous vehicles in most VRP studies, which may be true for the majority of land transport (e.g., trucking companies), but far from reality in shipping companies where they mostly operate a heterogeneous fleet of vessels. Further, in maritime transportation, concerns are usually not given to a high number of cities (ports) exceeding dozens or even hundreds as that would not be the case in most shipping operations. In other words, complexity in maritime logistics is derived more on the heterogeneity of the fleet rather than the number of ports. When the case is relatively small such as in Sambracos et al. (2004) where it involves 13 ports (including a depot port) and 25 sea links, VRP formulation can still be applied. Different approaches are also common. For example, in Karlaftis et al. (2004), a capacitated VRP with pick-ups, deliveries and time deadlines is formulated and solved using a hybrid GA. Another approach is used by Demir et al. (2012) to extend the VRPTW model into the pollution-routing problem (PRP).

This review highlights a gap in previous studies of maritime logistics collaboration. This paper therefore aims to enrich the literature in that area by studying the collaboration efforts and their impacts for two liner shipping companies. An extended VRPTW model is formulated and applied into generated instances and Indonesian archipelago will be used as the background of the study.

3 Methodology

We formally state the problem description as follows: two liner shipping companies (referred onwards as carriers) are operating a heterogeneous fleet of vessels and serving a number of ports from the same depot. Given today's norm in the shipping business where supply is larger than demand, these two carriers would like to collaborate by sharing their capacities. This strategy suggests one carrier to fill its unused capacities with orders from the other carrier going to the same destination, and reciprocally send its cargoes to the under-capacity vessels of the other carrier. Using this approach, carriers can avoid operating their under-utilised fleet. The objective is to minimise total fuel consumption.

A VRPTW-based model (Cordeau et al., 2002) is proposed with two extensions: firstly, slow-steaming decisions are catered to reflect the current environmental concerns; secondly, an investigation is carried out with regard to the distribution sharing of operational burdens measured in fuel consumption. The two carriers are of different sizes (otherwise the model can be treated from the point of view of one company simply by means of aggregation) and therefore the second extension is an important factor of the model in its relation to the overall fuel-consumption minimisation.

We further explain the mathematical model and the data setup process in the next two sub-sections.

3.1 Mathematical model

A VRP model can be described as a complete undirected graph $G = (V, E)$ with a node set $V = \{0, 1, \dots, n\}$ and an arc set E. Node 0 is the depot and the remaining nodes represent the customers, each with a non-negative demand. Each arc $(i, j) \in E$ has a non-negative travel cost $c_{i,j}$ associated with it and corresponds to the cost incurred for traversing from node i to node j. If the relationship $c_{i,j} = c_{j,i}$ is satisfied, the problem is called a symmetric VRP; one which is usually assumed in many VRP studies. The VRP problem consists of determining a set of k vehicle trips to minimise the total travel cost, such that:

1 each vehicle starts from and ends at the depot

2 each customer is visited exactly only once

3 the total demand in each trip does not exceed the vehicle capacity.

If a customer i has to be visited within a certain time frame $[e_i, l_i]$ where e_i is the earliest time and l_i is the latest time a visit is allowed, the problem is called VRPTW. In practice, a single-sided time window where $e_i = 0$ and $l_i > 0$ is equivalent to imposing a due-date to the service. Many real-life routing applications require this additional constraint, making this variant of VRP one of the popular ongoing research areas.

Concerns for a greener environment have prompted maritime actors to seek better ways of operations, for example by slow steaming to reduce gas emissions. In our model, we take this into account by formulating it as decision variables. This results in products of binary variables that require transformation to maintain the linearity of the model. In addition, because the purpose of the study is to investigate the impacts of collaboration between two carriers, a constraint related to this issue is added. From here on, we use the terms 'vessels' and 'ports' synonymously with 'vehicles' and 'customers', respectively, as in the usual VRP formulation. Let us first define the following sets, parameters and variables.

$\mathcal{C}$	set of carriers, indexed by a
$\mathcal{V}_a$	set of vessels of carrier a, indexed by v
$\mathcal{A}$	set of arcs (i, j) denoting a flow from port i to port j
$\mathcal{N}$	set of all ports $\mathcal{N} = \{1, 2, \ldots, n\}$; ; $\{1\}$ is the home-base port
$\mathcal{P}$	set of ports-of-call, or $\mathcal{N} \setminus \{1\}$
$c_{i,j}^{a,v}$	fuel consumption of vessel v of carrier a if it sails from port i to port j
$c_{i,j}^{a,v,-}$	fuel consumption of vessel v of carrier a if it sails from port i to port j with slow steaming
$t_{i,j}^{a,v}$	sailing time of vessel v of carrier a if it sails from port i to port j
$t_{i,j}^{a,v,-}$	sailing time of vessel v of carrier a if it sails from port i to port j with slow steaming
$C^{a,v}$	capacity of vessel v of carrier a
D_i	total demand of both carriers at port i (in TEUs)
T_i	due date at port i (in hours)
p_i	service time at port i
M	big M
a, b	minimum and maximum deviations of fuel-consumption sharing between the two carriers

$x_{i,j}^{a,v}$ binary variables for vessel v of carrier a in arc (i, j); $x_{i,j}^{a,v} = 1$ if the vessel traverses arc (i, j) and equals 0 otherwise

$f_{i,j}^{a,v}$ binary slow-steaming variables for vessel v of carrier a in arc (i, j); $f_{i,j}^{a,v} = 1$ if the vessel traverses arc (i, j) with reduced speed and equals 0 if it uses normal speed

$s_i^{a,v}$ time window for vessel v of carrier a at port i.

The extended VRPTW model can then be formulated as follows:

$$\text{Minimise} \sum_{a \in \mathcal{C}} \sum_{v \in \mathcal{V}_a} \sum_{i,j \in \mathcal{A}} x_{i,j}^{a,v} \left[f_{i,j}^{a,v} . c_{i,j}^{a,v,-} + \left(1 - f_{i,j}^{a,v}\right) . c_{i,j}^{a,v} \right] \tag{1}$$

Subject to:

$$\sum_{a \in \mathcal{C}} \sum_{v \in \mathcal{V}_a} \sum_{i,j \in \mathcal{A}} x_{i,j}^{a,v} . C^{a,v} \geq D_i \qquad \forall i \in \mathcal{P} \tag{2}$$

$$\sum_{a \in \mathcal{P}} D_i \sum_{j \in \mathcal{N}} x_{i,j}^{a,v} \leq C^{a,v} \qquad \forall a \in \mathcal{C}; v \in \mathcal{V}_a \tag{3}$$

$$\sum_{i \in \mathcal{N}} x_{i,k}^{a,v} - \sum_{j \in \mathcal{N}} x_{k,j}^{a,v} = 0 \qquad \forall k \in \mathcal{P}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{4}$$

$$x_{i,i}^{a,v} = 0 \qquad \forall i \in \mathcal{N}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{5}$$

$$\sum_{j \in \mathcal{P}} x_{1,j}^{a,v} \leq 1 \qquad \forall a \in \mathcal{C}; v \in \mathcal{V}_a \tag{6}$$

$$f_{i,j}^{a,v} \leq x_{i,j}^{a,v} \qquad \forall i, j \in \mathcal{A}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{7}$$

$$s_i^{a,v} \leq T_i \qquad \forall i \in \mathcal{P}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{8}$$

$$\begin{aligned} s_i^{a,v} &+ \left[f_{i,j}^{a,v} . t_{i,j}^{a,v,-} + \left(1 - f_{i,j}^{a,v}\right) . t_{i,j}^{a,v} \right] \\ &+ p_i - M\left(1 - x_{i,j}^{a,v}\right) \qquad \forall i \in \mathcal{N}; j \in \mathcal{P}; a \in \mathcal{C}; v \in \mathcal{V}_a \end{aligned} \tag{9}$$

$$\begin{aligned} a \leq &\sum_{v \in \mathcal{V}_1} \sum_{i,j \in \mathcal{A}} x_{i,j}^{1,v} . \left(f_{i,j}^{1,v} . c_{i,j}^{1,v,-} + \left(1 - f_{i,j}^{1,v}\right) . c_{i,j}^{1,v} \right) \\ -&\sum_{v \in \mathcal{V}_2} \sum_{i,j \in \mathcal{A}} x_{i,j}^{2,v} . \left(f_{i,j}^{2,v} . c_{i,j}^{2,v,-} + \left(1 - f_{i,j}^{2,v}\right) . c_{i,j}^{2,v} \right) \leq b \end{aligned} \tag{10}$$

$$x_{i,j}^{a,v}, f_{i,j}^{a,v} \in \{0,1\} \qquad \forall i, j \in \mathcal{A}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{11}$$

$$s_i^{a,v} \geq 0 \qquad \forall i \in \mathcal{N}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{12}$$

The objective function (1) is to minimise total fuel consumption. Note that binary decision variables $f_{i,j}^{a,v}$ are added for whether reduced or normal speed will be used by a particular vessel in a particular arc. An extra summation sign is also present to signify the involvement of more than one carrier. The per-nautical-mile fuel-consumption formula follows the quadratic function from Fagerholt et al. (2010) as shown in constraints (13) with single variable sailing speed s (in knots). This function is valid for speeds between 14 and 20 knots which will be the case in our study. We consider that fuel consumption is sufficient to reflect the operational burdens of the carriers, thus we avoid converting this figure to monetary values, particularly given the unstable oil prices in the current market and also to reduce too many approximations from other cost-relevant factors.

$$f(s) = 0.0036s^2 - 0.1015s + 0.8848 \tag{13}$$

Constraints (2) to (6) are the foundation of a VRP formulation, and constraints (8) and (9) are the addition for a VRPTW. Constraints (2) ensure that the demand in each port will be satisfied and constraints (3) dictate that such fulfilment by a vessel in several ports will not exceed the vessel's capacity. Constraints (4) are the flow equation to balance the incoming and outgoing trips to and from each port. Constraints (5) state that a vessel cannot travel inside the same node. Constraints (6) prevent a vessel to assume more than one tour. Constraints (7) dictate that decision for speed reduction can only be imposed if a vessel sails an arc. The products of binary variables resulting from the introduction of slow-steaming decisions are transformed to maintain the linearity of the model. Let $z_{i,j}^{a,v} = x_{i,j}^{a,v} . f_{i,j}^{a,v}$ and constraints (14) to (16) are added to the model. These constraints imply that constraints (7) can be omitted from the formulation since if $x_{i,j}^{a,v} = 0,$ whatever the value of $f_{i,j}^{a,v}$ will have no effect on the objective function. However, as a usual practice in mathematical programming, supplying bounds are always helpful to reduce computation time.

$$z_{i,j}^{a,v} \le x_{i,j}^{a,v} \qquad \forall i, j \in \mathcal{A}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{14}$$

$$z_{i,j}^{a,v} \le f_{i,j}^{a,v} \qquad \forall i, j \in \mathcal{A}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{15}$$

$$z_{i,j}^{a,v} \ge x_{i,j}^{a,v} + f_{i,j}^{a,v} - 1 \qquad \forall i, j \in \mathcal{A}; a \in \mathcal{C}; v \in \mathcal{V}_a \tag{16}$$

Time windows are observed by constraints (8) and (9). A single-sided time window T_i reflecting a due date that a vessel must arrive in a port is used as an upper bound of $s_i^{a,v}$. Given port service time p_i and the big M in constraint (9), the inequality constraints specify that if a vessel sails from port i to port j, either with reduced or normal speed, the vessel cannot arrive at port j before $s_i^{a,v} + \textit{travel time from port i to port j} + \textit{service time at port i}.$ Constraint (9) also eliminate sub-tours (Cordeau et al., 2007). The model is a mixed-integer program due to the presence of $s_i^{a,v}$.

An important part of the formulation is constraint (10) where the deviation of total fuel consumption between two carriers is measured. Parameters *a* and *b* serve as the bounds for the fuel-consumption sharing policies to be investigated. The case involves two carriers of different sizes and the collaboration bears a question as to how the division of operational burdens should be assigned to each carrier. More specifically, three different models correspond to three different policies will be evaluated:

1 open policy, where there is no restriction to the sharing requirement

2 proportionate-sharing policy, where the sharing is set in proportion to the size of the carriers

3 equal-sharing policy, where the sharing is set equal, or 50-50, regardless of the carriers' size.

3.2 Data setup process

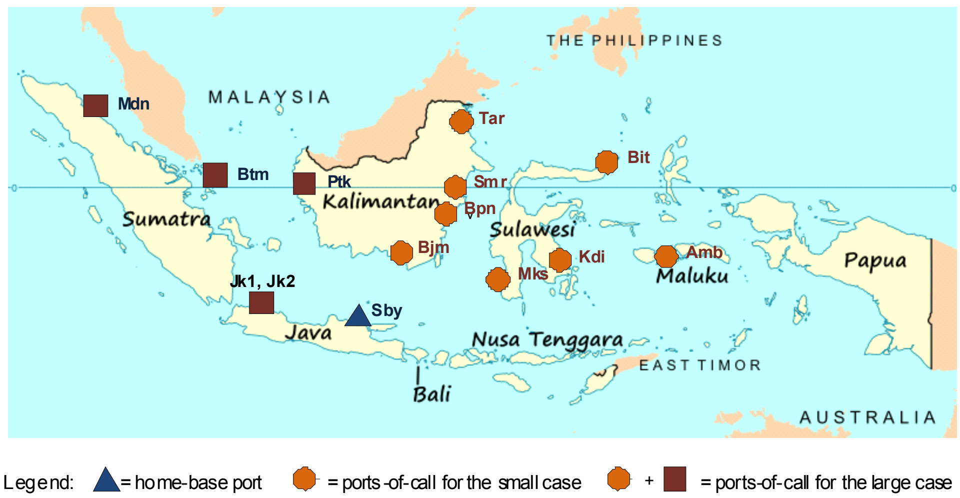
The case study uses the country Indonesia and its archipelago for the data background. As mentioned, studies on Indonesian maritime cases are very rare and this motivates us to conduct such exploration. However, the model proposed in the previous sub-section is general in nature and is applicable in other cases.

We explain next the process in generating the data for our experiment. The data are divided into cities and distances, vessels' particulars, demand, and the due dates. For the purpose of benchmark and further studies, all of the data can be found in this URL: http://ti.ubaya.ac.id/index.php/component/content/article/24-dosen/159-wibisono-jittamai-2014.html

3.2.1 Cities and distances

Over 17,500 islands span in the geographical layout of Indonesia between latitudes 6°N and 11°S and longitudes 95°E and 141°W, and cities in all corners of the country are almost equally important in the subjects of trade and economy. The two largest cities, the capital Jakarta situated on West Java and Surabaya on East Java, are both on the southern/south-western part of the archipelago. These two cities are heavily linked to the other regions of the country for various, especially business-related, affairs. In this study, the city of Surabaya is chosen as the depot, and two cases are developed: the small case with six vessels (4:2 for the ratio of fleet size between the two carriers) and eight ports; and the large case with nine vessels (6:3 for the same ratio) and 13 ports. The small case is basically orientated towards servicing the eastern part of the country. The geography and included ports in the study are illustrated in Figure 1. Distances between ports are measured using distancecalculator.globefeed.com, however, since these are Euclidean measures, some adjustments are made with 103% to 180% of the obtained measures maintaining triangular relationships ($c_{i,j} + c_{j,k} \geq c_{i,k}$). For example, between Pontianak (West Kalimantan) and Samarinda (East Kalimantan), a ship must travel via the Java Sea which clearly takes a longer distance than if the transport is made over land. Taking into account all possible links, the distances measured fall in the range of 63 to 2,396 nautical miles. The travel times are assumed deterministic based on these distances.

Figure 1 Map of Indonesia with cities being studied (see online version for colours)



3.2.2 Vessels' particulars

Two particulars of the vessels are involved in the data setup. These are:

1 capacities of the vessels, which are generated using a uniform distribution *U*[500; 1,500] TEUs (20-foot equivalent)

2 their speeds: a vessel with capacity ≤ 1,000 TEUs uses 15 knots and 19 knots for the slow speed and normal speed, respectively, whereas the upper half of the range uses 16 knots and 20 knots for the corresponding speeds.

The random generation for capacities is a one-time process and the results are used in all instances of the experiment. Of the six vessels in the small case, two are the slow/ low-capacity vessels and four are the fast/high-capacity vessels with the range of capacities between 708 to 1,390 TEUs. In the large case, there are five slow/low-capacity vessels and four fast/high-capacity vessels with the range of capacities in 530 to 1,390 TEUs.

The vessels in this case study are assumed homogenous in terms of age and other cost-related factors. This assumption is needed given the variety of cost elements in shipping operations and incorporating all of them could obscure the focus of the study which is to investigate the impacts of sharing policies on fuel consumption. However, one major cost element that cannot be neglected is the fixed cost of running a vessel. In the experiment, it is possible to obtain a result of lower consumption in one policy but by using an extra vessel, and certainly this is not comparable to a result of higher consumption with less number of vessels in the other policy. To deal with this issue, for each instance, we run the experiment twice if the results show there is a policy using a fewer number of vessels. On the second run, constraint (17) is imposed on all policies with n being the minimum number of vessels found in the first run.

$$\sum_{j\in\mathcal{P}} x_{j,1}^{a,v} \leq n \qquad \forall a \in \mathcal{C};\, v \in \mathcal{V}_a \tag{17}$$

3.2.3 Demand

Each carrier has customers of its own and these customers generate the demand. Similar to the capacities, the demands are also in TEUs and generated randomly. However, in order to get as close as possible to the reality and avoid blind randomisation, we based the generation from the OECD (2012) report, which provides data for container volumes through Indonesian ports in 2012, both for international and domestic traffic. Several cities are selected from the list of the major ports (the same with those in Figure 1 except for Kendari, which is added arbitrarily) and the domestic data are used. 10% of the weekly demand is then assumed as the market share of each carrier and ±50% is given for the range of the uniform distribution used in the demand generation. Demands are then generated for 12 instances both for the small and large cases. Table 1 summarises the process. The idea of capacity sharing collaboration is to make one carrier responsible for the demand of its partner carrier and of its own in some ports, and let the partner carrier take care of its demand in the other ports. Therefore during optimisation, only the total demand is relevant.

Table 1 Demand generation process

No.	*Port*	*Abbrev.*	*Domestic traffic 2012 (000 TEUs)*[1]	*Weekly 10% (TEUs)*	*Uniform dist.*
1	Jakarta	Jk1, Jk2	833	1,602	U[801; 2,403]
2	Medan	Mdn	278	535	U[267; 802]
3	Makassar	Mks	248	477	U[238; 715]
4	Banjarmasin	Bjm	118	227	U[113; 340]
5	Pontianak	Ptk	99	190	U[95; 286]
6	Samarinda	Smr	95	183	U[91; 274]
7	Bitung	Bit	63	121	U[61; 182]
8	Balikpapan	Bpn	35	67	U[34; 101]
9	Batam	Btm	26	50	U[25; 75]
10	Tarakan	Tar	17	33	U[16; 49]
11	Ambon	Amb	15	29	U[14; 43]
12	Kendari	Kdi	10	19	U[10; 29]

Note: [1]Based on OECD (2012).

The demand of Jakarta is very large and for simplicity we split the demand in this city into two equal sizes and created a duplicate city (both are identified as Jk1 and Jk2 with zero distance) that shares half of the demand. Since only one city has this problem, this approach is preferred to split-delivery formulation in order to reduce model complexity. Note that the total number of ports in the large case is therefore 13 instead of 12. Also, since the upper limit of demand in Jakarta still exceeds the upper limit of vessel capacity, some generated instances violating this have to be omitted.

3.2.3 Due dates

Since there is no sufficient information for the background of due dates establishment, the due dates are assigned by considering normal sailing time that can be achieved from the depot in Surabaya plus some slack that could allow a vessel to serve several more ports. Leaving the due dates completely open is not a practical approach, as that might produce a long tour for a vessel that is limited only by its capacity to serve as many ports as possible. The due dates for the small case are stricter than those for the large case, but none of the due date exceeds one week since the demand is on a weekly basis. In addition, port service times are set equally for 12 hours for all ports including the initial service at the home port in Surabaya. Rooms for further studies are open for the consideration of probabilistic port service times.

In summary, two cases are developed. The small case consists of six vessels and eight ports, and the large case consists of nine vessels and 13 ports. In each case, three models in relation to fuel-consumption sharing policies are evaluated: open policy, proportionate policy, and equal policy. Twelve instances are generated, plugged into the model, and run for optimisation.

4 Results and discussion

The parameters a and b in constraint (10) are determined as follows: first, a few instances were run without these constraints to probe the range of minimised total fuel consumption. The small case has this figure less than 2,000 and the large case has it less than 2,800, thus we set the upper bound b close to those figures so we have $a = 0$ and $b = 2{,}000$, and $a = 0$ and $b = 3{,}000$, respectively, for the small case and the large case in the open policy. For the proportionate-sharing policy, noting that carrier A offers two times of fleet size (4:2 in the small case and 6:3 in the large case) than carrier B, the fair proportion of fuel consumption consequently should be in 2:1 ratio. We therefore set $a = 600$ and $b = 700$, and $a = 800$ and $b = 900$, respectively, for the small case and the large case in this policy. Finally, in the equal-sharing policy, both carriers are expected to equally share the fuel consumption hence the upper bound b of the equation should be set as minimum as possible and it is set at 100 for both cases in this policy. Table 2 summarises these values for all scenarios. All instances for both cases and the three policies were run for optimisation using Lingo 11.0 on an Intel i5-2430M processor at 2.4 GHz and 4 MB of RAM. The running times for the small case reached 15 seconds maximum, whereas for the large case they spread from seconds to five hours.

Table 2 Values of a and b for all scenarios

	Small-case policies			*Large-case policies*		
	Open	*Proportionate*	*Equal*	*Open*	*Proportionate*	*Equal*
a	0	600	0	0	800	0
b	2000	700	100	3000	900	100

Results of the small case do not reveal much information and it is very likely due to the excess capacity (6,536) than the average demand of the 12 instances (2,299). The total fuel consumptions in all instances do not vary except in the last instance of open and proportionate policies. An interesting finding, however, can be seen from the distribution of fuel consumption between the two carriers. For the proportionate-sharing and equal-sharing policies, the distribution does not spread, naturally because the policies dictate so. However, the behaviour of such distribution is rather erratic in the open policy where on one instance the ratio is 1,836:118 and on the other 1317:637 (Figure 3). This finding is reconfirmed in the results of the large case.

The large case comes with total fleet capacity of 8,571 and is relatively tighter to the average demand of 6,311, compared to the same ratio in the small case. The first analysis concerns the effect of the randomised demand to the optimised fuel consumption. Figure 2 presents the scatter plots and the correlation coefficients between the total demand and the resulting optimised total fuel consumption of the three policies. The correlation coefficients of the open policy and the proportionate-sharing policy are statistically significant at 0.52% and 0.78%, respectively. Compared to these two policies, the equal-sharing policy has a weaker coefficient and it is significant at 5.45%. In general, we can assert that the fuel consumption is largely affected by the demand size except in the equal-sharing policy. However, these relationships do not tell the story of the consumption sharing that has to be analysed separately.

Figure 2 Scatter plots of total demand versus total fuel consumption for the large case

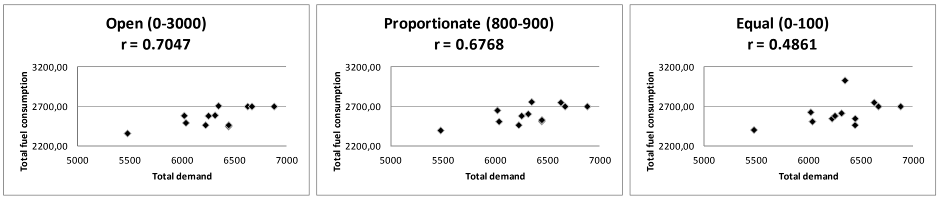


Figure 3 Distribution of fuel consumption between two carriers

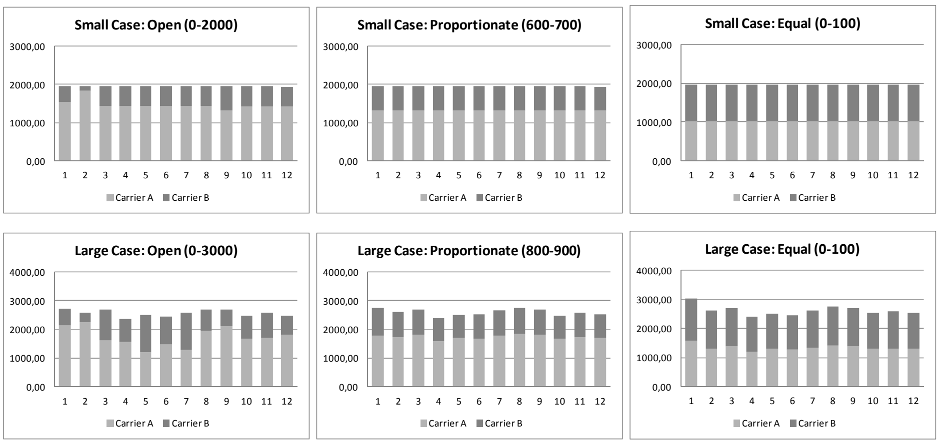


Table 3 Experiment results of the large case

Instance	*# of vessels*	*Demand (TEU)*	*Open policy*			*Proportionate-sharing policy*				*Equal-sharing policy*			
			Carrier A	*Carrier B*	*Total*	*Carrier A*	*Carrier B*	*Total*	*Gap*	*Carrier A*	*Carrier B*	*Total*	*Gap*
1	8	6,347	2,131	578	2,710	1,780	980	2,760	1.86%	1,563	1,469	3,032	11.91%
2	8	6,314	2,236	354	2,590	1,718	889	2,607	0.65%	1,310	1,307	2,617	1.05%
3	9	6,880	1,617	1,085	2,702	1,799	903	2,702	0.00%	1,397	1,305	2,702	0.00%
4	7	5,476	1,555	806	2,361	1,599	799	2,399	1.59%	1,203	1,202	2,405	1.86%
5	8	6,036	1,187	1,307	2,494	1,701	810	2,511	0.67%	1,295	1,216	2,511	0.67%
6	8	6,443	1,469	980	2,449	1,676	838	2,514	2.65%	1,264	1,202	2,466	0.68%
7	8	6,020	1,272	1,313	2,586	1,776	877	2,653	2.60%	1,316	1,313	2,629	1.69%
8	9	6,627	1,939	764	2,702	1,826	926	2,753	1.86%	1,425	1,328	2,753	1.86%
9	9	6,667	2,124	578	2,702	1,799	903	2,702	0.00%	1,397	1,305	2,702	0.00%
10	8	6,223	1,667	799	2,466	1,667	799	2,466	0.00%	1,306	1,243	2,549	3.36%
11	9	6,251	1,704	878	2,583	1,722	861	2,583	0.00%	1,303	1,280	2,583	0.00%
12	8	6,445	1,812	654	2,466	1,692	838	2,531	2.63%	1,306	1,243	2,549	3.36%
Mean		*6,311*			*2,568*			*2,598*	*1.21%*			*2,625*	*2.20%*
Variance		*132,239*			*14,389*			*13,768*				*26,760*	

As previously confirmed in the small case, an unclear pattern is observed from the distribution of fuel consumption between carrier A and carrier B in the open policy. On one hand, it is logical since the minimisation of total fuel consumption is not restricted by any rule. On the other hand, an important conclusion is obtained that, whenever a sharing policy is imposed, be that proportionate or equal, total fuel consumption shifts from its minimum value. We measure the optimality gap between the open policy and the two sharing policies and the results are presented in Table 3 together with the resulting fuel consumption. The gaps are relatively low except for instance #1 on equal-sharing policy that spikes to nearly 12%. This suggests that these gaps are instance-dependent and careful investigation is mandatory prior to utilising the policy.

Between the two sharing policies, observing that no policy dominates the other, we conducted a statistical test to check the significance level of differences between the policies. Since the data sets (instances) serve as the locking factor, two-tailed paired-t test is used in this case. The calculated two-tailed significance level of 0.2925 indicates that the difference in fuel consumption between these two policies is not significant. Since the underlying factor behind these policies is the ratio of fleet size, it implies that this ratio is not a significant factor affecting the total fuel consumption. Another finding is related to the variances in fuel consumption and it can be inferred from Table 3 that the proportionate-sharing policy has the lowest variance than the other two policies.

The slow-steaming decision variables $f_{i,j}^{a,v}$ exhibit certain behaviour that should be addressed. In the open policy, these variables help reduce the fuel consumption by finding combination of segments in a route that can be travelled using the slow speed. However, in the other policies, there are cases where these variables function to satisfy the bounds a and b in constraint (10) even if the application makes no sense. For example, a route can safely be serviced with slow steaming, but for the sake of satisfying the bounds, the resulting decision variables are to use the normal speed instead. The implication of this finding is that these variables have proper use only in the open policy.

Table 4 Example of one routing result

Case: Small
Policy: Proportionate
Instance: #1
Results:
Carrier A consumption = 1,317.27
Carrier B consumption = 636.81
Total consumption = 1,954.08

Carrier	*Vessel*	*Routing*[1]
A	A1	-
	A2	Sby – Mks – Kdi * Sby
	A3	Sby – Bpn * Sby
	A4	Sby – Amb * Bit * Sby
B	B1	Sby – Smr – Tar * Sby
	B2	Sby * Bjm * Sby

Note: [1]*Indicates slow steaming.

Overall, we can conclude that in a collaboration effort such as observed in this study, minimisation of operational burdens is a conflicting objective with the policies on how these burdens are to be shared. The minimised fuel consumptions in the open policy are demand-dependent and therefore cannot be predicted, thus the policy is difficult to be used as a basis for planning. For practical purpose, the sharing policies should be preferred. The choice of sharing policy (proportionate or equal) does not significantly affect fuel consumption, but since the proportionate-sharing policy has smaller variance, it is considered more predictable and therefore a better choice as a basis for the carriers to setup their liner route. An example of routing from one instance in the small case with the proportionate-sharing policy is provided in Table 4. Note that one vessel of carrier A is not assigned a trip thereby maximising the utilisation of the remaining five vessels.

5 Conclusions and remarks for future research

In this paper, we have investigated the impacts of capacity sharing that is reflected in fuel consumption between two collaborating liner shipping companies. Such collaboration is inevitable in the future as an effort to respond to the global challenge, especially if the supply of containerships' capacity remains larger than the demand as witnessed today. An extended VRPTW model is formulated incorporating slow-steaming considerations and the application of fuel-consumption sharing policies. This proposed model adds to the richness in the VRP studies and provides practical insights in the field of maritime logistics collaboration. For a case study, Indonesian archipelago is used for the background of data setup although it should be underlined that the model is general in nature and can be applied elsewhere. The selected ports and other pertinent data such as distances, vessels' speeds and capacities, demands, and due dates, are setup using certain mechanisms. Two cases are developed and in each case three policies are evaluated based on 12 generated instances.

The small case does not reveal important finding except for the random distribution of the fuel consumption between both carriers when it is minimised without any restriction, i.e., by employing the open policy. This finding is confirmed in the large case that exhibits a similar pattern. This indicates that the best solution does not provide a clear suggestion as to how the operational burdens, reflected in fuel consumption, should be shared. The two sharing policies, the proportionate-sharing and the equal-sharing policies, result in relatively higher total fuel consumption. Between these two sharing policies, a hypothesis test is performed and it suggests that the fuel consumption is not significantly different.

The optimal results in the open policy are impractical to be used as a basis for route planning since they fluctuate depending on the generated demand. The sharing policies, on the other hand, provide better guidance in operations although they cannot minimise the fuel consumption. Therefore, bearing in mind that whatever sharing policy to be selected is not the optimal solution, carriers can opt for either of the two sharing policies with no significant difference in the fuel consumption. However, if smaller variance in fuel consumption is preferred, then the proportionate-sharing policy outweighs the equal-sharing policy.

There are some directions in which this research can be improved. Firstly, it is possible to formulate the problem in multi-objective optimisation. In addition to minimise fuel consumption, a secondary objective can be added to represent either of the sharing policies (e.g., equal-sharing policy can be formulated as a minimisation of deviation in total fuel consumption). This versatile approach can possibly lead to more information on the impacts of collaboration. It is also possible to combine this approach with a heuristic/meta-heuristic to reduce computation time. Secondly, improvements can be pursued with regard to the integrity of the data used in the case study. Data in real-world problems are naturally stochastic and the deterministic treatment in some of the data in this research such as sailing times and port service times can be treated otherwise to bring the problem closer to reality. Transhipment is also a viable path of extension by employing vehicle routing problem with pickups and deliveries and time windows (VRPPDTW) instead of VRPTW. Finally, more detailed cost structures could also help in providing better picture of bottom-line results.

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