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Optimal sequence of container ships in a string

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ABSTRACT

Container ships in a string may not have the same capacity. Therefore, the sequence of ships affects the number of containers that are delayed at export ports due to demand uncertainty, for instance, “a large ship, followed by a small ship, then another large ship, and finally another small ship” is better than “a large ship, followed by another large ship, then a small ship, and finally another small ship”. We hence aim to determine the sequence of the ships in a string to minimize the delay of containers, without requiring the probability distribution functions for the future demand. We propose three rules to identify an optimal or near-optimal string. The rules have been proved to be effective based on extensive numerical experiments. A rough estimation indicates that over 6 million dollars/year could be saved for all liner services in the world by optimizing the sequences of ships.

1. Introduction

Liner shipping companies transport containerized cargoes on regularly scheduled services with fixed port rotations. The regular and reliable liner services make it possible for shippers (consigners or consignees) to arrange their production plans, manage their inventories, and arrange the delivery of final products (Wang, Meng, & Bell, 2013a). From shipping lines’ viewpoint, the capacities of the shipping services are fixed, at least in short terms. Hence, shipping lines try to attract as many cargoes as possible to fill up the slots on the ships.

Uncertainties in container shipment demand are one of the major challenges for planning and operating liner services. At the tactical level, the services must be determined before the future demand is revealed (Ng, 2014). At the operational level, the number of containers available for loading in a week from a shipper may be different from what she has committed to (Wang, Meng, & Liu, 2013b). There are a number of reasons for this. For example, the shipper’s production line is down and not enough products are assembled; or the shipper just changes her mind due to the changes in business environment. Fig. 1 shows the number of containers transported between four pairs of ports in each week of a year on a trans-Pacific and an Asia-Europe service operated by an Asia-based global shipping line. Although the demand (number of containers available for loading) and the number of containers transported are different, this figure is still a strong evidence of the randomness of demand.

To fill up ship slots, shipping lines adopt the strategy of overbooking (Ting & Tzeng, 2004). Similar to the airline industry, one rationale behind the practice of overbooking is the possible cancelations of reserved slots. Different from the airline industry, another rationale for shipping lines to overbook the capacities of the ships is that they can postpone the transportation of the containers. With very few exceptions, shipping lines almost never guarantee the date of delivery for containers (Fransoo & Lee, 2013). This makes it possible for shipping lines to accept more containers: if the number of containers available at a port is higher than the ship capacity, some of them will be transported in the next week. When the shipping market is down and hence shipping lines worry that they may not have enough demand in the next week, they tend to accept whatever shipping orders received. When shippers’ containers are stacked in the container yard of an export port because the ship that visits the port in that week is full, shippers will not be compensated explicitly. Nevertheless, shipping lines do incur intangible costs, e.g., loss of goodwill, because of the inferior services provided for the shippers. In addition, more yard space is required to storage the delayed containers (Zhen, Lee, & Chew, 2011). Moreover, when there are a large number of delayed containers from the previous week, the handling time at port is longer, which affects the berth allocation by port operators (Bierwirth & Meisel, 2010; Imai, Nishimura, & Papadimitriou, 2001; Jin, Lee, & Hu, 2015; Robenek, Umang, Bierlaire, & Ropke, 2014; Türkoğulları, Taşkın, Aras, & Altınel, 2014; Xu, Li, & Leung, 2012).

Deploying larger ships will reduce the average delay of containers under uncertain demand. However, larger ships have higher operating and voyage costs. Another possible approach, which is almost costless, is to optimize the sequence of ships in the string. Suppose

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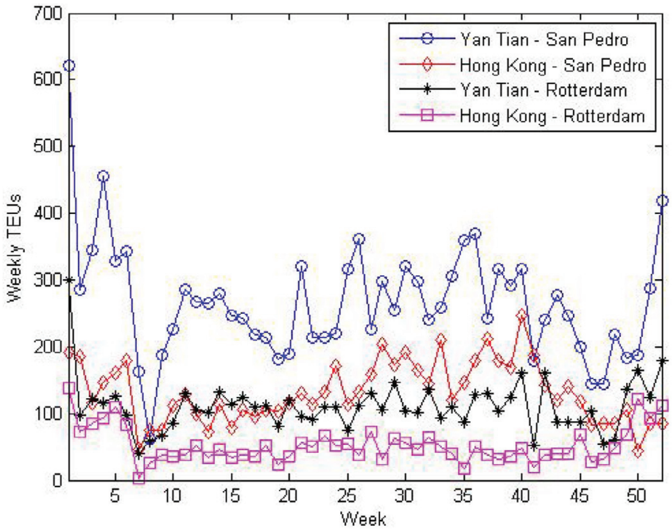

Fig. 1. Number of containers transported between four port pairs (TEU: twenty-foot equivalent units; source: Meng and Wang, 2012).

Table 1
The capacities of the ships in the string deployed on TP2.

Sequence	Vessel name	Capacity (TEUs)
1	ANTON SCHULTE	6966
2	MSC RANIA	8402
3	MSC TEXAS	8238
4	MSC TORONTO	8089
5	MSC HEIDI	8402
6	NAVARINO	8530

that six ships are deployed on a trans-Pacific service, the capacity of ships 1, 2, and 3 being 8,000 twenty-foot equivalent units (TEUs) and the capacity of ships 4, 5, and 6 being 8,200 TEUs. Since the demand is random and may exceed 8,000 or even 8,200 TEUs in some weeks, some containers that are available for loading in a week will have to wait for the ship that comes in the next week. Intuitively, the sequence of the string of ships $1 \to 4 \to 2 \to 5 \to 3 \to 6$ should outperform the string $1 \to 2 \to 3 \to 4 \to 5 \to 6$, as the capacity distribution of the former is more "uniform" and can thereby dissolve the now-and-then high demand more efficiently.

In reality, although shipping lines seek to deploy ships of similar sizes on a route to provide uniform shipping services in each week, the ships in a string may not necessarily have the same capacity in terms of the number of TEU slots. For example, Maersk Line and MSC jointly operate an Asia-to-the-US West Coast service – Transpacific 2 (TP2) with the port rotation Kaohsiung, Hong Kong, Xiamen, Shanghai, Ningbo, Long Beach, and back to Kaohsiung again (Maersk, 2014). Six ships are deployed to provide a weekly service, see Table 1 (Containership-Info, 2014; Schulte, 2014). We can see that only two ships (MSC RANIA and MSC HEIDI) are of the same size, and the difference between the capacities of two ships can be as large as $(8530 - 6966)/6966 \approx 22.5$ percent.

We identify the following two reasons that explain the ship size difference in a string: (i) Even if the string of ships was homogeneous, one of them may be under maintenance or repair, and hence another ship that may be different from the ones in the string has to come as a replacement. (ii) The rotation time of the route that the old string of ships needs to serve is changed, and new ships must be added to the string or some ships from the string have to serve other routes. For instance, when a string of mega-ships is delivered to replace an existing string on an Asia-Europe service, the latter string may be redeployed to an intra-Asia service due to the cascading effect (Cariou & Cheaitou, 2012). Some ships in the string will no long be needed as the intra-Asia service is shorter than the Asia-Europe one. A second example is service redesign due to business considerations, e.g., the pending expansion of the Panama Canal will enable post-Panama ships to visit the East Coast of the US from Asia via the Pacific Ocean (IAME, 2014). A third example is slow-steaming for saving bunker costs, which requires the insertion of one or two ships to an existing string (Fagerholt, Laporte, & Norstad, 2010).

This paper investigates how to determine the optimal sequence of ships in a string to minimize the expected number of delayed containers taking uncertain demand into consideration. We use the phrases "sequence of ships", "string" and "permutation" interchangeably. The main challenge for the problem is that it is almost impossible to predict the probability distribution functions for the future demand (Zhen & Wang, 2015). In fact, even if we have the historical data on the demand, the data may be of limited value because the shipping environment changes rapidly. Therefore, a good string should be "robust" in that it is optimal or near-optimal for any random demand.

The literature on container ship deployment all focuses on the selection of the sizes of ship for each string (Christiansen, Fagerholt, Nygreen, & Ronen, 2013; Meng, Wang, Andersson, & Thun, 2014). Ships are grouped into several types, and ships of the same type are assumed to be homogeneous. For instance, the capacity of a particular type of ship might be considered as the average capacity of the ships of the type. As a result, the sequence of the ships in a string does not affect the shipping operations because they are assumed to be of the same size. For instance, Meng and Wang (2010) developed a chanced constrained ship fleet deployment model that ensured at least a certain proportion of the demand must be fulfilled; Ng (2014) presented a robust optimization model for determining the deployment of ships to hedge against the worst-case scenario of demand. Our study could be considered as a further refinement of ship deployment after the conventional step that categorizes ships into types.

The contribution of this paper is that (i) we address a practical research problem that is of significant importance for shipping lines; (ii) we develop a model for calculating the delay of containers given a sequence of ships, and derive bounds for the best and worst sequences; and (iii) we identify rules for choosing a good string that is optimal or near-optimal among all possible permutations, without requiring the probability distribution functions of the random demand. The chosen string by the rules is demonstrated to be near-optimal for very general distribution functions of the random demand based on extensive numerical experiments.

The remainder of the paper is organized as follows. Section 2 describes the problem of determining the sequence of ships in a string. Section 3 presents a model for calculating the delay of containers given a sequence of ships. Section 4 proposes rules for choosing a good string that is optimal or near-optimal among all possible permutations. Section 5 reports the results of extensive numerical experiments for assessing the efficacy of the rules. Section 6 concludes.

2. Problem description

We consider the hit-haul leg of a long-haul liner service. The hit-haul leg is the leg on which the highest number of containers is carried. For instance, the leg after the last port of call in Asia in the hit-haul leg for trans-Pacific and Asia–Europe services, as the demand from Asia to the US/Europe is higher than that from the US/Europe to Asia. To simplify the exposition, we consider a liner service with only one export port (e.g., Shanghai) and one import port (e.g., Los Angeles), providing a weekly frequency, as most shipping services are weekly (Bell, Liu, Angeloudis, Fonzone, & Hosseinloo, 2011; Bell, Liu, Rioult, & Angeloudis, 2013; Wang, 2014; Wang & Meng, 2013).

A string of V ships are deployed on the service. The container capacity of ship v is denoted by E_v (TEUs), $v = 1, 2, \ldots, V$. Without loss