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Multi-objective optimization for planning liner shipping service with uncertain port times

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ABSTRACT

This paper considers a joint tactical planning problem for the number of ships, the planned maximum sailing speed, and the liner service schedule in order to simultaneously optimize the expected cost, the service reliability and the shipping emission in the presence of port time uncertainty. The problem is formulated into a stochastic multi-objective optimization problem at the operational level. The relationships between the objectives and the decision variables are established. A simulation-based non-dominated sorting genetic algorithm is then presented to solve this problem. A case study is provided to illustrate the results and the application of the model.

1. Introduction

Container liner shipping is a capital intensive, low-differentiation, highly competitive service industry (Song et al., 2005; Agarwal and Ergun, 2010). Economic recession and trade demand slowing down have led to overcapacity in transport service supply since 2008. Dynamic operations and uncertain activities associated with long geographical distances in container shipping bring challenges to the quality of shipping services. Increasing concerns about social and environmental impacts from shipping also affect shipping operations and performance. Therefore, it is vital for shipping lines to plan their shipping services appropriately taking into account multiple performance perspectives.

In the context of supply chain management, four performance measures are often adopted: cost, asset utilization, reliability, and responsiveness/flexibility. The first two are service provider's internal-facing measures for efficiency, while the last two are external customer-facing measures for service effectiveness (Lai et al., 2002). Following from this, the key performance indicators (KPI) of shipping lines should include two groups: operational efficiency and service effectiveness. The former emphasizes cost reduction and asset utilization/efficiency, whilst the latter emphasizes service differentiation and quality of service. In addition to these two groups, there is another group of KPIs, i.e. the social and environmental impacts of the shipping service. This group has attracted much attention in the last two decades and appears to have become more important due to greater concerns about global climate change and sustainability. This paper will address a liner shipping service planning problem from the above three perspectives simultaneously, with the emphasis on cost efficiency, service reliability, and CO_2 emission; addressing a clear yet important gap in the literature.

In the following, we review the relevant literature corresponding to the three groups of key performance indicators: operational efficiency, service effectiveness and environmental impact. The review focuses on literature that is closely related to liner service planning problems associated with the above performance measures explicitly or implicitly.

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1.1. Cost efficiency

Cutting costs has been the main task on shipping companies' agenda since the economic crisis in 2008. Various strategies and practices have been employed. These include shipping service network rationalization through internal optimization such as ship deployment, route scheduling, slow steaming, and empty container repositioning, or through external collaboration such as vertical integration with terminal operators and freight forwarders, and horizontal integration with other shipping companies to form strategic alliances (e.g. the emergence of M2 and Ocean Three alliances in 2014). From the modeling perspective, Brouer et al. (2014) and Tran and Haasis (2013) provided comprehensive reviews of the liner shipping network design problems. Meng et al. (2014) reviewed the studies focusing on containership routing and scheduling problems over the past 30 years. Dong and Song (2009) considered the joint container fleet sizing and empty container repositioning problem in a shipping system with uncertain customer demands, which implicitly improves the container asset utilization. Agarwal and Ergun (2010) and Zheng et al. (2015) modeled the liner alliances and presented capacity exchange mechanisms to achieve optimal ship capacity allocation among multiple shipping lines. Liu et al. (2014) presented a network design model including both the inland and maritime networks, which can be regarded as a vertical integration along the container transport supply chain. They focused on selecting candidate service routes to best meet a given set of global inland origin–destination demands. The models developed in this group aim to minimize the costs or maximize the revenue/profit. The majority of them concentrate on deterministic situations and use mathematical programming techniques. A detailed review of this group is not presented here due to its wide coverage. However, some specific studies of this group that are related to the KPIs of service effectiveness or shipping emissions will be reviewed within two other groups of KPIs.

1.2. Service effectiveness

In order to improve service effectiveness, shipping companies may seek vertical integration with other stakeholders or expand into logistics services (to offer one-stop service), provide more frequent and flexible service (e.g. Maersk's daily service), improve service reliability, offer more flexible closing times, and provide a wider shipping network and coverage. Service reliability is arguably the most important of these. A delayed vessel arrival at a port may impact on berth allocation and handling operations; this may further influence downstream supply chain members' operations, e.g. inland transportation operators' truck scheduling and shippers' inventory management. It also leads to the dissatisfaction of shippers and damages shipping liners' reputation. Low schedule reliability can have serious financial consequences for various players in the transport supply chain, e.g. it can significantly increase the operating costs of shipping lines and container terminals, and the inventory costs and production costs of shippers and manufacturers (Vernimmen et al., 2007).

However, due to the existence of various uncertainties in shipping operations at sea and in ports, it is well known that containerships often arrive at a port out of the scheduled time window, which is referred to as 'schedule unreliability'. It was reported that vessel arrival reliability against published schedules can be as low as 50% for many service routes (Notteboom, 2006; Vernimmen et al., 2007). More recent reports revealed that there has not been much improvement in terms of schedule reliability. For example, top-20 liners only reached an on-time performance up to 60% (Drewry, 2010). The global schedule reliability was at 63% in November and 59% in December in 2011 (SeaIntel Maritime Analysis, 2011). Drewry (2015) stated that only 49% and 55% of ships in the three key East–West trades arrived within one day (±24 h) of the advertised estimated arrival times in January and February 2015 respectively. In March 2015, the 2 M alliance achieved 68% schedule reliability, the CKYHE alliance was at 66%, whereas the Ocean Three was at 61% (Baker, 2015). It should be noted that most of the above statistics of the schedule reliability are based on the same-day arrival criterion (i.e. the vessel is regarded as on time arrival if it actually arrives at a port on the same day of the planned arrival time). In other words, schedule reliability in the strictest sense could be much worse.

Several empirical studies have examined the sources of schedule unreliability. Based on a survey on the East Asia–Europe route in 2004, Notteboom (2006) reported that port/terminal congestion (unexpected waiting times before berthing or before starting loading/discharging) accounted for 66%, port/terminal productivity below expectations (loading/discharging) accounted for 21%, unexpected waiting times in port channel access (pilotage, towage, tidal windows) accounted for 8%, and unexpected waiting times due to weather or on route mechanical problems for 5%. In summary the port related sources accounted for 94% of schedule unreliability. Vernimmen et al. (2007) showed that low schedule reliability could be caused by a number of factors and stated that many of them are beyond the control of container shipping lines, e.g. port congestion, bad weather, and labor strikes. Schedule reliability has a cascading effect. Namely, once a vessel is delayed at one port, it is likely to be delayed at other ports on its scheduled journey. Vernimmen et al. (2007) confirmed that port congestion in previous ports is the most important factor of schedule unreliability.

Although many sources of schedule reliability are beyond the control of shipping lines, shipping lines could mitigate their impact and improve schedule reliability through appropriate tactical and operational planning. One tactical measure is to deploy more vessels to the same service route, but maintain the same service frequency (e.g. the weekly service). This would allow more buffer times in each sea leg to absorb the uncertainty. This idea is closely related to the slow steaming practice. Slow steaming was introduced in 2008 mainly for reducing the high fuel cost, which accounted for over 50% of the total ship operational cost due to the high fuel price (e.g. Notteboom and Vernimmen, 2009; Cariou, 2011; Ronen, 2011). It was claimed that slow steaming would benefit the service reliability since ships have more room to speed up to buffer against uncertainties. However, there is a lack of quantitative research into how much slow steaming impacts service reliability. Only one