Transportation Research Part E 48 (2012) 863–880

Contents lists available at SciVerse ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times

Xiangtong Qi [a], Dong-Ping Song [b,*]

[a] Department of Industrial Engineering and Logistics Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[b] International Shipping & Logistics Group, School of Management, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

ARTICLE INFO

Article history:
Received 22 September 2011
Received in revised form 15 December 2011
Accepted 7 February 2012

Keywords:
Liner shipping
Fuel emission
Ship scheduling
Uncertainty
Stochastic optimization

ABSTRACT

We consider the problem of designing an optimal vessel schedule in the liner shipping route to minimize the total expected fuel consumption (and emissions) considering uncertain port times and frequency requirements on the liner schedule. The general optimal scheduling problem is formulated and tackled by simulation-based stochastic approximation methods. For special cases subject to the constraint of 100% service level, we prove the convexity and continuous differentiability of the objective function. Structural properties of the optimal schedule under certain conditions are obtained with useful managerial insights regarding the impact of port uncertainties. Case studies are given to illustrate the results.

1. Introduction

Emissions from maritime transport have been brought into attention increasingly in the last decade. International Maritime Organization (IMO) published two studies on green house gas (GHG) emissions from ships in 2000 and 2009, respectively (Skjølsvik et al., 2000; Buhaug et al., 2009). The second study provided a comprehensive and authoritative assessment of the level of GHG emitted by ships in the world, and estimated that shipping emitted 1046 million tonnes of CO_2 in 2007, which accounted for about 3.3% of the global emissions.

Container shipping has been one of the fastest growing sectors in the shipping industry in the past three decades and may well continue its rapid growth in the future (MEPC, 2009; Fransoo and Lee, in press). It is reported that containerships are by far the most important source of CO_2 emissions in the shipping industry, in both absolute and per tonne-km terms (Psaraftis and Kontovas, 2009). Corbett et al. (2009) stated that CO_2 emissions from containerships are 1.3, 2.2 and 2.5 times greater than those from bulk shipping, crude oil tankers, and general cargo ships, respectively. Therefore, reducing CO_2 emissions is an essential issue for the container shipping industry in achieving its environmental sustainability. A few studies have been conducted to quantify the impact of operational measures such as speed reduction, berth scheduling and route re-engineering on fuel consumptions and CO_2 emissions in container shipping, e.g., Corbett et al. (2009), Psaraftis et al. (2009), Fagerholt et al. (2010), Golias et al. (2010), Cariou (2011), Lee et al. (2012), Meng and Wang (2011), Du et al. (2011), and Song and Xu (2012).

From the economic perspective, the steep increase in oil prices in the past several years has pressed the shipping companies to adopt fuel-cutting strategies. As fuel consumption of a ship is typically a cubic function of sailing speed (e.g. Ronen,

* Corresponding author. Tel.: +44 1752 585630; fax: +44 1752 585633.
E-mail addresses: ieemqi@ust.hk (X. Qi), dongping.song@plymouth.ac.uk (D.-P. Song).

1366-5545/$ - see front matter
doi:10.1016/j.tre.2012.02.001

1982; Fagerholt et al., 2010), many operational strategies are directly linked to reducing ship speeds. For example, slow steaming has become a popular practice and been adopted by many shipping companies since 2008 (www.ci-online.co.uk). Since emissions from ships are proportional to the fuel consumption (e.g. Buhaug et al., 2009), slower speeds are generally regarded as both economically and environmentally beneficial.

Christiansen et al. (2004, 2007) provided a comprehensive review of the research on ship routing and scheduling and classified the literature into three categories: industrial shipping, tramp shipping, and liner shipping. Liner shipping has its unique characteristics, e.g., ships are usually deployed on a closed route with weekly frequency following a published schedule of sailings with a fixed port rotation, and laden/empty containers are loaded on/off the ships at each port-of-call (Song et al., 2005; Ronen, 2011). Quite a few authors have addressed the economic aspects (e.g. profit, capital investment, and operating costs) of the vessel routing and deployment in the liner shipping, e.g. Rana and Vickson (1991), Cho and Perakis (1996), Powell and Perakis (1997), Ting and Tzeng (2003), Shintani et al. (2007), Agarwal and Ergun (2008), Karlaftis et al. (2009), Notteboom and Vernimmen (2009), Alvarez (2009), Meng and Wang (2010), Wang and Meng (2011a,b), and Ronen (2011). However, as pointed out by Christiansen et al. (2007) and Ronen (2011), relatively little research has been published regarding optimizing the speed of vessels. Fagerholt et al. (2010) developed a shortest path approach to minimize fuel consumption (or emissions) by optimizing ship speed in deterministic fixed shipping routes subject to time window for the start of service at each port. Ronen (2011) analyzed the trade-off between speed reduction and adding vessels to a container liner route using a cost model. Meng and Wang (2011) determine service frequency, ship fleet deployment plan, and sailing speeds for a long-haul liner service route by minimizing average daily operating cost.

Uncertainty is another important characteristic in liner shipping, which may exist in equipment availability, sea transport legs or container ports due to various reasons such as congestion, uncertain handling time, and weather condition. For example, Cheung and Chen (1998) considered the uncertainties in container supplies, demands, and vessel capacity and their impact on empty container repositioning. A survey on the sources of schedule unreliability in the East Asia – Europe route for the fourth quarter of 2004 revealed that port/terminal congestion (unexpected waiting times before berthing or before starting loading/discharging) accounted for 65.5%, port/terminal productivity below expectations (loading/discharging) accounted for 20.6%, and unexpected waiting times in port channel access (pilotage, towage) accounted for 4.7% (Notteboom, 2006). Because of the cumulative effect, a delay at one port-of-call may cause delays at the rest of port-of-calls in the service route unless there are some mechanisms implemented to reduce port times (e.g. cut a port-of-call) or reduce sea times (e.g. increase vessel speed) to make up the lost time. It was reported that the vessel arrival reliability with respect to the published schedule could be as low as 50% for many service routes (Notteboom, 2006; Vernimmen et al., 2007). Clearly, uncertainty will impact on the vessel's reliability, fuel consumption and emissions, particularly in situations if the schedules were not well designed. For example, for a weekly service with ten vessels deployed, the round-trip journey time will be fixed at 70 days. For any vessel, if more time is scheduled to some legs, less time will be allocated to other legs. A port delay before a tight leg may force the vessel to sail at the maximum speed in order to respect the schedule, but the vessel could still fail to reach the next port on time, resulting in a deteriorate service level. Here a vessel's service level refers to the probability that the vessel is able to arrive at a port no later than the published planned arrival time. The delayed vessel arrival at a port may impact on berth allocation and handling operations, which may further influence downstream supply chain members' operations (e.g. inland transportation operators' truck scheduling, customers' inventory management). Poor vessel service level could lead to dissatisfaction of shippers and damage liners' reputation. Therefore, when designing the liner service schedules in advance, it is important to take into account the uncertainties in the system so that a reasonably high service level can be achieved.

In the literature, the majority of the above research on vessel routing, scheduling and deployment has not explicitly considered the stochastic aspect of the systems. This paper attempts to fill this research gap. Since port-related uncertainty is the dominant source of vessel schedule unreliability (Notteboom, 2006), we will concentrate on the port time uncertainty. More specifically, this study focuses on designing an optimal vessel schedule in a given shipping route with the aim to minimize the total fuel consumption (or emissions) by considering uncertain port times at each port-of-call and the frequency requirements on the liner schedule. Meanwhile, by introducing the penalty of being late, we are able to design an optimal vessel schedule with reasonably high service levels.

The remainder of the paper is organized as follows. The next section formulates the problem. The section after examines the optimal schedule and its structural properties for special cases with 100% service levels, as well as the stochastic approximation approach for the general case. Next we provide numerical studies to demonstrate the results, followed by conclusions.

2. The model and service level

Liner service differs from other shipping sectors mainly in its regularity. Usually, a set of vessels with similar sizes are deployed to call at a fixed sequence of ports in the shipping route to provide a weekly service, where a round trip visit of all port-of-calls is called a voyage. Vessels sail along the shipping route in consecutive voyages by following the published schedule, carrying containers over sea legs, and loading/unloading containers at port-of-calls. In order to describe the dynamics of the system, we introduce the following notation first.