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Green vessel scheduling in liner shipping: Modeling carbon dioxide emission costs in sea and at ports of call ☆

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ABSTRACT

Considering a substantial increase in volumes of the international seaborne trade and drastic climate changes due to carbon dioxide emissions, liner shipping companies have to improve planning of their vessel schedules and improve energy efficiency. This paper presents a novel mixed integer non-linear mathematical model for the green vessel scheduling problem, which directly accounts for the carbon dioxide emission costs in sea and at ports of call. The original non-linear model is linearized and then solved using CPLEX. A set of numerical experiments are conducted for a real-life liner shipping route to reveal managerial insights that can be of importance to liner shipping companies. Results indicate that the proposed mathematical model can serve as an efficient planning tool for liner shipping companies and may assist with evaluation of various carbon dioxide taxation schemes. Increasing carbon dioxide tax may substantially change the design of vessel schedules, incur additional route service costs, and improve the environmental sustainability. However, the effects from increasing carbon dioxide tax on the marine container terminal operations are found to be very limited.

Introduction

Maritime transportation is vital for the global trade with more than 10 billion tons of cargo transported by vessels (UNCTAD, 2015). However, the maritime transportation sector is responsible for a significant quantity of greenhouse gas (GHG) emissions, which are mainly represented by carbon dioxide (CO_2) emissions (Lindstad et al., 2011, 2012). According to the third GHG study, conducted by the International Maritime Organization (IMO), the overall CO_2 emissions from the international maritime shipping comprise approximately 2.2% of the global CO_2 emissions (IMO, 2014). If no actions are taken, the total production of CO_2 emissions can increase by 150–250% by 2050 due to increasing volumes of the international seaborne trade (Lindstad et al., 2012). The United States Environmental Protection Agency (EPA) underlines that CO_2 is a primary GHG that causes the climate change (EPA, 2017). CO_2 and other GHGs absorb the energy from sunlight and prevent loss of heat to space (Sun and Wang, 1996; Feroz et al., 2009; Sharma et al., 2012; Tseng and Hung, 2014; Stewart, 2015; Levin et al., 2017). The latter phenomenon is also known as "*GHG effect*". The average global temperatures are expected to increase between 1.4 °C and 5.8 °C by 2100 due to the GHG effect (Live Science, 2017). A rapid increase in the average temperatures due to CO_2 emissions may result in catastrophic consequences at the global level.

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To alleviate negative externalities and reduce CO_2 emissions produced by oceangoing vessels IMO enforced a number of regulations. In 2011, IMO developed a new chapter with amendments to MARPOL Annex VI, entitled as "*Regulations on energy efficiency for ships*" (IMO, 2017). According to those amendments, the vessels are obligated to attain a specific "*Energy Efficiency Design Index*", which is computed based on the vessel technical characteristics (i.e., rated installed shaft power, deadweight tonnage, and vessel speed at the designed load) and fuel type. Furthermore, liner shipping companies are required to comply with "*Ship Energy Efficiency Management Plan*". The latter aims to improve energy efficiency of vessels in a cost-effective manner (e.g., improve planning of the vessel voyage, proper cleaning of propellers, implementation of new technical measures, etc.).

In order to ensure a proper planning of the vessel voyage and improve energy efficiency, liner shipping companies have to directly account for the cost of CO_2 emissions, produced in sea and at ports of call (Schroten et al., 2011; Tran et al., 2016). Throughout scheduling of vessels, the liner shipping company is required to identify the arrival times at ports of call, vessel handling times at ports of call, departure times from ports of call, and vessel sailing speeds at voyage legs of the liner shipping route. This paper proposes a novel mixed integer non-linear model for the green vessel scheduling problem in a liner shipping route, which minimizes the total route service cost and accounts for the costs, associated with CO_2 production in sea and at ports due to container handling. The original mathematical formulation is linearized, and then solved using CPLEX. A number of computational experiments are conducted for the Asia-North America AZX route, served by the Nippon Yusen Kaisha (NYK) liner shipping company, to demonstrate applicability of the proposed methodology and reveal some important managerial insights. Unlike the published to date studies on vessel scheduling, which either completely ignore emissions produced by vessels or do model emissions without accounting for the associated costs, this study presents a holistic approach for modeling the CO_2 emissions, produced by oceangoing vessels in sea and at ports of call, and accounting for the associated costs. The developed mathematical model will serve as effective planning tool for liner shipping companies and facilitate construction of green vessel schedules.

The remainder of the manuscript is structured in the following manner. The second section presents an overview of the relevant literature with the main focus on the vessel scheduling models and environmental aspects. The third section provides a detailed description of the problem studied herein, while the fourth section presents a mixed integer non-linear model for the problem. The fifth section discusses the adopted solution methodology, while the sixth section describes the numerical experiments, performed in this study. The last section summarizes findings and outlines potential future research extensions.

Literature review

Decisions that have to be made by liner shipping companies can be categorized into three groups (Meng et al., 2014): 1) strategic decisions (e.g., fleet size and mix, alliance strategy, network design); 2) tactical decisions (e.g., frequency determination, fleet deployment, speed optimization, schedule construction); and 3) operational decisions (e.g., cargo booking, cargo routing, vessel rescheduling, potential reject of cargo). The literature review presented herein primarily focuses on a tactical level vessel scheduling problem. A critical review of the relevant studies is provided next.

Related work

All of the collected studies on vessel scheduling were divided in two groups. The first group of studies focuses on various operational aspects in vessel scheduling without explicitly capturing the environmental issues and emissions produced by vessels, while the second group of studies accounts for both operational and environmental aspects in vessel scheduling (i.e., "*green vessel scheduling*").

Vessel scheduling in liner shipping

Fagerholt (2001) studied a vessel scheduling problem in a liner shipping route, where port arrival time windows (TWs) could be violated. An additional cost was introduced to penalize violation of port arrival TWs. The objective minimized the total transportation and inconvenience costs. A set partitioning algorithm was developed to solve the problem. Numerical experiments demonstrated that the algorithmic performance was substantially affected with the problem size. Dulebenets (2015a) presented a Memetic Algorithm for the vessel scheduling problem, minimizing the total route service cost. The proposed solution algorithm was compared against the static secant approximation. Computational experiments showed that the developed Memetic Algorithm outperformed the static secant approximation in terms of solution quality and computational time. Wang et al. (2015) presented a methodology for assessing the perceived value of container transit time. The objective minimized the fuel consumption and container transit time costs. A number of computational examples demonstrated that the proposed approach could assist liner shipping companies with design of the optimal transit times and vessel sailing speeds between consecutive ports.

Certain studies modeled uncertainty in liner shipping scheduling operations. Chuang et al. (2010) formulated the vessel routing and scheduling problem with uncertain market conditions, port handling times, and vessel sailing times, maximizing the total profit. The problem was solved using a Fuzzy Evolutionary Algorithm. Qi and Song (2012) focused on the vessel scheduling problem, modeling the port handling time uncertainty. The objective minimized the total expected fuel con-