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The multi-port berth allocation problem with speed optimization and emission considerations

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ABSTRACT

The container shipping industry faces many interrelated challenges and opportunities, as its role in the global trading system has become increasingly important over the last decades. On the one side, collaboration between port terminals and shipping liners can lead to costs savings and help achieve a sustainable supply chain, and on the other side, the optimization of operations and sailing times leads to reductions in bunker consumption and, thus, to fuel cost and air emissions reductions. To that effect, there is an increasing need to address the integration opportunities and environmental issues related to container shipping through optimization. This paper focuses on the well known Berth Allocation Problem (BAP), an optimization problem assigning berthing times and positions to vessels in container terminals. We introduce a novel mathematical formulation that extends the classical BAP to cover multiple ports in a shipping network under the assumption of strong cooperation between shipping lines and terminals. Speed is optimized on all sailing legs between ports, demonstrating the effect of speed optimization in reducing the total time of the operation, as well as total fuel consumption and emissions. Furthermore, the model implementation shows that an accurate speed discretization can result in far better economic and environmental results.

1. Introduction

Maritime transport has been growing in importance during the last decades, achieving a dominant role in the global transportation system. The 2015 edition of the Review of Maritime Transport (UNCTAD, 2015) estimates that the global seaborne trade increased by 3.4% in 2014, reaching over 9.84 billion tons, thus more than 80% of global merchandise trade by volume is carried by sea and handled by ports worldwide. In recent years, increasing fuel prices, growing congestion, depressed market conditions and environmental issues, such as air emissions, have brought a new perspective to maritime transportation. Therefore, in addition to being efficient from an economic perspective, the global maritime chain has to significantly improve its environmental friendliness (Psaraftis and Kontovas, 2013).

The easiest way to estimate emissions from transportation (e.g. carbon dioxide, sulphur oxides etc) is to multiply the energy or fuel used by an appropriate emissions factor, which is the ratio of emissions produced per unit energy or unit fuel consumed (see Kontovas and Psaraftis (2016) for more on emissions calculations). For example, there is a linear relationship between fuel burned and CO_2 produced, with the proportionality constant being known as the carbon coefficient. These

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factors are empiricals, and for example, the IMO GHG study of 2014 used coefficients, which ranged from 3.114 kilograms CO_2 per kilogram fuel for Heavy Fuel Oil (HFO) to 3.206 kilograms CO_2 per kilogram fuel for Marine Diesel Oil (MDO).

The latest IMO study (IMO, 2014) provided updated estimates of CO_2 emissions from international shipping from 2007 to 2012. The 2012 figure, estimated by a bottom up method, was 796 million tonnes, down from 885 million (updated figure) in 2007, or 2.2% of global CO_2 emissions. CO_2 from all shipping was estimated at 940 million tonnes, down from 1100 tonnes in 2007. According to a recent analysis (Psaraftis and Kontovas, 2009), containerships are the top CO_2 emitters in the world fleet, the high speed in comparison with other ship types being the major reason. This work focuses on two major interrelated challenges for the container shipping industry: (a) the increasing containerized trade opens up new opportunities for improving the cooperation between container terminal operators and liner shipping companies in order to reduce logistics costs and achieve efficient transportation systems, and (b) efficient and integrated operations, especially in terms of idle time minimization, correspond to savings in fuel consumption and bunker cost, but also in environmental benefits, in terms of reduced emissions.

More precisely the benefits from the integration that we present are as follows; (a) liner operators reduce their operating cost through fuel savings due to optimal speed selection and improved efficiency, (b) terminal operators streamline the use of the available berths increasing the efficiency of the terminals and (c) in most of the cases, there is also an environmental benefit due to reduced fuel consumption and, thus, ship air emissions. This work addresses the operations at container terminals along with speed optimization on all sailing legs between ports of a shipping network. We develop a novel formulation for the Berth Allocation Problem (BAP) under the perspective of tackling the above mentioned challenges and achieve a win-win-win solution for both the logistics parties at play (container ports and liner shipping companies) and the environment.

The classical BAP aims at allocating the berthing positions and times for the vessels arriving at the port. Our work extends the classical BAP by optimizing berthing decisions at multiple ports of a predetermined port-visiting route (string) along with optimizing the speed at each leg. Our problem deals with determining arrival times, berthing times and berthing positions for each vessel for each port in the string where the handling time for each vessel is known for each port-berth combination. In addition, the sailing speeds on each leg along the string are optimized. In short, we discretize the possible sailing speeds and select the optimal speed value for each leg. The total fuel consumption, which depends on the selected speed, is part of the objective function. By doing so, we achieve reductions in fuel costs and air emissions, as both of them are directly proportional to fuel consumption. In the classical BAP, the known arrival times either impose a hard constraint on berthing time (i.e. dynamic BAP, Imai et al. (2001)), or it is assumed that all vessels are available to be berthed at the time of planning (i.e. static BAP). In this paper, the multi-port BAP deals with determining the arrival time for each vessel at each port. The classical BAP distinguishes between discrete and continuous versions of the problem. In the discrete BAP, each vessel fits in a berth which has pre-determined borders (Buhrkal et al., 2011), while the continuous BAP relaxes this assumption and allows each vessel to berth at any discretized point (e.g. it can be completely continuous (Lee et al., 2010), discretized per each k^{th} meter (Iris et al., 2015)) along the quay. In this paper, the problem is modeled by using a discrete layout, where each vessel occupies one berth along the quay.

The sailing speed of each vessel is taken from a predefined set, which allows for variable arrival and berthing times at ports, thus avoiding an early arrival to a harbor if already busy, by slowing down on the sailing leg. The problem definition also allows for vessels to speed up in case the next terminal is available for berthing. Our scenario implies that the pool of ships is managed in a collaborative way, where the benefits and costs of the objective (total service time and fuel consumption minimization) are shared between shipping lines and port terminal operators. The realistic applicability of the above problem needs further investigation since shipping companies (that control the operation of vessels) and port operators (that control port operations such as berthing) are usually different entities with often conflicting interests. This is discussed in Sections 2.4 and 5.

The contribution of this paper is multi-fold. First of all, this study presents optimal solutions (for many instances) for the collaborative berth allocation and speed optimization problem for all ports and legs of a given shipping network. Secondly, we show that the collaborative problem presented in this paper can reduce emissions up to 42% in the entire network compared to the conventional design speed based planning in practice. Thirdly, we show that the increasing oil prices encourage slow steaming and in many cases even at the expense of prompt arrival to ports. Finally, the difference between emissions at sea and emissions during dwell times are also discussed in the context of berth availability for each port of the network.

The rest of this paper is organized as follows. Section 2 reviews the relevant literature, provides an introduction to the BAP (see Section 2.1), the integration of speed optimization into it (see Section 2.3), and the co-operation of container shipping lines and terminal operators (Section 2.4). Section 3 describes the combined Multi-Port Berth Allocation and Speed Optimization Problem. In Section 3.2, the integer linear programming formulation (ILP) is presented for the problem and enhancements for this formulation are communicated. Section 4 presents and discusses the results of some case studies and, finally, Section 5 presents the conclusions and a final discussion of the proposed model.

2. Background and literature review

Maritime container terminals represent a node of intermodal change between different means of transport. The handling of containers in a terminal is a complex process that includes operations in seaside, yardside and hinterland. Researchers