Berth and quay-crane allocation problem considering fuel consumption and emissions from vessels

Qing-Mi Hu, Zhi-Hua Hu, Yuquan Du

Abstract

Resolving the berth and quay-crane allocation problem improves the efficiency of seaside operations by optimally allocating berthing spaces and quay cranes to vessels, typically by considering a vessel’s sailing speed and arrival time at a port as constant parameters, while ignoring the impact of arrival times on fuel consumption and emissions when sailing. This work applied a novel nonlinear multi-objective mixed-integer programming model that considered a vessel’s fuel consumption and emissions, and then transformed this model into a second-order mixed-integer cone programming model to solve the problem’s computational intractability. Furthermore, the impact of number of allocated quay cranes on port operational cost, and a vessel’s fuel consumption and emissions was analyzed. Additionally, a vessel’s emissions while moored are also calculated based on wait time. Experimental results demonstrate that the new berth and quay-crane allocation strategy with a vessel’s arrival time as a decision variable can significantly improve vessels’ fuel consumption and emissions, the air quality around ports and utilization of berths and quay cranes without reducing service quality.

1. Introduction

Port operators and shipping companies are the major players in port operations. Port operators attempt to optimize the utilization of port resources (e.g., berths and quay cranes) and many make great efforts to reduce their environmental impact. On the one hand, increasing utilization of port resources greatly improves an operator’s profit. Utilization efficiency of berths, cranes, and other resources are emphasized. Seaside operations are typically recognized as bottlenecks, limiting port performance. On the other hand, vessels that are served contribute to environmental pollution in port areas. For instance, noise pollution and air pollution adversely affect the health of people living in port areas. The data for the world showed that ocean-going vessels accounted for 27% of CO₂, 98.9% of SO₂, 48% of NOₓ, and 58.3% of fine particles of all port emissions at 2010 (Starcrest Consulting Group, 2010). Therefore, many port operators and authorities are very concerned with reducing port-related pollution. To reduce operational cost and minimize environmental pollution, shipping companies strive to reduce a vessel’s fuel consumption. Both economic concerns (e.g., fuel consumption) and environmental concerns (e.g., vessel emissions) markedly influence choices of port operators and shipping companies. Dedes et al. (2012), Song and Xu (2012), and Fagerholt et al. (2010) developed some decision-making strategies for problem of port environment protection and vessel fuel consumption optimization.

To optimize utilization of port resources and reduce a vessel’s fuel consumption and emissions, this work attempts to optimize operational schedule at ports and vessels’ shipping schedule. Moreover, service quality provided by port operators to vessels must not be reduced. Closely related issues have been studied at strategic levels by Corbett et al. (2009), Schrooten et al. (2008) and Qi and Song (2012). This study applies a novel strategy for the continuous berth and quay-crane allocation problem (BCAP), in which arrival times of vessels are formulated as decision variables of a nonlinear multi-objective mixed-integer programming model. The nonlinear objective is transformed into a second-order cone programming (SOCP) model. Further, vessel emissions while moored are calculated based on two parameters: wait time and emission factors. Finally, resource utilization at a port, impact of the number of quay cranes on port operational cost, and a vessel’s fuel consumption and emissions are analyzed.

Compared to pioneering studies, including that of Park and Kim (2003), which formulated the continuous BCAP, and that by Du et al. (2011), which addressed the berth allocation problem (BAP) while considering a vessel’s fuel consumption and emissions, this study contributes to literature in the following ways. First, the fuel consumption and emissions of vessels are considered in an integral
model of BCAP. Therefore, a multi-objective model is constructed for a tradeoff analysis between costs and environmental issues. Second, because the handling time of vessels at port markedly impact sailing times and speeds, the effects of quay-crane assignment are incorporated into the proposed model. This inclusion increases the flexibility when adjusting the schedules of vessels. Third, to the best of our knowledge, emissions from vessels during mooring periods are first quantified in literature for BAPs. Thus, emissions from vessels are examined for when moored and sailing. Fourth, arrival times of vessels at ports are formulated as decision variables, such that sailing speeds and quay-crane utilization can be balanced by adjusting the berthing times of vessels.

The remainder of this paper is organized as follows. Section 2 provides a concise literature review. Section 3 formally describes the procedures for calculating fuel consumption by and emissions from vessels. Section 4 presents the proposed mathematical formulations. Section 5 reports experimental results, which verify proposed approaches. This work concludes with Section 6 and further research directions are suggested.

2. Literature review

The BAP and quay crane assignment problem (QCAP) are foundational problems to solve when seeking to optimize container terminal operations because berths and quay cranes are critical resources. For a detailed review of research on the BAP and QCAP, see Bierwirth and Meisel (2010), Steenken et al. (2004), and Stahlbock and Voß (2008). According to literature, the BCAP can be divided into two categories. First, the BCAP can be modeled as two sub-problems, berth allocation and quay-crane allocation problems. The former considers static versus dynamic vessel arrivals, and discrete versus continuous berthing to minimize total wait time for vessels and to optimize vessel’s berthing time and berthing position (e.g., Brown et al., 1994; Imai et al., 2001; Kim and Moon, 2003; Li et al., 1998). The latter focuses on how to best allocate a suitable number of quay cranes to each vessel, and tries to reduce moving times for quay cranes or improve their operational efficiency at seaport operations (e.g., Daganzo, 1989; Goodchild and Daganzo, 2007; Lee et al., 2008).

Instead of using BAP and QCAP as two sub-problems, the integrated scheduling method formulates two sub-problems in a complete model. Since a vessel’s time at port depends largely on number of allocated quay cranes, Park and Kim (2003) established a mixed-integer programming model to identify the optimal berthing position, berthing time, and number of allocated quay cranes for each vessel. Imai et al. (2008), Liang et al. (2008) and Chang et al. (2010) also formulated models integrating BAP and QCAP. Imai et al. (2008) studied the quay-crane path optimization problem in the context of a discrete BAP.

These studies solved the BCAP by primarily considering wait time for vessels, lowest-cost berthing location, departure time, quay crane moving times, and operational efficiency. Only a few studies considered the fuel consumption and emissions by vessels. Golas et al. (2009) and Lang and Veenstra (2010) formulated a BAP that considered fuel consumption. Golas et al. (2009) regarded arrival times of vessels as decision variables when they formulated a BAP. They attempted to reduce fuel consumption and emissions by minimizing total wait time for vessels; they assumed that as wait time declined, a vessel’s port-related fuel consumption and emissions declined. Lang and Veenstra (2010) also considered the arrival time of vessel’s as decision variable in a BAP, quantitatively analyzed fuel consumption by vessels. Alvarez et al. (2010) formulated a new berth allocation policy for both fuel saving and terminal productivity.

Du et al. (2011) recently considered arrival time for vessels as a decision variable in a BAP, and quantitatively analyzed fuel consumption and emissions by vessels while sailing. Moreover, the nonlinear function between fuel consumption rate and sailing speed is transformed into SOCP constraints. However, the impact of quay-crane allocation on fuel consumption and emissions by vessels was not considered. Later, based on Du et al. (2011) and Wang et al. (2013) proposed static and dynamic quadratic outer approximation approaches that efficiently handle the general nonlinear function between fuel consumption rate and sailing speed.

These studies did not consider the impact of quay-crane allocation on fuel consumption and emissions. Moreover, emissions while moored are not considered in current formulations. To overcome these limitations, this work formulates a novel BCAP model that considers fuel consumption and emissions by vessels, and analyzes the impact of number of allocated quay cranes on port operational cost, and fuel consumption and emissions by vessels.

3. Fuel consumption and emissions

A schedule returned by solving a BCAP is closely related to a shipping schedule. Arrival times of vessels determined by a shipping schedule influence markedly the berthing plan; inversely, the berthing plan may delay the departure of a vessel, which significantly influences the shipping schedule. Additionally, the quay-crane allocation schedule determines operational time for vessels, directly affecting at-port duration and departure time. These further affect the amount of emissions from vessels and the shipping schedule. Therefore, a close relationship between the BCAP and shipping schedule requires that ports and shipping companies work together. A port may ask a vessel to slow or accelerate to meet a specific loading/unloading time slot to minimize fuel consumption and emissions while sailing and/or moored. Notably, port operators should consider operational efficiency for the ships they serve, improve the utilization degree of port-related resources, and negotiate with shipping companies to optimize the arrival time for vessels.

The fuel consumption of vessels while sailing is affected mainly by distance to port and sailing speed. Further, sailing distance and sailing speed directly determine arrival time at port. Du et al. (2011) analyzed in detail the relationship between fuel consumption and sailing distance and speed. A berthing plan begins at time zero, and arrival time of vessel i is denoted by \( a_i \); for a vessel i, its shipping company controls arrival time \( a_i \) in an interval \([a, b]\) by adjusting sailing speed, where \( a \) and \( b \) are determined by its maximum sailing speed and minimum sailing speed individually; the distance from vessel i to a port is denoted by \( m_i \) when the berthing plan begins, where \( i \in [1, 2 \ldots N] \) denotes a vessel set. Fuel consumption of vessel i then can be derived by Eq. (1), where \( \lambda^0, \lambda^1 > 0 \) are regression coefficients, and \( u_i \in [3.5, 4.5] \). For feeders, \( u_i = 3.5 \); for medium-sized vessels, \( u_i = 4 \); and for jumbo vessels, \( u_i = 4.5 \). There is an optimal sailing speed \( s^* \) when the fuel consumption is minimized, which can be achieved by minimizing fuel consumption \( F_i \) in Eq. (1). A vessel can decelerate to save fuel consumption current speed exceeds \( s^* \), or it can accelerate to save fuel if current speed is slower than \( s^* \). The optimal sailing speed \( s_i \) of vessel i can be derived by Eq. (2).

\[
F_i = \left( \frac{\lambda^0}{\lambda^1} \cdot \frac{m_i}{u_i} \right)^{1/u_i} \cdot a_i + \lambda^1 \cdot m_i \cdot a_i^{1-u_i} \quad (1)
\]

\[
S_i = \left( \frac{\lambda^0}{\lambda^1(u_i - 1)} \right)^{1/u_i} \quad (2)
\]