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# Berth allocation and quay crane assignment in a container terminal for the trade-off between time-saving and energy-saving

Junliang He *

*Engineering Research Center of Container Supply Chain Technology, Ministry of Education, Shanghai Maritime University, Shanghai 201306, PR China*

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A B S T R A C T

This paper addresses the problem of integrated berth allocation and quay crane (QC) assignment for the trade-off between time-saving and energy-saving. This problem is formulated as a mixed integer programming model (MIP), in order to minimize the total departure delay of all vessels and the total handling energy consumption of all vessels by QCs. Furthermore, an integrated simulation and optimization method is developed, where the simulation is designed for evaluation and optimization algorithm is designed for searching solution space. Finally, numerical experiments are conducted to verify the effectiveness of the proposed method.



## 1. Introduction

The competition among container terminals has been getting fiercer and fiercer. Almost all container terminals are bearing the pressure of attracting more customers. Moreover, with the increase of sizes of container vessels, container terminals are encountering another challenge, i.e., the rapid handling of containers for mega-vessels. Thus, container terminals must shorten the vessel turnaround time, which is an impact factor of the improvement of their service level. However, due to high cost of the handling equipment and scarcity of land resources, container terminals can hardly purchase additional handling equipment or expand their territory to promote the efficiency and service level. Therefore, the reasonable space resource allocation and scheduling of handling equipment are critical to enhancing the service level of container terminals.

Green port recently has been becoming the mainstream in the sustainable development of global economy. Therefore, energy-saving is another goal of container terminals. We should save energy of container terminals as much as possible, but it cannot be implemented at the expense of the cost of the service level. All container terminals must seek appropriate approaches to save energy without reducing the throughput or hampering the service level. In this respect, the main energy consumption of container terminals is significantly impacted by berth allocation, yard allocation, and the scheduling of handling equipment. We can save energy by using clean energy or energy-saving devices. However, due to high cost of the energy-saving devices, this paper focuses on how to realize energy-saving at the operational level without additional equipment investment.

As the most important space resource and handling equipment, berth and quay crane (QC) play an important role in maintaining the service level and controlling energy consumption of container terminals. In particular, the integrated berth allocation and QC assignment problem (B&QCAP) secure a crucial position in the operation of container terminal. An effective berth allocation and QC assignment can significantly shorten the total vessels' turnaround time and save total energy consumption of all vessels. However, most studies on port operations solely aim to improve the efficiency of container terminals, and do not consider energy-saving. Therefore, it's imperative to develop an effective approach for the B&QCAP by considering the trade-off between efficiency and energy consumption.

This paper is organized as follows. Relevant literature is reviewed in Section 2. In Section 3, the B&QCAP is described. In Section 4, the relationships among energy consumption, QC hours demand, berth allocation and QC assignment are firstly analyzed, and then, a mixed integer programming model (MIP) is formulated for the B&QCAP. An integrated simulation and optimization method is proposed for solving the MIP in Section 5. Numerical experiments are conducted in Section 6 to evaluate the effectiveness of the proposed solution methods. Conclusions and future research are given in the last section.

* Address: 1550 Haigang Avenue, Lingang New Port City, Logistics Engineering School, Shanghai Maritime University, Shanghai 201306, PR China.

*E-mail address:* soldierlianglian@163.com

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## 2. Literature review

Up to present, intensive research were attempted in the area of port operations, such as the berth allocation, storage space allocation, QC assignment and internal truck scheduling. Also the literature of case reports were almost exploding [1,2]. For a comprehensive overview on B&QCAP, see the review work given by [3,4]. However, most of related works have only referred to the handling efficiency of container terminals. Only a few studies addressed the energy-saving of container terminals at the operational level, not to speak of the modeling the trade-off between handling efficiency and energy consumption. In this section, only literature review of studies directly related to B&QCAP and energy-saving of container terminals at operational level is conducted.

For B&QCAP, there are many related works. In order to consider handling priorities and preferred berth for vessels, the B&QCAP was extended and priorities were addressed by adding penalty costs for violating a vessel's planning departure time ([5–7]. Considering interference among QCs, marginal productivity of QCs was modeled and was included in the B&QCAP model by Meisel and Bierwirth [8]. Cost structure of the B&QCAP was also proposed by them. To solve the problem a construction heuristic, local refinement procedures, and two meta-heuristics were developed by them. Furthermore, the model of Meisel and Bierwirth [8] has been extended considering periodic balancing utilization of QCs by Hu [9], and the rolling-horizon heuristics; neighborhood search heuristics and parallel computing were proposed for obtaining the optimize solution by him. Zhang et al. [10] addressed B&QCAP considering the coverage ranges of quay cranes and allows for limited adjustments of quay cranes during loading and discharging, and proposed a sub-gradient optimization technique to solve this problem. Yang et al. [11] developed an evolutionary algorithm with nested loops for B&QCAP, where two inner loops are proposed for resolving berth allocation and quay crane assignment respectively, and an outer loop is used to search approximate solution. Regarding the number of cranes assigned to a vessel during the time the vessel is at the berth, there are two main policies: time-invariant and time-variant QC assignment. For time-variant QC assignment policy, the assumption that the number of cranes may change dynamically between the minimum and maximum number of QCs were proposed in many related works [7,12,13]. Almost all of them suggested that time-variant QC assignment can promote the total handling efficiency. Time-invariant QC assignment policy also was considered in some related works [14,15]. Most of them argued that time-invariant QC assignment policy is too restrictive. However, this policy can either reduce large setup losses due to reallocation of quay cranes, or reduce computational complexity. The comparison between the two policies was addressed by Iris et al. [16]. Their conclusion is that time-invariant QC assignment policy may result in an additional cost. Similarly, Rodriguez-Molins et al. [17] presented the time-invariant QC assignment policy and the time-variant QC assignment policy for modeling QCAP in the B&QCAP, and proposed a GRASP-based meta-heuristic for solving this problem. Since vessel's arrival and handling time is uncertain, some studies addressed the B&QCAP under uncertainties and considered the robustness of model and algorithm [18–20].

In energy-saving of container terminals at operational level, only a few literatures can be found. Most of works are related to the energy-saving of vessels in sailing period. In order to minimize the fuel consumption of vessels, Golias et al. [21] and Lang and Veenstra [22] proposed that it can be realized by the way of potential coordination opportunity between terminal operators and shipping line. Therefore, the arrival time of vessels was regarded as decision variables instead of previously-known parameters when formulating the berth allocation problem in their works. Golias et al. [21] tried to reduce fuel consumption and vessel emissions by minimizing the total waiting time of vessels, based on the assumption that the shorter the waiting time is, the less the fuel consumption and vessel emissions. Lang and Veenstra [22] provided a direct quantitative analysis on fuel consumption of a vessel and minimized the fuel consumption for sailing with a customized simulation tool. The optimization approaches of vessel sailing speed for minimizing the fuel consumption were proposed by Du et al. [23] and Wang et al. [24]. Furthermore, Du et al. [23] conducted the vessel emission (in sailing periods) calculation with the widely-used emission factors. Using policies and sailing speed optimization of vessels to improve harbor congestion and marine fuel consumption were addressed by Alvarez et al. [25]. Aiming at the energy-saving of terminals, Chang et al. [26] developed a MIP model for B&QCAP considering total energy consumption of all vessels. To reduce emissions from idling truck engines at container terminals, Chen et al. [27] developed a bi-objective model to minimizing both truck waiting times and truck arrival pattern change. He et al. [28] addressed the problem of sharing internal trucks among multiple container terminals considering transportation energy consumption. In order to reduce energy consumption of yard crane, He et al. [29] revealed negatively correlated relationship between the energy-saving and high efficiency of yard crane scheduling problem, and provided an appropriate approach for balancing the two objectives. Similarly, the integrated handling equipment scheduling model for minimizing energy consumption was formulated by He et al. [30].

Overall, B&QCAP is a well researched domain. However, to the best of our knowledge, the efficient model and method at the operational level for the trade-off between improving efficiency and energy-saving in B&QCAP are lacking. Our study thus focuses on the new and practical research topic.

## 3. Problem description

B&QCAP includes three interrelated aspects of berthing position, berthing time and the number of cranes to be allocated to each vessel during a given planning horizon. Fig. 1 illustrates B&QCAP problem in the two-dimensional space. The horizontal axis represents the berthing position along the quayside, while the vertical one represents the berthing time. Each rectangle represents a vessel to be served. The height of a rectangle denotes the handling time of the corresponding vessel, while the length of a rectangle represents the vessel length. The horizontal and vertical coordinates of the lower left corner of a rectangle represent the berthing position and the berthing time of the corresponding vessel, respectively.

The berth allocation problem and the QC assignment problem are strongly related. The turnaround time of a vessel at berth depends on the number of QCs allocated to a vessel, and the QC assignment for the vessel depends on its berthing position. Therefore, the two problems should be integrated. In general, the primary objective of B&QCAP is the minimization of the total departure delay of all vessels in a planning horizon. With the embracing of green port concept, almost all container terminals seek energy-saving and emission reduction. Therefore, the minimization of total handling energy consumption of QCs for all vessels in a planning horizon is another objective of B&QCAP.

For berth allocation, all vessels should be arranged for available berths without any collisions. Both berthing position and berthing time are two important decision factors. If they are reasonably planned, more vessels can be arranged for available berths in the same time period, and the total departure delay can also be