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Heuristics for solving continuous berth allocation problem considering periodic balancing utilization of cranes ☆

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ABSTRACT

This study investigates a berth allocation problem considering the periodic balancing utilization of quay cranes in container terminals. The proposed model considers that the quay cranes allocated to a work shift should be fully used and other real-world considerations, such as the continuous quay line, the penalties for early arrivals and departure delays. To solve the model, several heuristics are developed: the model for large problems is decomposed into sub-models that are solved by rolling-horizon heuristics; neighborhood search heuristics are used for optimizing a berthing order of vessels; parallel computing is used to improve the algorithmic performance. The method performs well when applied to real-world large-scale instances with promising computation time that is linearly related to the number of vessels.

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1. Introduction

The operating costs of container terminals are becoming increasingly important as global competition among container terminals increases and the shipping market goes into recession. While providing high-quality services to vessel owners, port operators seek to keep the operating costs as low as possible. Additionally, in many seaports, port operators must face problems of increased labor costs and shortages of specialized workers. Cost reduction requires careful consideration of seaside resources – especially berths and quay cranes (QCs), which determine the utilization of other resources, such as yard cranes, container trucks, labor resources and energy. Berths and QCs are important resources in the berth allocation problem (BAP) and the QC assignment problem (QCAP). Generally, for these operational planning problems, the total number of quay cranes has been decided, so the major purpose is how to efficiently assign each vessel to a berth with appropriate number of QCs such that shipper's expected arrival and departure times can be met as close as possible. However, a typical problem arising in many large container terminals, involves the imbalance utilization of QCs during a work shift. For example, four QCs are allocated to work during a four-hour shift, whereas only in the first hour four QCs are in use and during other hours in the same shift three QCs are idle. Therefore, the four QCs are not fully utilized. In practice, this imbalance utilization of QCs will lead to the imbalance utilization of yard cranes, trucks, various drivers and other operational resources.

Bierwirth and Meisel (2010) reviewed integrated methods for solving the BAP and QCAP. The BAP is one of the most important planning problems in container terminal operations (Steenken, Voss, & Stahlbock, 2004; Stahlbock & Voss, 2008). The BAP involves assigning a berthing position and a berthing time to every vessel that is expected to be served within a specified planning horizon (Meisel & Bierwirth, 2009), taking into account the priorities, lengths, and handling times of the vessels. In many studies (Guan & Cheung, 2004; Kim & Moon, 2003; Wang & Lim, 2007), the QCAP is not considered as a part of the BAP and the handling times are typically assumed to be fixed and known in advance, although in practice the handling time of a vessel is inversely proportional to the number of QCs that are assigned to it (Park & Kim, 2003). Fig. 1 presents a solution to a BAP. A quay is divided into 10 m segments and the time is divided into hours. The width of rectangle in Fig. 1 represents the length of a vessel (including clearance) and the height represents the handling time. The lower-left vertex of each rectangle represents the corresponding vessel's berthing position and berthing time. Fig. 1 presents the following four parameters for vessel #1: berthing time, berthing position, handling time, and number of QCs assigned to each time segment in the handling

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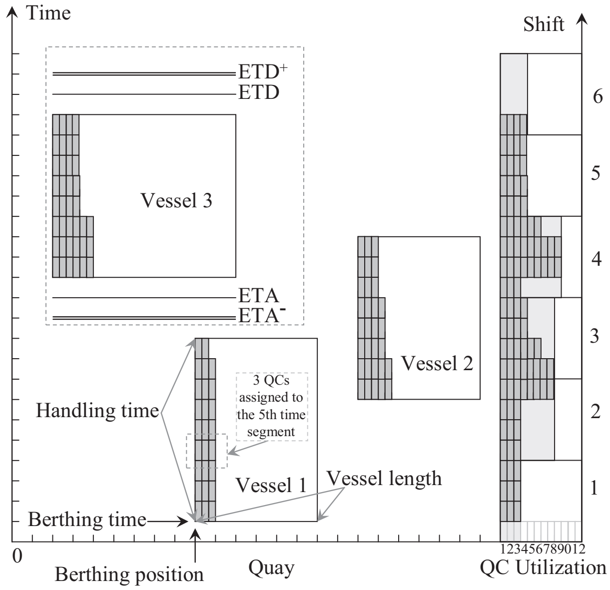

Fig. 1. An example of a berth plan and the related parameters.

time window. Fig. 1 also presents the following parameters for vessel #3: the expected time of arrival (ETA), the earliest time of arrival with any possible choice of speeding the vessel up (ETA^-), expected time of departure (ETD), and latest time of departure without penalty (ETD^+). In a feasible berth plan, the rectangles do not overlap with each other; the vessel handling workload represented by the area of the rectangle is met by the plan; and the rectangle is within a planning horizon of the vessel. In each time segment, the number of used QCs should not exceed the number of available QCs. Fig. 1 presents the QC utilization results for the three vessels. The container terminal has twelve QCs. The berth plan covers 24 h, which are divided into six work shifts, as presented in the right bar in Fig. 1. The utilization of QCs is restricted by setting the number of available QCs as the upper boundary on the number of QCs assigned to vessels in any time. In Fig. 1, nine QCs are used in only two time segments, and nine QC hours are idle in shift #4 when nine QCs are configured for shift #4.

The features of the periodic balancing utilization of QCs (QCPBU) are elucidated in the following based on Fig. 1. Considering the work schedule in units of work shift in container terminals, Fig. 1 presents the assignment of QCs to each time segment and to each work shift. Three, eight, eight, nine, four and four QCs are assigned to the shifts (1–6), respectively. However, conflicts arise from the two assignment solutions in unit of time segment (hour) and work shift (e.g., four hours). The numbers of valid QC hours (Park & Kim, 2003) ("a valid QC hour" means that a QC operates a vessel at that hour) are 9, 17, 22, 27, 16, and 4 in shifts 1–6, respectively. Based on the numbers of available QC hours in these six shifts (12, 32, 32, 36, 16 and 16), the numbers of hours in which QCs are not used are 3, 15, 10, 9, 0 and 12, and the QC utilization ratios are 0.75, 0.5313, 0.6875, 0.75, 1.0, and 0.25. The minimum, mean and maximum QC utilization ratios are 0.25, 0.6615 and 1.0, respectively. A higher QC utilization ratio in a work shift indicates a higher degree of QCPBU in a BAP. Here, "periodic" means work shift and the corresponding period can be extended to a time period of any length, and "balancing utilization" refers to minimizing the number of idle QC hours.

This study extends the formulations and algorithms of Meisel and Bierwirth (2009) to incorporate the QCPBU in a berth allocation and crane assignment problem (BACAP). Park and Kim (2003) have pioneered work on BACAP, while Meisel and Bierwirth (2009) formulated the BACAP more efficiently. Further, heuristics are developed to solve the BACAP with consideration of QCPBU.

This study concerns the effect of QCPBU on the BACAP using proposed heuristics. It is organized as follows. The following section reviews the relevant literature. In Section 3 the problem is formulated as mixed-integer linear programming (MILP) models. In Section 4, the heuristics for solving the models are described. In Section 5, the proposed formulations and heuristics are computationally studied. Finally, contributions and conclusions are drawn in Section 6.

2. Related studies

The BACAP is a kind of BAP in which a calling vessel can be moored at an arbitrary position if sufficient space is available. The BAPs are grouped into discrete and continuous problems, and into static and dynamic problems (Imai, Nishimura, & Papadimitriou, 2001; Imai, Sun, Nishimura, & Papadimitriou, 2005). The BACAP examined in this study is a continuous and dynamic one. In the discrete BAP, the quay is partitioned into sections, called berths, one of which can serve one vessel at any time. The arrival times of vessels are ignored in the static BAP while in the dynamic BAP a constraint is considered on the earliest possible berthing time that cannot be earlier than an arrival time for each vessel. In most researches on BACAP, fixed handling times are assumed by ignoring the effect of QCs on the handling times, and the main objective is to minimize the cost measured by hours of using QCs.

Park and Kim (2003) considered the integration of the continuous BAP and the QCAP in a BACAP. In their BACAP, the arrival times of vessels imposed no hard constraints on the berthing times. Imai et al. (2005) proposed a MILP model and a heuristic solution method based on a Lagrangean relaxation to determine the berthing positions, the berthing times, and the QC assignments. Time-variable QC assignments are common in practice but had not received attention until Park and Kim (2003). Park and Kim (2003) assumed that the QC productivity is proportional to the number of QCs that can simultaneously serve a vessel. Later, Meisel and Bierwirth (2009) also examined the BACAP, emphasizing the importance of QC productivity in berth planning, in which the marginal productivity of QCs that are assigned to a vessel decreases and the handling time increases as the vessels are berthed farther from their desired position on the quay. Park and Kim (2003) and Meisel and Bierwirth (2009) provided results for berth plans for up to 40 vessels. Zhang, Zheng, Zhang, Shi, and Armstrong (2010) extended the model that was developed by Park and Kim (2003) by considering the coverage ranges of QCs.

Lim (1998) and Meisel and Bierwirth (2009) considered the metrics that are related to resource utilization. However, they did not consider the effects of QCPBU on BAPs. Based on the classification developed by Meisel and Bierwirth (2009), the problem that is considered in this study is classified as: *cont* | *dyn* | *pos, QCPBU, QCAP* | $\sum(w_1 speed + w_2 tard + w_3 res)$, where QCPBU indicates the objective of maximizing the periodic balancing utilization degree of QCs.

Meisel and Bierwirth (2013) provided a framework for integrating the three decisions (concerning berth allocation, QC assignment, and QC scheduling). The framework has three phases: Phase I estimates the productivity rates of QCs from vessels' stowage plans; these productivity rates are used in Phase II to make berthing decisions and to assign QC capacities to vessels, and Phase III determines detailed QC schedules and makes the decisions. Heuristics are used to solve the sub-problems within the framework. The integrated planning is computationally tractable

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