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The quay crane scheduling problem with nonzero crane repositioning time and vessel stability constraints

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A B S T R A C T

The continuous growth in worldwide container terminals' traffic resulted in an increasing interest for the Quay Crane Scheduling Problem (QCSP) in research and practice. This problem consists of scheduling the discharge and load operations of the containers of a vessel by a set of quay cranes; the objective is to minimize the completion time in an attempt to increase container terminal throughput. In the literature, most of the proposed studies focus on improving model formulation and solution methods with a trend, in most recent papers, to incorporate more realistic features of the problem. Despite the importance given by practitioners to vessel stability in scheduling discharge and load operations, there is little research that considers this constraint. This paper presents a novel MIP formulation of the QCSP that takes into account vessel stability constraints. Furthermore, the proposed model is very flexible in handling various settings of the QCSP, such as those related to crane traveling time, task preemption and unidirectional quay crane operating mode. In order to tackle problem complexity, a Genetic Algorithm (GA) is proposed. Computational results validate the MIP formulation on small-sized problems and highlight the performance of the proposed GA.

1. Introduction

Globalization entails a steep increase in the containerized freight flow over the last decades (UNCTAD, 2011) and this increase is expected to continue in the future. As a result, container terminals are continuously challenged to accommodate the growth of container volume by maximizing their operational efficiency, and investing in new handling technology and extended terminal infrastructure. This effort is additionally motivated by the need of container terminals to face the fierce competition with other terminals. The availability and the speed of service operations are henceforth the keys to attracting and retaining vessel operators. Providing container terminals with models and methods that lead to shortened vessel handling time and increase terminals' throughput capacity is undeniably essential to help seaports respond to the incrementing container streams through the universal supply chain system and achieve a competitive advantage. Therefore, the last two decades witnessed an increasing number of research papers that aim to advance seaport operations with the use of quantitative methods. Recent classification of the existing models can be found in Bierwirth and Meisel (2010) that has been extended in Carlo, Vis, and Roodbergen (2013) and Bierwirth and Meisel (2015).

Container terminals can be divided into four main areas: the berth, the quay, the yard and the gate. The berth and the quay areas are considered seaside, while the yard and the gate are considered landside (Carlo et al., 2013). Once a vessel is berthed, three main operations are processed: loading/unloading containers between vessels and landside trucks, transporting containers between berths and the storage yard, and loading/unloading containers between landside trucks and storage yard. The vessel is divided into several bays and each container is unloaded from or loaded onto a given bay according to the stowage plan; at any time, at most one QC can perform operations on a bay. The cost of constructing berths and handling equipment such as the quay cranes (QCs), used for loading and unloading containers from and onto vessels, is extremely high. Therefore, major emphasis in the literature has been placed on optimizing the utilization of these two critical resources: the berths and the QCs. Three seaside operation problems are distinguished in the literature Bierwirth and Meisel (2010): (1) the Berth Allocation Problem (BAP), (2) the Quay Crane Assignment Problem (QCAP), and (3) the Quay Crane Scheduling Problem (QCSP). This paper tackles the QCSP. The latter aims at finding the schedule for the QCs serving a vessel that minimizes the total handling time. The QCSP includes both the assignment of container handling operations to specific QCs and the time schedule for these operations.

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The existing literature provides different ways of modeling the QCSP, as summarized by the classification scheme presented by Bierwirth and Meisel (2010). The authors classify the models according to four attributes: task, crane, interference, and performance measure. The task attribute specifies task definition and related constraints. Tasks of QCs are defined on the basis of container groups belonging to the same bay, set of bays, or bay areas (Meisel & Bierwirth, 2011). The crane attribute describes the assumptions made regarding QCs, such as their initial position and movement speed. The interference attribute is used to describe the spatial constraints of QCs' movements, namely non-crossing and safety margin constraints. QCs move along the quay on a single rail track and are not allowed to cross one another. Moreover, a safety distance should be kept between adjacent QCs. The fourth attribute specifies the objective function of the QCSP. Carlo et al. (2013) extend this QCSP classification scheme to include further details on the QCSP, such as the safety margin for indented berths and performance measures related to the utilization of landside equipment.

In the vast majority of QCSP models, tasks are defined on the basis of bays or container groups. Non-crossing constraints are commonly considered, while safety margin constraints and QC traveling time have been less involved. Task preemption is generally not allowed. Since QCSP with non-crossing constraints is an NP-hard problem (Guan, Yang, & Zhou, 2013), most of the proposed methods are still not fit to solve large-sized problem instances. Moreover, some realistic features of the QCSP have been seldom incorporated in the proposed models. For example, despite the importance given by practitioners to vessel stability in crane scheduling, there is little research that considers this constraint.

In the current paper, we present a novel MIP formulation of the QCSP that takes into account vessel stability constraints. Furthermore, the proposed model captures various practical constraints of the QCSP, such as non-crossing, safety margin and crane traveling time constraints. In order to tackle problem complexity, a Genetic Algorithm (GA) is designed to solve medium- and large-sized problems.

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on the QCSP with a focus on works which define tasks on the basis of bays and container groups. Section 3 describes the addressed QCSP problem and the proposed mathematical model. Section 4 introduces the developed GA and the lower bound algorithm proposed to assess the performance of the GA. Section 5 reports computational experiments and results. Finally, Section 6 concludes this work with important findings as well as directions and recommendations for future research on this topic.

2. Literature review

The crane scheduling problem while considering bays as tasks was initially studied by Daganzo (1989). The QCs are assigned to bays for certain time slots in order to minimize the total weighted completion times of vessels. As preemption is allowed, more than one QC can perform operations on a bay. Peterkofsky and Daganzo (1990) further investigate the problem and propose a branch-and-bound (B&B) solution approach. These two early studies do not however consider non-crossing and safety margin constraints. Lim, Rodrigues, Xiao, and Zhu (2004) and Kim and Park (2004) are the first papers that address spatial constraints. Lim et al. (2004) consider non-crossing constraints, safety distance between QCs and non-simultaneous constraints among bays. The objective is to find the QC-to-bay assignment that maximizes the throughput under these constraints. Dynamic programming algorithms, a probabilistic tabu search, and a squeaky wheel optimization heuristic are proposed to solve the problem. This work has been extended by incorporating task processing time in order to find the QC schedule that minimizes the makespan (Zhu & Lim, 2006; Lim, Rodrigues, & Xu, 2007). In Zhu and Lim (2006), the authors prove that by considering only non-crossing constraints, the problem becomes NP-complete. The problem is solved by a B&B algorithm and a simulated annealing heuristic. Lee, Wang, and Miao (2008) study the same problem, confirm its NP-completeness and solve it using a Genetic Algorithm (GA). In Lim et al. (2007), the authors prove that for the QCSP with complete bays, there is an optimal schedule among the unidirectional ones; those where all QCs adopt, after their initial repositioning, the same movement direction. This seminal result entails a reduction of the search space to unidirectional schedules when seeking to optimally solve the QCSP with complete bays. Moreover, under the premise of unidirectional QC scheduling, crossing of QCs cannot happen, while the QCSP reduces to a QC-to-bay assignment problem. All the aforementioned studies do not consider QC traveling time constraints. In Guan et al. (2013), the authors tackle the problem while taking into account non-crossing and QC traveling time constraints and assume that the partition of work units on bays ensures the required safety distance between QCs. A time–space network flow formulation is adopted and used to solve small-sized instances by standard solvers. For medium-sized instances, the authors develop a Lagrangian relaxation approach to obtain a tight lower bound and near-optimal solutions. Furthermore, to face the soaring complexity of large-sized problems, the authors develop two heuristics. In order to assess the quality of the proposed heuristics, a lower bound is determined based on the optimal solution of the preemptive QC schedule solved using a dynamic programming algorithm. Liu, Wan, and Wang (2006) study the QCSP for multiple vessels with different ready times. The objective is to minimize the maximum relative tardiness of vessel departures. The problem is broken down into two levels: the vessel-level and the berth-level. The vessel-level problem is a QCSP and is formulated as a MIP model that anchors the structure of unidirectional schedules. The latter takes into account initial crane positions, non-crossing, safety margin and QC traveling time constraints. The reduction of the search space to unidirectional schedules allows for solving non-trivial instances by a standard solver. Furthermore, the paper compares the preemptive and the non-preemptive QC scheduling approaches and highlights the improvements obtained by adopting the preemptive one.

Kim and Park (2004) are the first who address the QCSP for container groups. They propose a model that considers precedence constraints among tasks, QC traveling time, non-crossing constraints and enforces safety distance by setting a non-simultaneity constraint between tasks located in adjacent bays. The objective is to minimize the weighted sum of the makespan and QCs completion times. A B&B algorithm and a Greedy Randomized Adaptive Search Procedure (GRASP) are proposed. This model has been later refined by Moccia, Cordeau, Gaudioso, and Laporte (2006) in order to account for safety margin constraints in a more stringent way. A branch-and-cut (B&C) algorithm is developed to solve medium- and large-sized instances. The algorithm succeeds in improving solutions for the benchmarks of Kim and Park (2004). To solve the same problem, Sammara, Cordeau, Laporte, and Moccia (2007) propose a tabu search (TS) algorithm where neighborhoods are defined on the basis of a disjunctive graph. The computing time is significantly reduced at the expense of a slightly weaker solution quality with comparison to the B&C algorithm. Bierwirth and Meisel (2009) disclose the weakness of the model proposed in Moccia et al. (2006) and propose a model that incorporates a temporal distance between tasks in order to enforce non-crossing and safety margin constraints. Although there is not necessarily a unidirectional schedule among the