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An Integrated Quay Crane Assignment and Scheduling Problem

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ABSTRACT

As maritime container transport is developing rapidly, the need arises for efficient operations at container terminals. One of the most important determinants of container handling efficiency is the productivity of quay cranes, which are responsible for unloading and loading operations for container vessels. For this reason, the Quay Crane Assignment Problem (QCAP) and the Quay Crane Scheduling Problem (QCSP) have received increasing attention in the literature and the present paper deals with the integration of these interrelated problems. A formulation is developed for the Quay Crane Assignment and Scheduling Problem (QCASP), which accounts for crane positioning conditions and a Genetic Algorithm (GA) is developed to solve the QCASP. Both the model formulation and the solution methodology are presented in detail and computational analysis is conducted in order to evaluate the performance of the proposed GA. The results obtained from the GA are compared with the results from an exact technique, thus providing complete information about the performance of the heuristic in terms of solution quality.

1. Introduction

An increase in the number of transshipped container goods has been marked over the recent decades, due to globalization. Container terminals are called to meet the challenge of accommodating very large vessels, which are capable of carrying 10,000–12,000 twenty-foot equivalent container units (TEUs). A systematic approach to container terminal optimization therefore becomes necessary in order to overcome this challenge.

As far as container terminal operations are concerned, they can be divided into quayside and yard side operations, as illustrated in Fig. 1. On the one hand, quayside operations involve allocating berths to arriving ships, known as the Berth Allocation Problem (BAP), the assignment of cranes to ships, known as the Quay Crane Assignment Problem (QCAP) as well as the sequencing of quay crane operations, known as the Quay Crane Scheduling Problem (QCSP). On the other hand, yard side operations include the allocation of containers to certain storage locations, the scheduling of container transporting vehicles and the scheduling of yard cranes for optimal container storage sequence.

Because Quay Cranes (QCs) are the most expensive equipment utilized at container terminals, their performance largely affects the container throughput and handling efficiency (Meisel, 2011). QCs move on a single rail track alongside the quay of the port, as depicted in Fig. 1. As soon as a ship is positioned at the berth, QCs are responsible for the unloading and loading of containers from and to the vessel. The planning of QC operations is part of the quayside operations of a container terminal and consists of the QCAP and QCSP. These problems are frequently integrated, as they are interrelated.

The QCAP is basically an assignment problem which considers additional parameters, such as service agreements contracted with vessel operators, dictating a minimum or maximum number of cranes that can be assigned to a vessel, the available QCs at the port, the number of vessels berthed within a given planning horizon, the container workload on each vessel, and whether or not cranes are allowed to perform handling operations on more than one ship within a planning horizon.

The QCSP is a scheduling problem, more complicated than the QCAP, as it decides upon the sequencing of the QCs' handling tasks and the points in time at which these are performed. An important aspect of the QCSP is the fact that positioning conditions must be enforced at all times. More specifically, since cranes travel on a single rail, they are not allowed to cross one another. These are known as the non-crossing constraints. Furthermore, assuming that cranes are indexed based on their position, middle-indexed cranes cannot serve end bays, because again this would violate the non-crossing conditions. In several models clearance conditions are also accounted for, in order to prevent adjacent cranes from being positioned too close to one another. Yard congestion constraints are also considered in certain cases, where it is important to ensure that there will not be traffic at the yard storage areas at any point in time.

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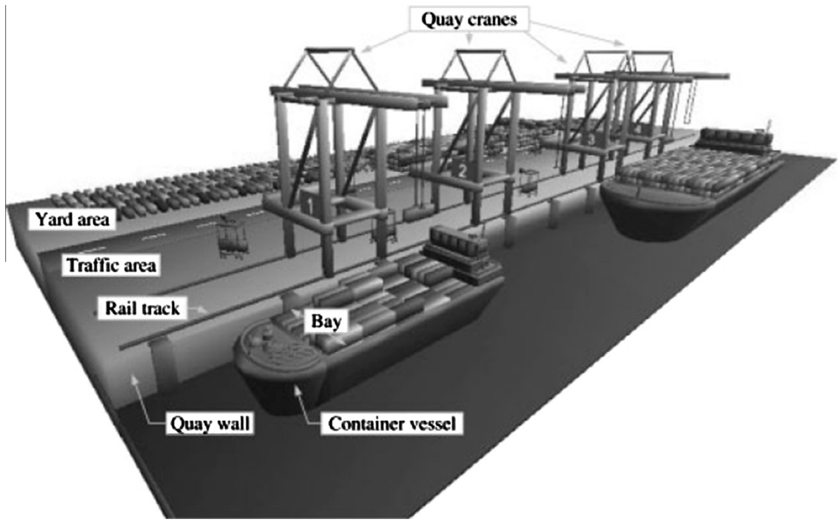

Fig. 1. Schematic representation of container terminal layout. *Source:* 'The Quay Crane Scheduling Problem with Time Windows', Frank Meisel.

In the current paper, we propose an integrated model for the QCAP and the QCSP, namely the Quay Crane Assignment and Scheduling Problem (QCASP). The purpose of the model is to assign cranes to ships that are berthed within a given planning horizon. Furthermore, the model specifically decides which crane is allocated to which bays and it aims to minimize the time required for the completion of the handling of the latest ship, i.e. the ship carrying the largest number of containers, which is expected to take the most time at the berth. This article presents the implementation of a Genetic Algorithm (GA) for solving the QCASP and reports the results of the computational studies performed for certain problem instances.

The main contribution of this paper is in the integration of the QCAP and QCSP, two interrelated problems that have mostly been dealt with independently in the literature. Furthermore, the developed model holds the advantage of simplicity, while at the same time it considers realistic circumstances, as it accounts for all positioning constraints in order to generate practical solutions. The disadvantage of the large number of variables is overcome through the use of a GA specifically developed for this problem. Although heuristics have been largely implemented in the literature, the present paper thoroughly evaluates the performance of the GA, since it compares the solution with a solution generated through an exact approach.

The present paper is structured as follows: Section 2 provides a literature review on the QCSP, focusing on the models built and the solution approaches developed for these problems. Section 3 contains the detailed problem description and its mathematical formulation, while Section 4 introduces the GA that was developed to solve this specific problem. Section 5 reports the results of the computational analysis and evaluates the performance of the proposed heuristic, while Section 6 concludes the article with the important findings of this work, as well as directions and recommendations for future research on this topic.

2. Literature review

Several models are proposed in the literature for the QCSP and a very useful classification of these models can be found in the work of Bierwirth and Meisel (2010). As far as the problem formulation is concerned, the prevalent objective is the minimization of the makespan required to complete tasks. In the work of Kim and Park (2004) the authors minimize the weighted sum of the makespan and the total completion time, but the drawback of their formulation in terms of constraints is that they do not consider crane clearance conditions, i.e. constraints that ensure that cranes will be positioned at least certain bays apart, and they only consider the single-ship case. Clearance conditions were added to the model of Kim and Park (2004) by Moccia, Cordeau, Gaudioso, and Laporte (2005), rendering the formulation more robust. Both formulations have since been used in numerous works.

Legato, Mazza, and Trunfio (2008) minimize the maximum makespan required to complete the number of existing tasks. Their Mixed Integer Programming (MIP) formulation allocates quay cranes to tasks and time slots, without considering ships or bays. Jung, Park, Lee, and Kim, and Ryu (2006) employ time windows in which cranes can be assigned to perform a task; the single ship case is only considered and the authors assume ship-clusters which containers cannot be loaded into or unloaded from simultaneously. Lee, Qiu Wang, and Miao (2008) develop a MIP formulation for the QCSP with handling priority for each ship bay. The objective function is therefore a minimization function of the sum of the weighted completion times of every ship bay.

Liu, Wan, and Wang (2006) formulate an MIP whose objective is to minimize the maximum relative tardiness of vessel departures. In terms of model assumptions, the authors consider the aggregated workload of each bay, which is the product of the number of containers to be handled in the bay and the average processing time per container. As is commonly the case, each vessel is partitioned into bays, and so is the berth. Clearance constraints between adjacent cranes are considered, while productivity is assumed identical for all quay cranes and interference amongst them is ignored.

The early work of Daganzo (1989), who first introduced the crane scheduling problem, develops an exact MIP for the loading of ships, assigning cranes to bays for certain time slots, such that the overall workload is well balanced for cranes. The objective is to minimize the aggregate cost of delay incurred on the vessels, unlike what became prevalent thereafter. Another note on the author's formulation is that several important factors are not considered, such as crane interference and crossing. The work of Zhang and Kim (2009) also introduces a different objective than that seen prevalent in the literature: the aim of their MIP formulation is to minimize the total number of cycles of QC activities on one ship, rather than to minimize the makespan. Tavakkoli-Moghaddam, Makui, Salahi, Bazzazi, and Taheri (2009) integrate the quay crane scheduling and allocation problem (QCSAP) in their work. They