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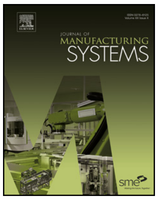

Technical Paper

The Quay Crane Scheduling Problem

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ABSTRACT

The recent growth in worldwide container terminals' traffic resulted in a crucial need for optimization models to manage the seaside operations and resources. Along with the recent increase in ship size and the container volume, the advancements in the field of Quay Crane Scheduling introduced the need for new modeling approaches. This is the motivation behind the current paper, which focuses on developing a novel yet simple formulation to address the Quay Crane Scheduling Problem (QCSP). The objective of the problem is to determine the sequence of discharge operations of a vessel that a set number of quay cranes will perform so that the completion time of the operations is minimized. The major contribution is attributed to the way that minimization is performed, which is by minimizing the differences between the container loads stacked over a number of bays and by maintaining a balanced load across the bays. Furthermore, important considerations are taken into account, such as the bidirectional movement of cranes and the ability to travel between bays even before completion of all container tasks. These realistic assumptions usually increase model complexity; however, in the current work this is offset by the novel simple objective. This paper presents a mixed-integer programming (MIP) formulation for the problem, which has been validated through multiple test runs with different parameters. Results demonstrate that the problem is solved extremely efficiently, especially for small problem sizes.

1. Introduction

The invention of standard-sized shipping containers in the late 18th century, also known as "containerization", has revolutionized the shipping industry. It has permitted a smoother handling of material goods and improved shipping operations that led to visualization of a smaller world, while it has also translated into novel magnitudes of income, allowing the world economy to experience unprecedented growth from this sector [13]. In order to sustain this growth, seaport terminals around the world are striving to keep up with the increase in the volume of containers' traffic: many of them are currently preparing to meet the challenge of handling ultra large container vessels capable of carrying 15,000 TEUs and beyond [18]. Baird [1] provided a brief insight into the continuous growth in ship sizes and overall traffic. However, this rapid increase in container traffic is not matched by an equal growth in seaport capacities, which poses a challenge for seaport terminals to overcome.

The increase in the number of container terminals (CT) worldwide comes hand in hand with the soaring competition factor. The customers are presented with a set of choices amongst competing service offers, where the terminal operators providing a higher caliber of services will deliver quality services that attract and retain customers by continuously meeting demand at all times. This made seaports strive to distinguish themselves from others by elevating the provided services to a platform that supports attracting a higher volume of ships, and a larger magnitude of shipments. Seaports are in a critical state where there exists a need to consider more efficient operations planning and management, thus a pending need arises for tailored solutions that address this challenge. Therefore, this area of research is receiving growing attention to help boost the performance of container terminals.

Seaports around the world are service providers that offer their facilities to ship and cargo owners. Their services can be divided mainly into seaside (quayside) services and landside (yard) services. These services include a set of loading/unloading operations as well as moving the cargo from the ship to the storage yard and vice versa. The seaside operations in particular involve the utilization of two critical resources, namely the quay space and the quay cranes (QC). Most of the literature addressing the seaside operations planning problems divides them into three independent problems which aim to optimize the utilization of these two resources: (1) the Berth Allocation Problem (BAP), (2) the Quay Crane Assignment Problem (QCAP), and (3) the Quay Crane Scheduling Problem (QCSP) Meisel [16]. The BAP has been more frequently addressed, such as in the work of Simrin and Diabat [21]

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and Simrin et al. [22], as well as that of Al Zaabi and Diabat [24]. The current paper tackles the problem of scheduling Quay Cranes, namely the Quay Crane Scheduling Problem (QCSP). Solving this problem to optimality can assist in shortening the time that vessels spend at the port, and in efficiently utilizing the available QCs, which are amongst the most expensive equipment in container terminals. The existing literature provides different ways of modeling the QCSP with ranging levels of detail; container groups, complete bays, and bay areas, as summarized by Bierwirth and Meisel [3]. The majority of these models have common assumptions such as non-preemption and unidirectional movement, which no longer reflects the practical scenario that accommodates the increasing ship size and QC capabilities in having it move at a higher speed. This serves as a motivation for the developed model in this paper.

The main contribution of the current paper lies in the novelty of the objective function, whose aim is to minimize the relative difference in remaining container workload between bays. To the best of our knowledge, this approach has not been adopted in past literature. However, the study performed in this paper concludes that the proposed objective leads to optimal crane schedules, in the sense that handling time is minimized and therefore lower costs are incurred for vessel operators, while the port resources are utilized efficiently. The important advantage of the current approach is the relaxation of the non-preemption assumption, which prevents the QC from moving between bays before finishing the assigned task completely. This accommodates a more realistic scenario that takes advantage of the flexibility, and hence produces a better solution. The QCSP is usually one of high complexity; hence, this paper proposes a simple yet accurate approach to generate the optimal solution through a simple formulation that is solved in a time efficient manner. The proposed formulation can be also extended to include the relaxed constraints (i.e. traveling time between bays) as will be described briefly in the formulation section.

In the following sections of this paper, a literature review on the QCSP is described in Section 2. Following that, Section 3 details the assumptions, the problem definition, and the novel formulation approach of the QCSP. In Section 4, a set of experiments was performed to evaluate the effectiveness of the proposed model. Finally, Section 5 concludes the study's findings and provides certain directions for future research.

2. Literature review

Providing container terminals with models and methods that lead to operational efficiency is undeniably essential to help seaports respond to the incrementing container streams through the universal supply chain system. Therefore, recent years witnessed an increasing number of research papers that aim to advance seaport operations. A useful classification of the existing models is presented by Bierwirth and Meisel [3]. In the current review, notable works will be described that cover the range of problem formulation types, mainly with respect to the objective function, and whose solution techniques generate satisfactory results for the QCSP.

The crane scheduling problem was initially addressed by Daganzo [6], who developed an MIP model for the loading of ships. His model assigned cranes to bays at specific time slots, in a way that ensured a balance for the total workload between cranes. The author proposes both exact and heuristic solution methods, while the objective of the model is the minimization of the total cost of delay incurred on the vessels, unlike what became prevalent thereafter, which is the minimization of the makespan required to complete tasks. Note that this primary work does not consider crane interference. The author solved small-sized instances of the model using a simple technique that he developed based on some optimality principles and some other common-sense observation. Later work of Peterkofsky and Daganzo [20] solved larger instances of the model using the branch-and-bound method. Zeng et al. [25] developed a mixed-integer programming model for quay crane dual-cycling scheduling. Their model considers the stowage plan of outbound containers and the operation sequence of quay cranes. They solved the model using a heuristic method, called bi-level genetic algorithm.

Lee et al. [12] proposed a formulation based on assigning bay areas to QCs, while assuming individual throughput rates for each crane. Their objective was the maximization of the total throughput and they propose several heuristics to solve it. In later work of Lim et. al [14] a formulation based on complete bays was proposed. They showed that there is always an optimal schedule among the unidirectional cranes when being assigned to complete bays. These formulations did not take detailed crane schedules into consideration nor did they use the minimization of the makespan as an objective. This can be found in the work of Kim and Park [11], in which the authors minimize the weighted sum of the makespan and the total completion time. In their work, however, clearance conditions are not enforced, i.e. constraints that guarantee a certain distance between adjacent QCs. This weakness was corrected by Moccia and Cordeau [19], who added these constraints, rendering the formulation more robust. Both formulations have since been referenced in numerous works. As far as solution methodologies are concerned, Kim and Park [11] suggested a branch-and-bound method to solve small-sized instances and a heuristic algorithm known as 'greedy randomized adaptive search procedure' (GRASP), in order to improve the performance of their branch-and-bound algorithm. Nonetheless, the authors did not discourse computational complexity that justifies the adoption of the heuristic algorithm developed. Succeeding Kim and Park's study, Liu et al. [15] considered the quay crane scheduling problem at container terminals where arriving vessels have different ready times, while Moccia et al. [19] solved instances which cannot be solved by Kim and Park's using a branch-and-cut algorithm.

One of the works that uses the MIP developed by Moccia and Cordeau [19] is that of Bierwirth and Meisel [2], in which the authors propose a heuristic solution procedure based on the branch-and-bound algorithm. The algorithm searches a subset of above average quality schedules and it exploits efficient criteria for branching and bounding, with respect to crane interference. The authors compared their approach to recent competing ones and they reported satisfactory results, especially for problem instances with a small number of cranes, with the significant advantage of reduced computational effort. According to the authors, the efficiency of the method can be attributed to the exclusive consideration of unidirectional schedules. Later work of Meisel [17] utilizes a different approach for Quay Crane Scheduling, where QCs are only available at certain time windows. The objective of the developed MIP is the minimization of total vessel handling time, determined by the latest completion time among all tasks. While the author solves this problem by searching the solution space of unidirectional schedules, he concludes that the optimal solution does not necessarily lie in the space of unidirectional schedules, but solutions are still of high quality.

The objective of the formulation of Liu et al. [15] is to minimize the maximum relative tardiness of vessel departures. In terms of model assumptions, the authors consider the aggregate workload of each bay, taken as the product of the number of containers to be handled in the bay and the average processing time per container, while vessels and the berth are partitioned into bays. This work does consider clearance constraints between adjacent cranes; productivity is assumed identical for all quay cranes and crane interference is ignored. The authors propose a heuristic decomposition approach to break down the problem into two smaller,