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Hybrid evolutionary computation methods for quay crane scheduling problems

Su Nguyen [a,*], Mengjie Zhang [a], Mark Johnston [b], Kay Chen Tan [c]

[a] School of Engineering and Computer Science, Victoria University of Wellington, New Zealand
[b] School of Mathematics, Statistics and Operations Research, Victoria University of Wellington, New Zealand
[c] Department of Electrical and Computer Engineering, National University of Singapore, Singapore

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ABSTRACT

Quay crane scheduling is one of the most important operations in seaport terminals. The effectiveness of this operation can directly influence the overall performance as well as the competitive advantages of the terminal. This paper develops a new priority-based schedule construction procedure to generate quay crane schedules. From this procedure, two new hybrid evolutionary computation methods based on genetic algorithm (GA) and genetic programming (GP) are developed. The key difference between the two methods is their representations which decide how priorities of tasks are determined. While GA employs a permutation representation to decide the priorities of tasks, GP represents its individuals as a priority function which is used to calculate the priorities of tasks. A local search heuristic is also proposed to improve the quality of solutions obtained by GA and GP. The proposed hybrid evolutionary computation methods are tested on a large set of benchmark instances and the computational results show that they are competitive and efficient as compared to the existing methods. Many new best known solutions for the benchmark instances are discovered by using these methods. In addition, the proposed methods also show their flexibility when applied to generate robust solutions for quay crane scheduling problems under uncertainty. The results show that the obtained robust solutions are better than those obtained from the deterministic inputs.

1. Introduction

Container terminals play an important role in modern sea-freight transportation. With the rapid annual growth rates of the shipped container volume, container terminals have become the bottlenecks in the global supply chain [1] and the effectiveness of the container terminal is an important factor for liner shipping companies to decrease their cost [2]. In addition, a container terminal also needs to improve its service to compete with other terminals. In order to improve their productivity and customer satisfaction, it is important that the terminals can effectively utilise their expensive resources such as ship berthing areas, quay cranes, and yard cranes [3]. To support terminal operational decisions, many operations research methods have been proposed [4–7].

Quay crane (QC) scheduling is one of the most important operations within a container terminal because the effectiveness of this activity can strongly influence the productivity of the entire container terminal. The aim of the quay crane scheduling problem (QCSP) is to find a good schedule for the loading/unloading operations of a vessel with a given number of quay cranes in order to minimise the overall vessel handling time (or makespan) [8]. An illustration of the working QCs at a vessel is shown in Fig. 1. In this case, a number of QCs are allocated to the vessel for loading/unloading operations of containers (20 ft or 40 ft). All QCs move on a railway line parallel to the vessel and QCs are not allowed to cross each other. Different models focusing on different levels of complexity of the problems have been investigated. Bierwirth and Meisel [6] have provided a detailed classification of the existing models to handle QCSPs. Three main problem classes that are most popular in the research community are: (1) QCSP with container groups, (2) QCSP with complete bays (each bay is considered as a single task), and (3) QCSP with bay areas (a set of bays of a vessel is treated as a task to be exclusively handled by one QC) [6,8].

The focus of this paper is QCSP with container groups in which containers of the same bay of the vessel are grouped as different tasks to be assigned to different QCs. In these problems, each task is located at a bay position of the vessel and the precedence constraints need to be satisfied due to the stacking dependent accessibility of tasks located in the same bay. To avoid congestion at the yard blocks, some tasks are also not allowed to be processed simultaneously [9]. Each QC has a ready time and an initial bay position. When operating, all QCs must not cross each other and two QCs cannot work at the same bay location and their safety

* Corresponding author. Tel.: +64 212582258.
E-mail address: Su.Nguyen@ecs.vuw.ac.nz (S. Nguyen).

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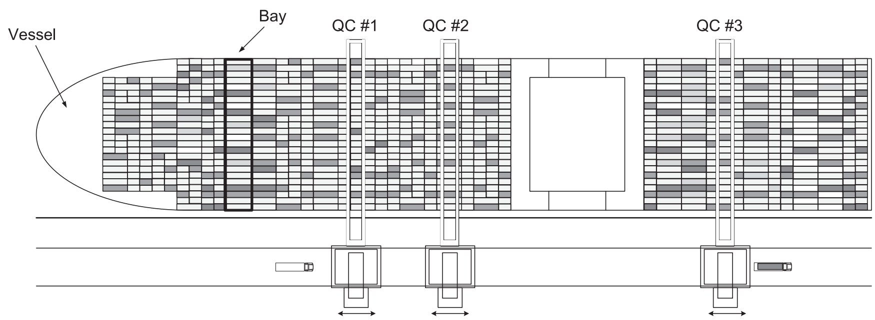

Fig. 1. Illustration of QCs working on a vessel.

distance (measured in unit of bays) have to be maintained [8]. The readers can refer to Kim and Park [10] and Bierwirth and Meisel [6] for detailed examples of QCSP. Many methods have been proposed in the literature to deal with these problems [9–14]. However, there are still two major limitations with these methods. First, the running times of these methods increase rapidly as the problem size increases. Second, although some methods can provide very good solutions, they are not flexible enough to cope with practical requirements (e.g. coping with the uncertainty, integrating with other operation decisions).

1.1. Goals

The overall goal of this work is to develop new methods for QCSPs with container groups which can effectively find near-optimal schedules within reasonable computational times and have the flexibility to taking into account different requirements of the real-world applications. Due to the effective search of near-optimal solutions for scheduling problems [11,12], we propose new evolutionary computation methods to tackle QCSPs with container groups. The research objectives of this work can be summarised as follows:

1. Developing new hybrid methods that combine the advantages of evolutionary computation methods and a local search heuristic for QCSPs.
2. Comparing the proposed methods with the existing methods in the literature and analysing their advantages and disadvantages.
3. Extending the methods to handle the QCSPs with uncertain processing times.
4. Analysing the behaviour of the proposed methods.

The novelty of the proposed methods is the use of a new priority-based schedule construction procedure, where the priorities are determined based on two representations that allow the proposed methods to simultaneously decide the assignments of tasks to quay cranes and the sequencing of tasks. In the first representation, the individual is represented as an order of tasks to be processed by the available quay cranes, which is usually found in applications of genetic algorithm (GA) [15] for scheduling problems. The second representation is a priority function in a tree form, which is widely used in genetic programming (GP) [16,17]. Different from the individuals in the first representation that can be directly used as the priorities for task assignment and sequencing, the tree-based individuals will indirectly calculate the priorities of tasks based on the status/attributes of tasks and quay cranes at the moments that scheduling decisions need to be made. While GA as well as some other evolutionary computation methods such as particle swarm optimisation (PSO) or ant colony optimisation (ACO) has been applied regularly in the scheduling literature (PSO and ACO have not been applied to solve QCSPs with container groups), GP is not a conventional method for these problems from the optimisation viewpoint. Therefore, it would be interesting to have a comparison of these two methods in this work. Two advantages of GA and GP are that they are easy to be implemented, and that they are flexible enough to be extended to deal with different objectives or to be integrated with other operation decisions. In order to further improve the quality of the scheduling solutions, we also introduce a new simple local search procedure to refine the schedules obtained by GA and GP. This paper also presents the first work that compares the performance of the simulation-optimisation methods with that of deterministic methods to handle QCSPs with uncertain handling times.

1.2. Organisation

The rest of this paper is organised as follows. An overview of existing methods used to deal with QCSPs are presented in Section 2 and we give a mathematical programming model of the considered QCSP in Section 3. In Section 4, details about the new hybrid methods are provided to show how they can be used to solve QCSPs. Sections 5 and 6 show the experimental design and the results obtained by the proposed methods on a large number of benchmark instances. Section 7 extends the proposed methods to deal with QCSPs under uncertainty. Further discussion about the proposed methods is presented in Section 8. Finally, we provide conclusions and highlight future research directions.

2. Related work

Study of QCSPs was initiated with the early work of Daganzo [18] who investigated the problem with multiple vessels at a berth and cranes which can move freely. An exact method was provided to deal with small problems. Perterkofsky and Daganzo [19] proposed a branch-and-bound algorithm to solve real size problems. However, these studies did not consider interference between the quay cranes.

Kim and Park [10] further investigated this problem at a greater level of detail by dividing a task into smaller fractions (referred to as clusters or container groups) as compared to those from Daganzo [18] and Perterkofsky and Daganzo [19]. They also included realistic constraints such as quay crane ready times, non-crossing and precedence constraints in their model. A first formal mixed-integer linear program (MILP) was also presented in this work to avoid interference and later this was improved by Moccia et al. [13], Sammarra et al. [14] and Bierwirth and Meisel [9]. Unfortunately, QCSPs with the interference constraints are too complex to be solved to optimality by MILP solvers. Kim and Park [10] developed a branch-and-bound (B&B) algorithm to find optimal *non-delay* schedules with minimum makespan (the completion time of the last task). However, B&B can only solve problems with fewer than 20 tasks. Moccia et al. [13] proposed a