Expert Systems with Applications 41 (2014) 6959–6965

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

A multi-vessel quay crane assignment and scheduling problem: Formulation and heuristic solution approach

Yi-Min Fu, Ali Diabat *, I-Tsung Tsai

Department of Engineering Systems and Management, Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Article history:
Available online 10 May 2014

Keywords:
Quay crane assignment
Quay crane scheduling
Genetic algorithms
Integrated models

ABSTRACT

This paper presents a new approach to analyze the integrated quay crane assignment and scheduling problem (QCASP). The problem determines the assignment of quay cranes to vessels and the sequence of tasks to be processed by each quay crane simultaneously, and accounts for important considerations such as safety margins between quay cranes (QCs), ordering conditions and vessel priority. Furthermore, QCs can travel from one vessel to another vessel whenever tasks are complete. The integrated problem is difficult to solve with exact methods due to its complexity. Therefore, a genetic algorithm (GA) is proposed to solve the integrated QCASP. Computational results validate the performance of the proposed GA.

1. Introduction

International trade plays a crucial role in global economy and it relies heavily on maritime transport, which accounts for approximately 90% of global trade transport (International Chamber of Shipping, 2014). The continuous increase of maritime transport has led to the containerization of goods, which facilitates the growth of this sector, making it an even more important component of international trade. Ports and container terminals are vital nodes in the network as they accommodate the transshipment of goods and then connect them to the rest of the transport network. Fig. 1 shows that global container traffic, as measured in twenty-foot equivalent units (TEUs), has more than doubled between 2001 and 2010.

Port operation involves a sequence of activities that require careful planning and execution to ensure maximum container throughput. Upon arrival at the port, the vessel will be assigned to a berthing position, where the offload and upload operations of containers are performed. Following the assignment of a berth, the vessel's containers are discharged by assigned QCs according to a work schedule, and distributed to one of the storage blocks in the yard. The containers are then delivered by internal transportation to truck and train operation areas, where the containers are loaded onto trucks and/or trains to be transported to desired destinations. The operations that take place before the container reaches the storage yard are referred to as quayside operations, as they take place near the quay of the container terminal. Operations taking place on the yard, where containers are stacked and stored, are known as yard side operations.

The cost of constructing berths and operating equipment such as the QCs is extremely high. Therefore, a major focus of the literature has been on the optimization of three quayside operation problems that are related to the utilization of berths and QCs. The first one is the assignment of quay space and service time to vessels, namely the berth allocation problem (BAP). The second one is the quay crane assignment problem (QCAP), which determines the allocation of quay cranes to vessels. In general, the number of QCs assigned to a vessel determines the handling time of the vessel. The fewer cranes assigned to a vessel, the longer time it takes to handle the ship. The last problem is the quay crane scheduling problem (QCSP), which determines the sequence of containers being processed by each crane to minimize the total handling time of the vessel.

The modeling approaches for quayside operations vary by the assumptions on: (1) vessel arrival time: the *static* berth allocation problem assumes all vessels have arrived when the berthing plan is to be determined, whereas the *dynamic* berth allocation problem allows vessels to arrive during the planning horizon (Imai, Nishimura, & Papadimitriou, 2001), (2) quay layout: a quay with a *discrete* layout has a fixed number of berths. Each berth can accommodate up to one vessel at a time (Imai, Chen, Nishimura, & Papadimitriou, 2008a; Imai, Nishimura, & Papadimitriou, 2008b). For a quay with a *continuous* layout, vessels will berth along the quay side as long as space allows. Continuous quay layout is therefore more efficient for space utilization but is also more difficult to solve for the optimal berthing plan (Meisel & Bierwirth, 2009), (3) vessel handling time: the static handling time model

* Corresponding author. Tel.: +971 2810 9101; fax: 971 2810 9901.
E-mail address: adiabat@masdar.ac.ae (A. Diabat).

http://dx.doi.org/10.1016/j.eswa.2014.05.002
0957-4174/

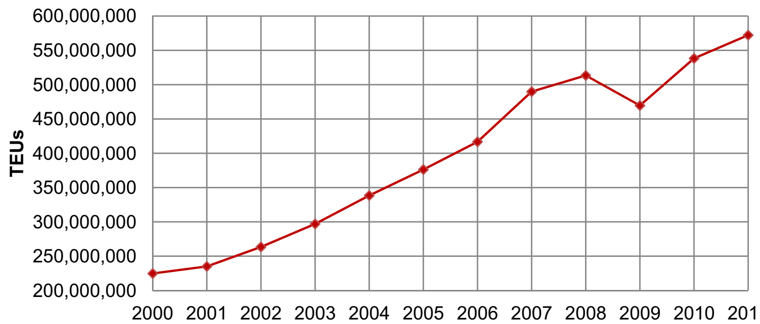

Fig. 1. Container terminal traffic (The World Bank, 2014).

assumes handling time to be fixed and known in advance, whereas the dynamic handling time model assumes that the handling time is a function of the berthing position of the vessel, the number of cranes assigned to the vessel, and the work schedules of the cranes.

Integrated quayside operation models have been proposed to improve overall efficiency of quayside operations. Park and Kim (2005), as well as Meisel and Bierwirth (2009) study BAP and QCAP with integrated models. Tavakkoli-Moghaddam, Makui, Salahi, Bazzazi, and Taheri (2009) propose a model that studies the quay crane assignment and scheduling problem (QCASP). It is known that BAP needs to be solved together with QCAP when the vessel handling time is dynamic, as the number of quay cranes assigned to the vessels needs to be considered in the berth allocation planning phase. If the problems are solved independently, for instance, deciding the berthing time without considering the number of QCs serving the vessels means that the actual vessel handling time can be different from the given berthing time, which results in idling berths or delays in accepting new vessels. Since QC allocation affects the sequencing of QCs, QCs can be better utilized when QCAP and QCSP are considered simultaneously.

In this paper, we develop a model to integrate quay crane assignment and scheduling problems. Then, a genetic algorithm is proposed to determine the near optimal solution for the given problem. This paper thus makes a contribution by developing a new formulation to model the complex problem in an integrated manner, and proposing a customized genetic algorithm to solve the proposed formulation in an efficient manner.

The paper is organized as follows. Section 2 reviews the literature. Section 3 presents the formulation of the model. Section 4 introduces and explains the solution approach. Section 5 shows an experimental analysis of the model. Finally, Section 6 summarizes the results of the study and discusses potential directions for future research.

2. Literature review

Several studies on QCAP and QCSP have been conducted to improve the performance of container terminal operations. The QCSP was first discussed by Daganzo (1989), in which a container group is defined as a task. The problem is formulated as a mixed integer programming (MIP) model and the total weighted departure time of vessels is minimized. Daganzo's definition of a task is different from this paper, in which a task is defined as the loading or unloading operation of a single container, rather than a container group.

Kim and Park (2004) present an MIP model for the QCSP. The authors define a cluster as a collection of adjacent containers of the same group. They then define a loading/unloading operation for every cluster as a task in the formulation. Precedence relationships among clusters are considered. A branch and bound (B&B) method is then proposed to solve the QCSP. The paper provides a comparison between the B&B method and a heuristic search algorithm, namely greedy randomized adaptive search procedure (GRASP).

Interference constraints are introduced in the paper presented by Bierwirth and Meisel (2009). In an attempt to incorporate more realistic assumptions, the authors consider non-crossing constraints and clearance constraints for QCs (i.e. safety margin between adjacent QCs). The problem is also formulated as an MIP model and is solved with a tree-search-based heuristic solution procedure. An optimal solution for the QCSP with container groups can be found with a non-unidirectional schedule. Meisel (2011) introduces the concept of time windows in the QCSP, according to which each QC is restricted to serve a certain vessel within a certain pre-defined time window. QCs are discharged from low-priority vessels to high-priority vessels.

Park and Kim (2005) were the first to integrate the berth allocation and crane scheduling problem through a two-phase process. They determine the berthing time and position of each vessel as well as the number of cranes to be allocated to the vessel in the first phase. The objective of the first phase is to minimize the weighted sum of the handling cost of containers and the penalty cost incurred by unpunctual berthing. In the second phase, they schedule the assignment of individual quay cranes based on the results of the first phase.

To improve the approach presented by Park and Kim (2005), Meisel and Bierwirth (2009) present a model that takes into account the effect of the interference among QCs and the workload of horizontal transport means on terminal productivity. A Squeaky Wheel Optimization heuristic is proposed by the authors to generate the solutions, which they report always yields improved results compared to those obtained from the Lagrangian heuristic proposed by Park and Kim (2005).

Tavakkoli-Moghaddam et al. (2009) extend the model proposed by Kim and Park (2004) to model a set of vessels in parallel. This paper formulates an MIP model for the integrated QCSAP. In the dynamic planning horizon a QC is assigned from the incumbent vessel to the next vessel after the completion of all the tasks in the incumbent vessel. A genetic algorithm is proposed to obtain a near optimal solution for this complex and large-scale problem.

Choo, Klabjan, and Simchi-Levi (2009) introduce a multi-vessel problem in the QCSP. Yard congestion constraints are considered to link the vessels. Clearance constraints are also included in this paper. The authors address the single-ship case by reformulating an MIP model as a generalized set covering formulation, while the multi-ship case is decomposed in the spirit of Lagrangian relaxation. Both cases are then solved using B&P.

The recent work of Diabat & Theodorou, 2014) introduces a new type of formulation, which practically transforms the integrated