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An analytical framework for integrated maritime terminal scheduling problems with time windows

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ABSTRACT

Container transport, an integral part of intercontinental trade, has steadily increased over the past few decades. The productivity of such a system, in part, hinges on the efficient allocation of terminal resources such that the container transit time is minimized. This study provides an analytical framework, which entails efficient scheduling of quay and yard cranes, to minimize the time spent by containers at a terminal. A mixed-integer programming model is developed to capture the two-stage multi-processor characteristic of the problem, where each crane has specific time window availability. A genetic algorithm equipped with a novel decoding procedure is developed. The mixed-integer model is tested on a number of problem instances of varying sizes to gain managerial insights.

1. Introduction

Intercontinental trade, primarily conducted through container transport on ships, has steadily grown in size over the past few decades. According to the United Nations Conference on Trade and Development, global container throughput experienced a 5.9 percent growth in 2011, the highest annual growth ever (UNCTAD, 2012). In line with the increasing global trend, around 45 mn containers were handled by the major ports in North America (Colliers, 2012). The statistic was equally impressive for Canadian ports, which collectively handled 4.8 mn containers in 2010, almost a two-third increase from the volume a decade ago (CIY, 2012). For example, the Port of Montreal processed around 1.4 mn containers in 2011, which showed a 34 percent increase over the volume in 2000. The increased need for outsourcing and the existence of supply chain partners in different parts of the world imply continued reliance on intercontinental trade (and container transport), and calls for effective allocation of resources to both improve the lead-time and also make the chain more competitive. Efficient operations in a marine terminal, one of the transshipment points in intercontinental freight movement, are crucial to realizing the two objectives.

Marine container terminal operations can be broadly divided into container loading/unloading performed by quay cranes and yard cranes, where the former attend to the ships, and the latter is responsible for moving containers from dockside stacks (storage) to the intermodal trains and trucks. Note that any port related delays could entail much higher costs for the container ship operators and the final customers, not to mention the unanticipated congestion at the terminal and the associated questions about reliability (Crainic, 2007). It should be clear that the efficient allocation of the two types of cranes could significantly impact the turnaround time (the time spent to make a transport vehicle ready for departure after its arrival) of container ships, trucks and intermodal trains, thereby improving port productivity, primarily achieved through increased container throughput and/or decreased processing time.

This paper investigates the integrated scheduling of quay cranes for seaside and yard cranes for landside operations, and proposes a two-stage multi-processor scheduling model with time windows (TMSTW). More specifically, in the first stage, containers from n_1 ships are unloaded by m_1 quay cranes and stacked. Each quay crane is available in certain time windows during the twenty-four hour period, and is offline for maintenance the remaining time. For this stage, a job is defined as the unloading of all containers from a berthed ship. In the second stage, the unloaded containers would be retrieved from the temporary stacks (storage) by m_2 yard cranes, and placed on the intermodal trains and trucks to be transported to n_2 customers. Since more than one container may be destined to a single customer, a job in the second stage is defined as the loading of all containers belonging to one shipment. Finally, each yard crane has an availability time window, and the loading

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Sets

I	set of stages, indexed by i
V_i	set of cranes in stage i, indexed by $v = \{1, 2, \ldots, m_i\}$
J_i	set of jobs in stage i, indexed by $j = \{1, 2, \ldots, n_i\}$
T_{iv}	set of availability time windows for crane v in stage i, indexed by $u = \{1, 2, \ldots, k_{iv}\}$
S_j	set of precedent jobs in J_1 for job j in stage 2, indexed by s

Decision variables

C_{ij}	completion time of job j in stage i
X^u_{ivj}	$\begin{cases} 1, & \text{if job } j \text{ is assigned to the time window } u \text{ of crane } v \text{ instage } i \\ 0 & \text{otherwise} \end{cases}$
Z_{ijf}	$\begin{cases} 1, & \text{if job } j \text{ precedes job } f \text{ in stage } i \\ 0 & \text{otherwise} \end{cases}$

Parameters

Q	a large positive integer
P_{ij}	processing time of job j in stage i
W_{ij}	weight of job j in stage i
Y_{ij}	size of job j in stage i (i.e., number of cranes required)
D^u_{iv}	end of time window u for crane v in stage i
R^u_{iv}	start of time window u for crane v in stage i
m_i	number of cranes in stage i
n_i	number of jobs in stage i
k_{iv}	number of available time windows for crane v in stage i

operation can start only after the unloading of the relevant containers from the ship. Hence, the objective of this study is to schedule the operations in the two stages so that the (total) weighted completion time is minimized.

The rest of this paper is organized as follows. Section 2 reviews the related research, while a formal problem definition is outlined in Section 3. Section 4 outlines the sets and indices before presenting the mixed-integer programming model, which is NP-hard. Section 5 develops a genetic algorithm, equipped with a novel decoding procedure, to solve the proposed model. Section 6 discusses the results and analysis of numerous problem instances of varying size, and compares the performance of the proposed solution technique with another meta-heuristic technique. Finally, Section 7 contains the conclusion and highlights the contribution of this work.

2. Literature review

The relevant literature in regards to the maritime terminal scheduling can be organized under two threads: seaside operations with time windows; and, the integrated seaside and landside operations.

Seaside operation deals with determining the service sequence for each crane and the associated schedule, i.e., quay crane scheduling problem (QCSP). This problem was first introduced by Daganzo (1989), who proposed a methodology for scheduling a given number of cranes to the ship bays at the minimum aggregate delay cost. Subsequently, Peterkofsky and Daganzo (1990) considered the same problem as an open shop scheduling problem with parallel and identical machines, where jobs consist of independent single-stage preemptable tasks (running job can be interrupted for some time and resumed later). Although this area has received increased attention from academic researchers over the past decade, but given our focus on integrated operations we invite readers to refer to Bierwirth and Meisel (2010) and Carlo et al. (2013) for the relevant works.

Bierwirth and Meisel (2009) incorporated time window in the QCSP and proposed a heuristic solution method, which was subsequently improved in standalone work by Meisel (2011). Legato et al. (2012) studied independent unidirectional quay crane scheduling under time windows by assuming that cranes can move in different directions, and made use of a branch and bound technique to solve the model. Setting aside the idea of generating unidirectional schedules, Unsal and Oguz (2013) developed a constraint programming (CP) approach to solve the quay crane scheduling problem with time windows. Their computational experiments outperformed the results of Legato et al. (2012) in terms of the obtained lower bound.

The integration of seaside and landside operations has been studied by a few researchers. Chen et al. (2007) investigated the scheduling of different types of terminal equipment, such as quay cranes, yard cranes, and yard vehicles. A hybrid flow shop scheduling approach with precedence and blocking constraints was used to formulate the problem, which was solved using a tabu search solution technique. On the other hand, Chen and Lee (2009) attempted to minimize the makespan involving unpacking operations of inbound carriers and collection operations of outbound carriers. The problem was formulated as a cross docking flow shop problem, in which there were exactly two stages with one machine and a set of jobs in each stage. This model was extended by Chen and Song (2009), who considered the problem with more than one parallel machine in at least one of the two stages.

The model proposed in this research, like the integrated scheduling problem discussed above, examines a two-stage problem with precedence constraints. However, two distinct characteristics make this research unique from the previous studies. *First*, multiple cranes with their own availability time windows are available in each stage. As indicated earlier, these time windows enable us to incorporate unavailability, which could be for maintenance, adherence to labor regulations, and so on. *Second*, the proposed model allows multiprocessor tasks, i.e., each job may require several cranes simultaneously. To the best of our knowledge, Guan et al. (2002) is the only study that considered the multiprocessor scheduling problem in container terminals. The authors investigated the ship berth allocation problem where the objective was to minimize the total weighted completion time of ships. The model proposed in this work is distinct from earlier studies, since it considers both time windows and multi-processors in both stages to investigate the scheduling of cranes in a marine terminal. More specifically, the goal of our model is to schedule the quay cranes to unload inbound ships and the yard cranes to load outbound intermodal trains and trucks.

3. Problem statement

The proposed research focuses on the terminal level operations and seeks to answer the following question: what is the most efficient way to schedule a given set of quay cranes on the berthed