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Comparative evaluation of resource cycle strategies on operating and environmental impact in container terminals

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ABSTRACT

This paper examines the use of single and dual cycle operations for three types of resources, namely, quay cranes, vehicles, and yard cranes to improve the operating efficiency and reduce the energy consumption in a container terminal. Various cycle strategies are proposed and their corresponding estimation models, describing the stowage distributions of outbound and inbound containers on a ship and the storage sharing level of blocks in the yard, are formulated to estimate the total number of cycles for the resources. Statistical analyses are conducted to evaluate and compare the effect of different cycle strategies on the cycle reductions. From the experiment results, it was found that collaboration between resources with the single cycle operation always outperforms that under the dual cycle operation without collaboration.

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Introduction

Containerization is a major technological innovation that has revolutionized the nature of maritime-based freight transport by introducing a substantial degree of standardization in port services. With containerization, ports in the same region can no longer rely on specialization to maintain market share. Inter-port competition intensifies as ports become closer substitutes to one another while developments in inter-modal transportations exacerbate the degree of competition by bringing about overlapping port hinterlands. Among the many factors contributing to the competitiveness of a container terminal, of particular importance to the shippers is the time in port for ships. In general, time spent in port loading and unloading cargo is regarded as unproductive time of a ship (Fuentes and Couvillion, 2004). To the port operators, rapid container turnover, as facilitated by a high speed of loading and unloading containers, is also beneficial by enabling higher utilizations of port resources and enhancing operational efficiency. Driven by the growing awareness about environmental issues among consumers, governments and businesses, port operators face pressure to reduce their ecological footprints at the same time.

A typical operational sequence of unloading and loading containers on container ships is follows: When a ship arrives at the terminal, it is assigned to the designated berth if it is available. Otherwise, the ship must wait until a berth becomes available. After the ship enters a berth, quay cranes (QCs) are assigned to the ship. Subsequently, the QCs that are deployed on the ship start to unload and load containers onto/from the ship in accordance to the pre-specified sequence. Apart from the QCs, yard cranes (YCs) and vehicles are the other two most representative types among the numerous types of handling

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resources. YCs are usually situated at the blocks and serve vehicles for sea side (ship) operations and road trucks for land side (consignee) operations in the storing and retrieving of containers in the yard. Meanwhile, vehicles travel between the yard and quay to transport containers for ship operations.

The conventional operational process of a container terminal follows the single cycle operation for each type of resource. Typically, vehicles make empty travels when they come back to the QCs after transporting inbound containers onto the yard. Both QCs and YCs also have empty travels (known as cycles in the extant literature) when they move back to the ship (bay) after releasing the inbound (outbound) containers to vehicles. If the resources are able to conduct handling (or transportation) operations through dual cycle operations of a combination of QCs, YCs, and vehicles, then it may be possible to reduce the empty travels and improve the operating efficiency in a container terminal. For example, a QC may perform an unloading activity[1] for a vehicle and a loading activity for another vehicle without an empty movement. Meanwhile, the reduction in the number of cycles also provides a promising avenue to improve the energy efficiency in the daily operations at a container terminal and reduce the corresponding carbon dioxide emissions. According to Yang and Lin (2013), a RMGC (Rail Mounted Gantry Crane) and a RTGC (Rubber Tyred Gantry Crane) require 3.34 kW/h and 2.41 kW/h per cycle, respectively. In other words, for every unit decrease in the number of cycle, the terminal enjoys a savings of 3.34 kW/h and 2.41 kW/h in energy consumption for RMGC and RTGC.

This paper explores cycle strategies aimed at improving the operations efficiency and reducing the energy consumption in the container handling process at a container terminal. Several cycle operation modes comprising single and dual cycles for QCs, YCs and vehicles are examined and 4 cycle strategies are proposed through various combinations of the 5 cycle operation modes. The analytical models are developed to characterize and estimate the total number of cycles for a ship under the proposed cycle strategies, with a smaller number of cycles generally representing a more efficient container handling of resources and lower energy consumption for the same amount of containers handled. Through numerical experiments, an investigation on the efficiencies of the proposed cycle strategies is carried out under various stowage distributions of the outbound and inbound containers on the ship. An overall evaluation of the strategies is then put forward based on their best and average performances across the 9 stowage distributions considered. To the extent of our knowledge, this paper represents the first attempt to analyze both the operating efficiency and the energy efficiency arising from single and dual cycle operations for the key resources used in container handling.

The rest of this paper is organized as follows. The next section reviews the literature on the single and dual cycle operations for handling resources in container terminals and related sectors. Section 'Operating scenarios: Cycles, modes and strategies' introduces five cycle operation modes adopted by the three resources in combinations. Section 'Cycle strategies and estimation models' proposes four cycle strategies that can possibly to reduce the number of cycles, and constructs analytical models to estimate the number of total cycles for a ship that incorporates the proposed cycle strategies. Section 'N umerical analyzes and results' conducts the numerical experiments for comparing the operating and energy efficiencies under the proposed cycle strategies. Section 'Conclusions' summarizes the results and concludes the study.

Literature review

Many studies have examined the cycle estimation of a handling machine. Kim (1997) proposed a formula for estimating the total number of handling occurrences, including re-handling, which is required to retrieve all the inbound containers that are stacked in a yard bay. de Castilho and Daganzo (1993) proposed analytical formulas for the expectation and variance of the number of relocations that are required to retrieve a container from a yard bay. Lee and Kim (2010) and Wiese et al. (2011) proposed analytic expressions for estimating the expectation and the variance of the cycle time for various types of operation of YCs, which considers the speeds for gantry travel, trolley travel, and hoisting/lowering movements. Vidovic and Kim (2006) proposed a method for estimating the cycle-time of three-stage, material handling systems that consisted of a QC, a YC, and multiple vehicles by using a Markov-chain model and a mathematical approximation.

Some recent literatures study the dual cycle operations for dispatching vehicles. Kim and Bae (2004) proposed a dispatching method for automated guided vehicles (AGVs) to minimize the delay time of QCs and transportation time of AGVs under the dual cycle operations of individual QCs. They showed that the proposed algorithm outperformed the conventional rules such as the shortest travel time/distance, and the earliest due date via a simulation study. Grunow et al. (2004) introduced several assignment patterns and used them to dispatch AGVs considering the multiples locations for picking up or releasing containers in a container terminal. Grunow et al. (2006) generalized the previous work of Grunow et al. (2004) by allowing AGVs to perform the operation following either single or dual cycle operations. They compared the typical on-line dispatching rules with the proposed off-line heuristic algorithm based on the assignment patterns.

Related to the dual cycle operations in the quayside operation, Goodchild and Daganzo (2006) introduced the dual cycle of a QC for loading and loading containers simultaneously at a ship bay. They assumed that the containers at a stack are handled consecutively. Thus, if a QC starts to unload or load containers at a stack, then it should not be disturbed by other jobs until the work related to the stack is completed. On basis of this assumption, they defined the dual cycle operation as a two-machine flow shop scheduling problem and applied the well-known Jonson's rule to find the unloading and loading

[1] We make a distinction between the terms 'operation' and 'activity' such as an operation comprises a series of activities and each activity constitutes a specific task performed by the resource.

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