Transportation Research Part C 44 (2014) 214–230

Contents lists available at ScienceDirect

Transportation Research Part C

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

Energy-aware control for automated container terminals using integrated flow shop scheduling and optimal control

Jianbin Xin *, Rudy R. Negenborn, Gabriël Lodewijks

Department of Maritime and Transport Technology, Delft University of Technology, Mekelweg 2, 2628CD Delft, The Netherlands

A R T I C L E I N F O

Article history:
Received 15 October 2013
Received in revised form 26 March 2014
Accepted 26 March 2014

Keywords:
Automated container terminals
Flow shop scheduling
Optimal control
Energy consumption

A B S T R A C T

The performance of container terminals needs to be improved to handle the growth of transported containers and maintain port sustainability. This paper provides a methodology for improving the handling capacity of an automated container terminal in an energy-efficient way. The behavior of a container terminal is considered as consisting of a higher level and a lower level represented by discrete-event dynamics and continuous-time dynamics, respectively. These dynamics represent the behavior of a large number of terminal equipment. The dynamics need to be controlled. For controlling the higher level dynamics, a minimal makespan problem is solved. For this, the minimal time required by equipment for performing an operation at the lower level is needed. The minimal time for performing an operation at the lower level is obtained using Pontryagin's Minimum Principle. The actual operation time allowed by the higher level for processing an operation at the lower level is subsequently determined by a scheduling algorithm at the higher level. Given an actual operation time, the lower level dynamics are controlled using optimal control to achieve minimal energy consumption while respecting the time constraint. Simulation studies illustrate how energy-efficient management of equipment for the minimal makespan could be obtained using the proposed methodology.

1. Introduction

Over the last decades, there has been a significant growth of global freight transport due to the enormous commercial trade. Over 60% of worldwide deep-sea cargo is transported by containers (Stahlbock and Voß, 2007). The management of freight transport needs to accommodate this increasing supply of containers. Intermodal transport (Crainic and Kim, 2007) is hereby considered frequently as an option since it provides flexibility and scalability as different transport modalities can cover different areas with respect to transport distance. As an intermodal transport hub, a container terminal represents the interface between the modality of vessel, barge, train and truck. Therefore, container terminals play a crucial role in freight transport.

The increasing amount of containers that arrive and depart with container ships provides much pressure for terminal operators. In 2000, the capacity of a container vessel was at most 6000–8000 TEU; in 2013, the number of containers carried by a container vessel can be up to 18,000 TEU (Rodrigue et al., 2013), and this number is expected to increase further. The turnaround time of a container vessel could increase significantly, if no appropriate measures are taken. Hence, the handling capacity of a container terminal must be maximized to reduce the turnaround time of a container vessel. Meanwhile, energy

* Corresponding author. Tel.: +31 15 2784730; fax: +31 15 2781397.
E-mail address: j.xin@tudelft.nl (J. Xin).

http://dx.doi.org/10.1016/j.trc.2014.03.014
0968-090X/

consumption needs to be reduced to adapt sustainability. Contrarily to building new terminal infrastructures, terminal management can be improved in order to maximize the performance of the existing infrastructure, possibly in an economical way.

The research on management of container terminals has received much attention in the transportation society (see Stahlbock and Voß, 2007 for a comprehensive survey). In order to simplify the management, several works investigate an independent terminal area, like the quayside (Golias et al., 2010; Chen et al., 2012), the transport area of AGVs (Liu et al., 2004; Angeloudis and Bell, 2010) or the stacking area (Ng and Mak, 2006; Saurí and Martín, 2011). However, the transport of a container depends on interactions of multiple pieces of equipment from areas all over the container terminal. This motivates the research of integrated areas of a container terminal (Soriguera et al., 2006; Lee et al., 2009; Petering, 2011; Chen et al., 2013) and the complete terminal (Bielli et al., 2006; Ha et al., 2007; Yin et al., 2011; Henesey et al., 2009; Alessandri et al., 2008; Contu et al., 2011).

Despite the accumulation of literature on container terminal control, there is a remarkable absence of research that provides management of equipment at the operational level, taking into account the dynamics and constraints of equipment. Traditional approaches, e.g., object-oriented approaches (Bielli et al., 2006; Ha et al., 2007), agent-oriented programming (Yin et al., 2011; Henesey et al., 2009) and mathematics-based approaches (Alessandri et al., 2008; Contu et al., 2011), typically investigate the performance of container terminals from a strategic perspective. However, those approaches do not consider the link between the dynamics of equipment and the performance of the terminal. The lack of this connection could result in inapplicability of these methods in practice. Besides this, little attention has been paid to sustainability of container terminals. As an example of the order of magnitude, the yearly electricity consumption of the ECT Delta terminal in Rotterdam is around 45,000 MW h per year with a yearly transshipment volume of 4,260,000 TEU (van Duin and Geerlings, 2011). The importance of energy consumption reduction in container terminals is emphasized in the works by Wijlhuizen and Meeussen (2008) and van Duin and Geerlings (2011). Nevertheless, there, the investigation of energy consumption in container terminals was addressed at the strategic level, instead of the operational level. Consequently, it is still not clear how energy consumption can be reduced when it comes to operational container terminal management.

The aim of this paper is to investigate how to improve the operational performance of an automated container terminal at the operational level when combining the handling capacity and energy consumption objectives. For this, the operational dynamics of a container terminal are considered two interacting levels for which a hierarchical controller is proposed. This paper considers the energy-efficient control for the case of a quay crane, multiple automated guided vehicles and multiple automated stacking cranes. To model the case of multiple pieces of equipment in a stage, a hybrid flow shop representation is proposed. A bi-level optimization problem is formulated for determining time windows that maximize the space for energy efficiency, while minimizing the overall completion time. Then a stage controller is proposed for assigning the time window of each operation to a particular piece of equipment in each stage. The actions for each piece of equipment are then determined so as to achieve the desired performance using optimal control. This paper also proposes a benchmark system for evaluating the performance and elaborating details in container terminals. This paper extends and further details the initial work reported in Xin et al. (2013). In that paper, a simplified setup was considered with one single quay crane, one single automated guided vehicle and one single automated stacking crane. Therefore, in that paper the assignment of containers to equipment was straightforward. That paper also only conducted one simulation of a simple container terminal scenario in which all containers are transported for the same destination in a fixed order.

This paper is organized as follows. In Section 2 the decomposition of the dynamics of automated container terminals involving three types of equipment is given. Section 3 proposes a hierarchical architecture for controlling the equipment. Section 4 proposes a benchmark system for an automated container terminal. Section 5 illustrates the potential of the proposed approach in multiple simulation studies using the benchmark system. Section 6 concludes this paper and provides directions for future research.

2. Modeling of container handling equipment

In general, in a container terminal there are multiple types of equipment used to handle containers (Stahlbock and Voß, 2007). A container terminal is referred to as an automated container terminal when the equipment can be controlled fully automatically without any human intervention. Currently there exist several automated container terminals (e.g., ECT Delta, ECT Euromax, and RWG in Rotterdam and HHLA in Hamburg), while new ones are being built (e.g., APM terminal MV2 in Rotterdam). In such an automated terminal, there are multiple quay cranes (QCs), multiple automated guided vehicles (AGVs) and multiple automated stacking cranes (ASCs) for transporting containers from a vessel to the stacking area and vice versa. Each QC considers a particular bay which consists of several rows of containers. In this paper, one QC, multiple AGVs, and multiple ASCs are considered for transporting containers as the first setup for illustrating the hierarchical control structure proposed.

In our system, the layout of the equipment is as shown in Fig. 1. In a typical unloading cycle, a QC picks up a container from the vessel and then unloads it to an AGV. The AGV moves with the container from the quayside to the stacking area, where a container is unloaded by an ASC. The ASC then transports the container to the position in the storage area. In a loading cycle these movements are reversed. Accelerations, decelerations and steering angles (if applicable) of the pieces of equipment have to be determined in an optimal way. In addition, the moment at which containers are transported from one piece of equipment to the next will be determined. In this paper, for the sake of simplicity only the horizontal trajectory