ARTICLE IN PRESS

Transportation Research Part D xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part D

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

Modeling assignment of quay cranes using queueing theory for minimizing CO_2 emission at a container terminal

Ding Liu [a,b,c], Ying-En Ge [a,*]

[a] College of Transport and Communications, Shanghai Maritime University, 1550 Haigang Avenue, Pudong, Shanghai, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[c] Shenzhen Urban Transport Planning & Design Institute, China

A R T I C L E I N F O

Article history:
Received 29 June 2016
Revised 5 April 2017
Accepted 9 June 2017
Available online xxxx

Keywords:
Quay crane
Automatic guided vehicles
CO_2 emission
Container terminals
Queueing theory

A B S T R A C T

Quay cranes (QCs) play a significant role in CO_2 emission of the operations of global supply chains, since huge global container traffic requires a considerable number of handing operations of QCs. The traditional studies of QC assignment mainly aim to investigate the scheduling efficiency of QCs and seldom touch on CO_2 emission or other green transportation objectives and the resulting models are normally mixed-integer programming (MIP) problems and solved by heuristic algorithms. In this paper, a convex mathematical programming model is proposed for the QC assignment problem, in which the queueing theory is used to model the queueing behavior of automatic guided vehicles (AGVs). The objective of the proposed model is to minimize CO_2 emission during an unloading process of containers from QCs to AGVs by optimizing the number of QCs. The analytical solution of the number of QCs is obtained to the proposed model. It is found that the optimal number of QCs increases with the expected arrival rate of AGVs and the mean fuel consumption per AGV per hour but it decreases with the mean queue service rate of QCs and the electricity consumption per QC per hour.

1. Introduction

1.1. Background and literature review

The global container traffic experiences a rapidly continuous growth in the past two decades worldwide (Wang and Lu, 2005; Petering and Murty, 2009; Zhang and Wang, 2016). Specifically, for instance, the world container traffic increases from 483,554,000 teu (teu: 20 foot equivalent units) in 2009 to 689,091,000 teu in 2015 (Data sources: www.drewry.co.uk). The huge global container traffic requires a large number of handing operations (loading and unloading) of containers from quay cranes (QCs) to internal trucks or automatic guided vehicles (AGVs), or vice versa, at container terminals. Hence, the handling operations of QCs play a significant role in CO_2 emission of the operations of global supply chains.

The traditional studies of QC assignment mainly aim to investigate the scheduling efficiency of QCs and seldom concern CO_2 emission or other green transportation objectives and the resulting models are normally mixed-integer programming (MIP) problems and solved heuristically. Table 1 lists some major traditional models for QC assignment in terms of model objective, model type and algorithm. As shown in Table 1, Daganzo (1989) introduced an exact MIP for the loading of ships,

* Corresponding author.
E-mail address: yege@shmtu.edu.cn (Y.-E. Ge).

http://dx.doi.org/10.1016/j.trd.2017.06.006

Table 1
Some major traditional models for QC assignment.

Literature	Model objective	Model type	Algorithm
Daganzo (1989)	Minimizing the aggregate cost of delay	MIP	An exact and approximate heuristic solution
Kim and Park (2004)	Minimizing the weighted sum of makespan and the total completion time	MIP	Greedy randomized adaptive search procedure
Lee et al. (2008)	Minimizing the sum of weighted completion times for all ship bays	MIP	Genetic algorithm (GA)
Zhang and Kim (2009)	Maximizing the number of dual cycle operations of QCs	MIP	Hybrid heuristic approach
Chung and Choy (2012)	Minimizing the weighted sum of makespan and the total completion time	MIP	GA
Diabat and Theodorou (2014)	Minimizing the time required for completion of the handling of the latest ship	MIP	GA
He et al. (2015)	Minimizing the total departure delay and the total energy consumption of all vessels	MIP	GA and particle swarm optimization algorithm (PSO)

assigning cranes to bays for certain time slots. The objective was to serve all ships and minimize the aggregate cost of delay. Both an exact solution and an approximate one were presented to solve the model. Kim and Park (2004) proposed an MIP model to minimize the weighted sum of the makespan and the total completion time and a heuristic search algorithm, called greedy randomized adaptive search procedure was used to solve the proposed model. Chung and Choy (2012) developed a modified genetic algorithm (GA) for solving the model proposed in Kim and Park (2004).

Lee et al. (2008) proposed an MIP model to minimize the sum of weighted completion times for all ship bays and chose a GA to obtain satisfactory solutions. Zhang and Kim (2009) formulated an MIP model to maximize the number of dual cycle operations of QCs at container terminals and used a hybrid heuristic approach to solve the formulated model. In Diabat and Theodorou (2014), an MIP formulation for QC assignment and scheduling was developed to minimize the time required for completion of the handling of the latest ship, namely the ship carrying the largest number of containers was expected to take the most time at the berth and a GA was used to solve the formulated model.

It can be seen in Table 1 that the objectives of the traditional models for QC assignment are not concerned with CO_2 emission. These models are mainly MIP ones and solved heuristically. Hence, the near-optimal solutions can be obtained but the optimal solutions are not guaranteed. By contrast, the model to be proposed in this paper is to minimize CO_2 emission during unloading containers from QCs to AGVs. It is a convex mathematical programming model, and the analytical solution of the optimal number of QCs can be obtained.

The QC assignment problem (QCAP) refers to the assignment of QCs to vessels while the QC scheduling problem (QCSP) refers to the determination of work plans for the cranes (Bierwirth and Meisel, 2010, 2015). "Typical objectives of the QCAP aim at minimizing crane productivity losses by reducing the number of crane setups at vessels and the crane travel times." A QC scheduling is to determine a starting time of every task for a crane. The usual objective of the QCSP is minimizing the makespan of the QC schedule (Meisel and Bierwirth, 2011). Bierwirth and Meisel (2015) presents a literature review of 120 new publications on berth allocation, QC assignment, and QC scheduling at seaport container terminals.

Table 2 summarizes the crane and truck data for cargo handling in the Port of Los Angeles in 2014 (Starcrest Consulting Group, 2015). The table includes the count of equipment, engine type, annual operating hours, and CO_2 emission. Since the engine type of wharf cranes is electric, its CO_2 emission is not given in this report. The min, max and average power of wharf cranes are also not presented.

From Table 2, it can be seen that the CO_2 emission of QCs for cargo handling is significant, compared with trucks in the Port of Los Angeles in 2014. The total CO_2 emission of QCs for cargo handling is 1594.5 tonnes in the Port of Los Angeles in 2014 while that of trucks is 1725 tonnes. Hence, it is necessary to consider the CO_2 emission of QCs while investigating CO_2 emissions for cargo handling.

Table 2
CO_2 emission of cranes and trucks during cargo handling in the Port of Los Angeles in 2014 (Source: Starcrest Consulting Group, 2015, pp. 39–43[a]).

Equipment		Engine type	Count	Hour average	CO_2 (tonnes)	Percent
Quay crane	Crane	Diesel	9	469	411	48.03%
	Wharf Crane	Electric	84	478	1183.5	
Truck		Diesel	19	960	1725	51.97%
Total CO_2 emissions		–	–	–	3319.5	100%

[a] The CO_2 emission of wharf cranes is not given in this report and is estimated as follows. The wharf cranes in the Port of Log Angeles are provided by Paceco CORP, Mitsubushi, Noell, and ZPMC. The electric Power is 4.16 kV (Yeh et al., 2006). An average power of 40 kW is used for calculation of CO_2 emission. The CO_2 emission coefficient of electricity for the port of Los Angeles is 1073.65 lb CO_2/MW h (1 lb = 0.45359 kg), namely 0.7369 kg/kW h. The CO_2 emission of wharf cranes is calculated by $0.7369 \times 40 \times 478 \times 84 \div 1000 = 1183.5$ (tonnes) (Source: https://www.epa.gov/sites/production/files/2015–07/documents/emission-factors_2014.pdf).

Please cite this article in press as: Liu, D., Ge, Y.-E. Modeling assignment of quay cranes using queueing theory for minimizing CO_2 emission at a container terminal. Transport. Res. Part D (2017), http://dx.doi.org/10.1016/j.trd.2017.06.006