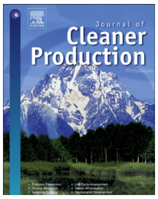
Journal of Cleaner Production xxx (2016) 1–10

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Optimal allocation of resources for yard crane network management to minimize carbon dioxide emissions

Yun Peng [a, b], Wenyuan Wang [a, b, *], Xiangqun Song [a, b], Qi Zhang [a, b]

[a] *Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, 116023, PR China*
[b] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, 116023, PR China*

ARTICLE INFO

Article history:
Received 7 February 2015
Received in revised form
28 January 2016
Accepted 28 April 2016
Available online xxx

Keywords:
Container terminals
Container gantry crane
Energy replacement management
Carbon emission reduction

ABSTRACT

Electric rubber tire container gantry cranes (ERTGs) have already been widely used to replace rubber tire container gantry cranes (RTGs) in many ports of the world, especially in China. ERTGs can reduce carbon dioxide emissions by shifting energy demand from diesel to electricity (energy replacement). It takes almost 6–12 months to change a RTG to an ERTG, and the changed yard cranes cannot work during the replacement phase due to the mechanical reformation and electrical power system construction etc. Therefore, the yard crane network will generate bottlenecks in the container flow and influence the service level when energy replacement happens. This paper focuses on the problem of allocating limited resources for yard cranes to reduce the carbon emissions. The main challenges are how to solve the energy replacement problem at a network level and how to cope with the high uncertainties in the container terminal transportation network. Therefore, we model the energy replacement problem with the purpose of minimizing the carbon emissions by combining an allocation resource mathematical model and a simulation model of the whole transportation network together. The first stage of the energy replacement problem is to make energy replacement decisions each year, while the second stage is to evaluate the value of a seaport's service level based on the realized decisions by running the simulation model. However, the service level indicator is a random variable dependent on the decisions in the mathematical model, which should be controlled to make the seaport work normally at a network level. As an example, the optimization and simulation procedures are applied to a major container terminal in China. The proposed model is general and can be applied to the energy replacement problem of any other seaport.

1. Introduction

Climate change is one of the most pressing issues faced by the world. In China, it is imperative to reduce carbon emissions in the transportation sector since it accounts for almost 10% of all sectors in recent years. As the largest contributor to carbon emissions, China released the No. 315 document in 2011, which set a target of reducing carbon dioxide emissions per unit of port throughput by 10% in seaports (Ministry of Transport, China, 2011). Seaports are important hubs and major energy consumers in the logistic chain of the transportation sector. Reducing carbon emissions and energy consumption in the seaports is crucial to achieving the climate goal. Therefore, as one of the major energy consumption equipment in seaports, container gantry cranes have already been changed from diesel drive into electric drive (energy replacement) in many Chinese ports. For a container terminal (CT), electric rubber tire container gantry cranes (ERTGs) are widely used to replace rubber tire container gantry cranes (RTGs) in many seaports (Xu, 2011; Fu, 2009). For example, an energy replacement project was initiated in Tianjin Port since 2008. 57 RTGs were changed in 2 years, which could save almost 13 thousand tons of standard coal equivalent per year after the project, and the unit energy consumption of yard cranes would be reduced by almost 80% after energy replacement (Cui, 2011). Energy replacement appears as one of the effective methods to reduce energy and carbon emissions. Since 2013, it has taken more than 40 million dollars to change 132 RTGs to ERTGs in Tianjin port, which can save about 33.7 thousand tons of carbon dioxide emissions per year. Therefore, it naturally raises a question: How should limited resources be allocated to competing RTGs for energy replacement so that the total carbon dioxide emissions emitted by yard cranes are minimized?

---

* Corresponding author. Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, 116023, PR China.
E-mail address: wangwenyuan@dlut.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.jclepro.2016.04.120
0959-6526/

Yard cranes (ERTGs or RTGs) are among the most crucial vulnerable components of a CT transportation network. They are also the most popular container handling machines for loading containers onto or unloading containers from trucks. However, individual components in a CT transportation network are not independent of each other. Any change in the network may have a significant impact. For example, when energy replacement happens, the yard cranes (YCs) cannot work during this period of time (It takes almost 6–12 months to change a RTG to an ERTG, including the mechanical reformation, electrical power system construction and the foundation construction. Besides, the cost of changing a RTG to an ERTG is about 300 thousand dollars, which depends on the reformation technology design and how many RTGs are changed together.), which may affect the connections between the yard and berths or gates in the CT transportation network. Therefore, the energy replacement decisions should be made at a network level.

There are many uncertainties in the CT network, such as the disasters caused by natural or human factors, the collisions of vessels or trucks, and mechanical failures etc. The random factors lie in all aspects of the network, which makes deterministic modeling techniques less relevant. Most studies about resource allocation models for a CT are focused on the berth and quay crane allocation problems. For example, Imai et al. (2008) addressed efficient berth and crane allocation scheduling at a multi-user container terminal by employing the genetic algorithm. They developed a heuristic to find an approximate solution, which is determined by a maximum flow problem. Then, Bierwirth and Meisel (2010) reviewed the relevant literature to provide a support in modeling problem characteristics and in suggesting applicable algorithms for berth allocation problems and quay crane scheduling problems. They developed new classification schemes for the problems, including the NP-hard berth allocation problem based on different vessels arrival times and handling times etc. Zampelli et al. (2013) proposed a novel approach based on constraint programming to combine berth and crane allocation. The costs of berth allocation, crane allocation, time windows, breaks and transition times during gang movement are optimized simultaneously. However, there are fewer studies on yard crane resource allocation problems, and most focuses on the problems of yard crane scheduling and deployment. Zhang et al. (2002) addressed the yard crane deployment problem by using a mixed integer programming model to minimize the total delayed workload in the yard. Given the forecasted workload of each block in each period of a day, the object was to find the optimal times and routes of crane movements among blocks. Based on mathematical models and algorithms, Murty et al. (2005) developed a decision support system to make the best use of the storage and minimize the berthing time of vessels, the waiting time of customer trucks, and the congestion on the roads. Ng and Mak (2005) found that the yard cranes were bulky, and often generated bottlenecks in the container flow due to their slow operations. It was essential to develop good yard crane work schedules to ensure a high throughput. Therefore, they proposed a branch and bound algorithm to schedule yard cranes with minimizing the sum of job waiting times. Kang et al. (2008) used a cyclic queue model to obtain the size of cranes and trucks, and an approach based on Markovian decision process was also proposed to provide dynamic operational policies for fleet management considering the distributed crane service times and truck travel times. Li et al. (2009) developed an efficient model for yard crane scheduling by taking into account realistic operational constraints such as inter-crane interference, fixed yard crane separation distances and simultaneous container storage or retrievals.

However, a CT system is very complex, including the process of vessels arriving or leaving though the waterway, vessels waiting for berthing and being handled by quay cranes, containers being transported to yards, berths or gates by trucks, and containers being handled by YCs etc. It's very hard to describe the problem by a stochastic programming mathematical model. In order to cope with the high uncertainty involved in the complex system, a simulation model is always used to solve the YC network problem. For example, Chang et al. (2011) developed a novel dynamic rolling-horizon decision strategy for yard crane scheduling. Due to the computational scale with regard to the yard crane scheduling problem, a heuristic algorithm, along with a simulation model, was then applied. In this case, they investigated a simulation model to alternate the periods and evaluate the task delaying. Marinov and Viegas (2009) built an event-based yard simulation model to simulate the flat-shunted yard operations, which took the shape of queuing network. The components of the queuing network were interconnected queuing systems that interacted with and influenced one another, so that the global impact of freight train operations were captured.

Nonetheless, the literature mentioned above was studied without considering the overall performance of a CT transportation network. Most exiting research only considers the benefits of ports or vessels. For example, Petering and Murty (2009) used the quay crane work rates to present the long-run performance of a seaport by building a discrete event simulation model. However, the quay crane work rates can not reflect how well the port provides service to vessels directly. The service level of a port is often selected as a comprehensive index on behalf of the whole performance of a seaport considering the benefits of ports and vessels (Wang, 2011), which will be discussed more in detail in the next section. Therefore, this paper will introduce a mathematical model for supporting energy replacement decision making, considering both investment amounts and carbon emissions. The investment amount is considered by taking into account a budget constraint, which is very useful for the ports controlled by the government. Sometimes, the government financial investment is very limited. In the paper, we will also discuss how the budget value can influence the energy replacement decision making. Otherwise, since the decision making problem should be made at a network level, a simulation model is built to study the impact of energy replacement decisions on the overall performance of a CT transportation network.

Another challenge in energy replacement decision problem is how to estimate the carbon emissions emitted by YCs. Most of the previous studies on energy replacement problem are concerned with the technological change design. For example, He (2008) described different performances of three-type (electrical cable reel, low-level electrical sliding and high-level electrical sliding) ERTGs, and compared the three types of ERTGs in cost, structural design and different application effects. Wang (2010) studied the characteristics of ERTGs and used a practical project to show how to schedule ERTGs. Zheng (2007) introduced two types of energy replacement design with different electric power. Several studies focused on the different energy consumption cost and carbon emissions between RTGs and ERTGs. For example, Yang (2009) was among the first to investigate the differences between RTGs and ERTGs, such as the handling rate, the energy consumption, and the lifetime. Later, Peng (2010), Qing (2010), and Liu et al. (2011) collected the carbon emission data from different ports and found that the operating cost was reduced after changing YCs from RTGs to ERTGs. Su (2006) analyzed the costs of RTGs and ERTGs, including the labor cost, the maintenance cost, and the energy consumption cost. In addition, Peng (2012) calculated the carbon emissions based on the given energy consumption value of each YC by collecting the data from 24 YCs. After comparing the direct and