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# Yard crane scheduling in a container terminal for the trade-off between efficiency and energy consumption

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ABSTRACT

Green transportation has recently been the focus of the transportation industry to sustain the development of global economy. Container terminals are key nodes in the global transportation network and energy-saving is a main goal for them. Yard crane (YC), as one type of handling equipment, plays an important role in the service efficiency and energy-saving of container terminals. However, traditional methods of YC scheduling solely aim to improve the efficiency of container terminals and do not refer to energy-saving. Therefore, it is imperative to seek an appropriate approach for YC scheduling that considers the trade-off between efficiency and energy consumption. In this paper, the YC scheduling problem is firstly converted into a vehicle routing problem with soft time windows (VRPSTW). This problem is formulated as a mixed integer programming (MIP) model, whose two objectives minimize the total completion delay of all task groups and the total energy consumption of all YCs. Subsequently, an integrated simulation optimization method is developed for solving the problem, where the simulation is designed for evaluating solutions and the optimization algorithm is designed for exploring the solution space. The optimization algorithm integrates the genetic algorithm (GA) and the particle swarm optimization (PSO) algorithm, where the GA is used for global search and the PSO is used for local search. Finally, computational experiments are conducted to validate the performance of the proposed method.



## 1. Introduction

The rapidly increasing concentration of pollutants in the environment has become a world-wide concern. Climate change due to carbon dioxide emissions from transportation is considered to be a significant environmental threat [1–3]. Not only do we have climate problems but we are also dealing with a resource depletion issue, especially energy resources, like oil, gas and coal. As a result, green transportation has recently been the focus of the transportation industry to sustain the development of global economy. Container terminals are key nodes in the global transportation network. Because of the considerable number of pieces of large handling equipment, container terminals play a significant role in energy consumption and pollutant emission in the entire container transportation network. Therefore, the operators of container terminals are facing the pressure on energy-saving and emission reduction. Accompanied with the world economic crisis, the competition among container terminals is getting fiercer and fiercer. Container terminals have to improve their service efficiency to attract more customers in the fierce competition environment. At the same time, the improvement of service efficiency cannot be implemented at the expense of the environment. Thus, the goal of container terminals at the operational level is to seek the optimal trade-off between energy-saving and service efficiency improvement. Since the energy consumption and service efficiency of container terminals are mainly contributed by the handling equipment, the scheduling of the handling equipment is critical.

The total energy consumption cost of the handling equipment of a container terminal is between 15% and 25% of the total cost of operations [4]. Yard crane (YC), as the most frequently-used handling equipment in a container yard, accounts for approximately 25–35% of the total energy consumption cost [5]. For example, the energy consumption of a container terminal in Tianjin port in 2013 was around 47,000,000 kW h for handling 2,320,000 twenty-foot equivalent units (TEUs), in which around 14,100,000 kW h was consumed by YCs.

YCs mainly perform four types of storage and retrieval operations, i.e., (1) storing import containers from vessels, denoted as SI; (2) retrieving import containers for carriers, denoted as RI; (3) storing export containers from carriers, denoted as SE; and (4) retrieving export containers for vessels, denoted as RE [6]. YC

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scheduling directly impacts the completion time of these operations and the total energy consumption of all YCs. As the importance of YC scheduling on service efficiency has been noticed for a long time, a number of studies have developed new operational approaches that can solely improve the efficiency of container terminals [7]. However, traditional methods of container terminal operations generally do not take into consideration energy-saving at the operational level. Thereby, this paper seeks an appropriate approach for the YC scheduling problem by considering the optimal trade-off between service efficiency and energy consumption. This paper is organized as follows. Section 2 reviews relevant literature. Section 3 describes our problem and converts it into a vehicle routing problem with soft time windows (VRPSTW). In Section 4, a mixed integer programming (MIP) model is formulated. A simulation optimization method is proposed in Section 5, and numerical experiments are presented in Section 6. Conclusions and future research are given in the last section.

## 2. Literature review

To date, there have been numerous studies on scheduling various handling equipment in container terminals, such as quay crane scheduling, YC scheduling and internal truck scheduling [8,9]. Most of these studies are devoted to promote the handling efficiency, whereas only a small number of works address the energy-saving of container terminals at the operational level. In this section, a brief review of studies highly related to YC scheduling and energy-saving of container terminals is provided.

For energy-saving of container terminals, most studies are focused on the macro level, such as green management practices, green port policies, and the impact and evaluation of carbon dioxide emissions [10–14]. In the scarce literature on energy-saving at the operational level, Chang et al. [15] optimized the combined problem of berth allocation and quay crane assignment by developing a rolling-horizon model based on objective programming. In their work, quay crane's energy consumption was considered. However, this work is indirectly biased towards energy consumption of quay cranes, which considered energy consumption could be reduced based on the constraint of vessel departing on time and the less the energy consumption of a quay crane per unit move. Du et al. [16] proposed an enriched berth allocation model considering the fuel consumption of vessels sailing to a focal port. The model calculated the vessel emission in the sailing periods using the widely-used emission factors, and analyzed the emission in the mooring periods through a post-optimization phase based on the waiting time of the vessels. Esmemr et al. [17] proposed a simulation model to discuss environmental damage caused by handling equipment in cargo handling operations of a Turkish port, and to obtain the optimal number of equipment to deploy to minimize the environment damage. Golias et al. [18] presented a berth-scheduling problem to minimize vessels' total departure delay and thereby indirectly reduce the total fuel consumption and emissions produced by the vessels while in transit to their next ports of call. Vessel arrival times were considered as a decision variable and were optimized to achieve the objective of departure delay minimization. The optimal vessel speeds were hence calculated and provided to ocean carriers. He et al. [19] presented an integer programming model for sharing internal trucks among multiple container terminals, where the minimization of transportation energy consumption was considered as one of two objectives. Alvarez et al. [20] proposed a simulation model to evaluate the potential benefits of berthing policies and shipping contracts, where marine fuel consumptions of the vessels were considered as a function of their sailing speeds. It can be seen that the above-mentioned studies on energy-saving mainly consider the cooperation between terminals and shipping lines to optimize vessel fuel consumption, rather than focus on the trade-off between energy consumption and operation efficiency at a container terminal.

Specifically for YC scheduling, most research uses operations research and/or simulation. Kim and Kim [21] developed a MIP model for a single YC scheduling problem, and an optimal routing algorithm for a transfer crane was proposed. Similarly, a GA was used for solving the same problem [22]. Moreover, Narasimhan and Palekar [23] developed an integer programming model for the transtainer routing problem, and designed a heuristic algorithm to solve the matching problem on a line at the root node of the branch-and-bound tree. Ng and Mak [24] addressed the problem of scheduling a yard crane that performs a given set of loading/unloading jobs with different ready times. The objective was to minimize the sum of job waiting times. A branch-and-bound algorithm was proposed to solve the scheduling problem optimally, embedding efficient and effective algorithms for finding lower and upper bounds. Zhang et al. [25] presented a MIP model for dynamic YC deployment to find the times and routes of crane movements among blocks, subject to the minimization of the total delay of the workloads. The model was solved by Lagrangean relaxation. To minimize the total unfinished workload at the end of each time period, Cheung et al. [26] formulated a mixed-integer linear program for the yard crane scheduling problem, and proposed a successive piecewise-linear approximation method for solving the problem. Ng [27] addressed the problem of scheduling multiple yard cranes with inter-crane interference in a yard zone to minimize the sum of truck waiting times in yard. Chen et al. [28] presented an integrated model to schedule yard cranes. The problem was formulated as a Hybrid Flow Shop Scheduling problem with Precedence and Blocking constraints. Cao et al. [29] focused on providing an efficient operation strategy for the double-rail-mounted gantry crane systems to load outbound containers. A MIP model was developed to formulate the problem, and a greedy heuristic algorithm, a simulated annealing (SA) algorithm and a combined scheduling heuristic were used to solve the proposed problem. Li et al. [30] developed an efficient model for YC scheduling that takes into account realistic operational constraints such as inter-crane interference, fixed YC separation distances and simultaneous container storage/retrievals. The model could be solved efficiently using heuristics and a rolling-horizon algorithm, yielding near optimal solutions in seconds. Petering and Murty [31] presented a simulation model to evaluate the blocks' length in a container yard and different YC scheduling strategies among blocks in the same zone. The experiments showed that the simulation model can be suitably customized to real, pure-transshipment ports. He et al. [32] developed an objective programming model for a YC scheduling problem based on a static rolling-horizon approach. In their work, a hybrid algorithm, consisting of a parallel GA and heuristic rules, was applied. Simulation was employed for evaluation. Chang et al. [33] proposed a dynamic rolling-horizon decision-making strategy for a YC scheduling problem, which can obtain more near optimal solutions than those generated by the corresponding static rolling-horizon approach.

Overall, YC scheduling is a well-researched domain. There are plenty of papers in this area. However, to the best of our knowledge, few scholars have considered energy-saving in their YC scheduling models. Our study thus fills in the gap in the literature on the conventional YC scheduling problem.

## 3. Problem description

### 3.1. Construction of task groups

In YC scheduling, a task means one move of a YC for loading/unloading containers, which may be one or two 20 feet containers,