Deploying Charging Stations for Battery-powered AGVs in Automated Container Terminals

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ABSTRACT

With the rapid development of battery and automated guided vehicle (AGV) technology, many mega ports plan to deploy battery-powered AGVs in the near future. The deploying charging stations for the battery-powered AGV (B-AGV) in terminals concerns a long-term decision on the capacity planning of charging stations and a short-term decision on charging control strategies for B-AGVs. As container terminal is a large-scale complex system, solving mathematical programming model is neither practical nor accurate. Hence a simulation approach is desired, which is easy to evaluate the performance of charging stations for the B-AGVs. This paper presents a simulation framework for deploying charging stations for the B-AGVs in terminals. We first describe the detailed factors in capacity planning of charging stations. Next, we show the framework and main modules in the terminal simulation model. Finally, we present comparison results when the number of charging stations varying. The proposed framework helps port managers to deploy the charging stations for the B-AGVs in terminals. Moreover, it also helps evaluate and improve the terminal performance in practice.

KEYWORDS: Automated container terminals; Battery-powered AGVs; Capacity planning; Simulation optimization;

1 INTRODUCTION

In the past decades, most ports utilize diesel engines to power terminal equipment, such as quay cranes, yard cranes, automated guided vehicles (AGV), and trucks (Lam et al., 2014). The diesel engines have the advantages of high-power and cost-efficient, while they also produce high pollution. Moreover, the diesel price fluctuates along with the change world. Hence, the ports are very interesting in alternative reliable energy sources. The electric power is one of the best choices because of zero emission and stable price (Zhu et al., 2018). With the rapid development and application of electric vehicles, the latest battery technology has guaranteed the carrying capability and durability of battery-powered AGV (B-AGV) under heavy-loaded situation. In the long term, B-AGVs are more beneficial than diesel AGVs because the reduced maintenance and energy cost can offset the higher initial acquisition cost (Schmidt et al., 2015). Now the deployment of B-AGV system is spreading fast around the world. For example, in Germany, HHLA Container Terminal Altenwerder has been testing and using B-AGVs for port operations since 2016; in China, Shanghai Yangshan port has the largest number of B-AGVs (130 units) in operation (Song and Ravesteijn, 2015); in Singapore, a living lab with nearly 30 B-AGVs is testing and for Next Generation Port at Tuas which may need nearly 400 B-AGVs per terminal.
Comparing with common transportation system, the B-AGV system need to deploy charging stations to recharge the battery. There are many factors that would strongly affect the performance of the B-AGV system, such as the location and capacity of charging stations, charging modes, charging control strategies, and battery types. For example, the major difference between the battery and diesel AGVs is the refilling time. The diesel vehicles only need just a few minutes to refill, while the B-AGVs may need 20 minutes or more to charge a battery from empty to full (Kawakami and Takata, 2012). Hence, the ports should build suitable number of charging stations to fulfil charging tasks of each B-AGV. However, currently there isn’t any efficient framework to help design the charging stations in the terminals and evaluate their performances. As container terminal is a large-scale complex system, solving mathematical programming model is neither practical nor accurate (Nam et al., 2002). Hence a simulation approach is desired, which is easy to evaluate the performance of charging stations for the B-AGVs. This paper presents a simulation framework for deploying charging stations for the B-AGVs in terminals.

2 FACTORS IN CAPACITY PLANNING

A simulation optimization framework is proposed to determine the capacity planning for mega container terminals in terms of the number of three types of resource (Li et al., 2017). In this study, we are interested in other design factors which will affect the performance of the terminal system. When deploying the B-AGV system, the following factors show important significances.

2.1 Charging modes

Two charging modes have been implemented in actual operation as shown in Figure 1, i.e., the Vehicle charging mode (VCM) and the Battery swapping mode (BSM) (Mukherjee and Gupta, 2015). In VCM, the vehicles need to park at stations to charge, and depart after several time. Since each charging station only occupy a small space and the capacity is one, several stations are required to be deployed across the yard. In BSM, vehicles can swap a battery in a few minutes and depart right after swapping. This mode requires battery swapping station which takes a larger space and can only be placed at the boundary area. In addition, extra batteries are needed for swapping.

![VCM and BSM](image)

Figure 1: Two B-AGV charging modes

2.2 Location and capacity designs of charging stations

The location design of charging stations has two main choices, i.e., centralized and decentralized layouts, as illustrated in Figure 2. In the centralized layout, the charging stations will be allocated together in the top area of the terminal, while in the decentralized layout, the charging stations will be allocated uniformly in the end points of yard blocks.

The location choosing is related to the battery charging modes. Usually, the VCM selects the decentralized layout, while the BSM chooses the centralized layout. The centralized layout of charging stations occupied less land than the decentralized layout. However, the B-AGVs travel longer distance to access the charging station in the centralized layout than the decentralized layout. In addition, the centralized layout may incur more safety issues on operating the terminal.
The capacity design of charging stations is also a significant factor affecting the system performance (Bai et al., 2019). It is important to build an adequate number of charging stations for the benefit of acceptable charging waiting time of vehicles. However, the construction cost of building charging stations is considerable expensive. Hence, the ports should build a suitable number of charging stations to fulfill charging tasks of each B-AGV. In general, it is a trade-off between efficiency, space, and cost.

2.3 Charging control strategies

Different with the traditional diesel vehicles, the B-AGVs need longer time to refill the batteries. Therefore, the charging control strategies will also significantly affect the system performance. There are three key factors to be determined for the B-AGV system, i.e., when, where and how much. The charging control strategies could be divided into two types, i.e., rule-based strategy and the smart strategy. The rule-based strategy is quite simply to implement, where the vehicles will be charged when they reach the given rules. For example, if the remaining battery of the vehicle is below 30%, it will be charged to full capacity. The smart strategy is more intelligent than the rule-based strategy, where the vehicles will be charged dynamically based on the workload of the terminal and vehicle conditions.

2.4 Battery types

There are four types of battery technologies used in practice, i.e., high capacity fast charging, high capacity slow charging, low capacity fast charging, and low capacity slow charging (Bansal, 2015). The differences between the technology will affect the price and service time. The most powerful battery is the high capacity fast charging, which has longer service time but with highest price. The most economical is the high capacity slow charging, of which the price is acceptable.

3 FRAMEWORK OF SIMULATION MODEL

The framework of the simulation model follows the operation process in the automated container terminal, which is illustrated in Figure 3. The vessels arrive the terminal and be assign to the berths according to the sizes. The tasks information will be sent to the port, which contains the loading/unloading containers. The central system will determine the schedules to process the containers. Then the quay cranes, yard cranes, and B-AGVs will perform the schedules. The loading containers will be first retrieved from yard blocks by yard cranes, then conveyed to berths area by B-AGVs, finally lifted to the vessels by quay cranes. The unloading containers will go through the reverse process. In addition, the B-AGVs will be charged following to the designed rules.
The terminal simulation model consists of three main components, layout module, control module, and parameter module. The layout module denotes the locations and topological relationships of the physical entities in terminal. The physical entities consist of vessels, quay cranes, yard cranes, yard blocks, containers, charging stations, B-AGVs, and outside trucks. The control module determines the operation process of the physical components. The parameter module determines the input and output parameters used in the system.

3.1 Layout module

The layout module is referred to the map of the terminals. It expresses the topological locations of the physical entities. The berths are located at the edges of the terminal facing the sea. The quay cranes are equally located at the berth area. The layout of yard blocks has three types, i.e., perpendicular, parallel, and hybrid layouts. In perpendicular layout, the long side of yard block is vertical to the long side of terminal berths, while in parallel layout, the long side of yard block is horizontal to the long side of terminal berths. The hybrid layout comprise a mixture of the above two types of layouts (Zhou et al., 2016). Each block has two yard cranes retrieving and storing containers. The traveling paths link between the berths and blocks, on which the B-AGVs move. For a given terminal layout, the distances between each entity are also determined.

3.2 Control module

The central level in the control module is terminal operation system (TOS), which consists of operation planning system (OPS) and equipment control system (ECS). The ECS contains quay crane management system (QCMS), block management system (BMS), and vehicle management system (VMS). The framework of TOS is illustrated in Figure 4. The OPS determines the central plan and allocates the berths, quay cranes and block area to the arrival vessels. Then the ECS will arrange the equipment and perform the schedules. The QCMS, BMS, and VMS will control the corresponding equipment to carry out the tasks. The control module significantly affects the traffic efficiency in the container terminal. The container processing sequence, container storage strategies, and vehicle moving strategies dynamically interact with each other and further influence the system performance (Zhou et al., 2017). We applied their strategies to handle with control module.
3.3 Parameter module

There are three types of parameters utilized in the simulation model, i.e., input, intermediate, and output parameters (Angeloudis and Bell, 2011). The input data contains basic information of terminal layout, technological parameters of each physical module, and information of tasks. The intermediate data are information generated in the simulation process, like battery statuses of each B-AGV and the processing time of each container. The output parameters are the key performance of the terminal, like throughput, average waiting time of the B-AGVs, and utilization of quay cranes, yard cranes, and charging stations. Table illustrates the main parameter used in the simulation model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Port: berths, blocks, topological graph of terminal layout.</td>
</tr>
<tr>
<td></td>
<td>Crane: quay cranes, yard cranes, processing time of quay and yard cranes</td>
</tr>
<tr>
<td></td>
<td>Task: vessels, arrive and departure time of vessels, loading and unloading containers, initial position of containers</td>
</tr>
<tr>
<td></td>
<td>Charging station: charging time for B-AGV from one status to full condition</td>
</tr>
<tr>
<td></td>
<td>B-AGV: battery capacity, battery consumption of travel activity on empty and loaded statuses</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Crane: time of quay cranes and yard cranes processing the containers</td>
</tr>
<tr>
<td></td>
<td>Task: allocation berth of each vessels, destination position of containers, processing sequence and time of containers</td>
</tr>
<tr>
<td></td>
<td>Charging station: time of station charging the vehicles</td>
</tr>
<tr>
<td></td>
<td>B-AGV: battery status of vehicles, time of vehicles processing the containers</td>
</tr>
<tr>
<td>Output</td>
<td>Port: annual throughput, wharf length utilization</td>
</tr>
<tr>
<td></td>
<td>Crane: quay cranes and yard cranes utilization</td>
</tr>
<tr>
<td></td>
<td>Task: finish and delay time of vessels</td>
</tr>
<tr>
<td></td>
<td>Charging station: charging station utilization</td>
</tr>
<tr>
<td></td>
<td>B-AGV: average time of vehicles waiting for charging, vehicles utilization</td>
</tr>
</tbody>
</table>
4 SIMULATION RESULTS

This section presents the simulation results for capacity planning of charging stations for the B-AGVs in terminal. Deploying charging stations in the port is a quite complex problem and the simulation model is a useful approach to solve it. In order to integrate difference modules/functions/algorithms, etc. we need a framework with good modularity (Zhou et al., 2018). An object-based discrete event simulation platform, named O’DES.Net, is an open-source and open-structured simulator. This study applies the framework to build the simulation model.

Singapore’s Tuas mega port plans to operate in 2021, which is a major milestone in Singapore’s next generation port. Green devices will be deployed in this port, including B-AGVs. Then we run the simulation model on a terminal of Tuas port. The wharf length indicates the size of the terminal, which is 8400 meters. The hourly rates of quay cranes, yard cranes and vehicles are average values from statistic data in practice, which are 60, 30 and 24 separately. The number of B-AGVs is 400 and the expected annual throughput is 20 million TEUs/year, which denote the requirements of port managers. The average moving speed for the B-AGV is 4.5 m/s. The yard block is on perpendicular layout, the charging station is on decentralized layout, and the battery type is high capacity fast charging in the model. The charging control strategy is the rule-based strategy, where the threshold value for recharging is 20%. The recharging setup time for B-AGV is 5 minutes. The discharging rate for the battery is 20% SOC/hour and charging rate is 4% SOC/min. The other parameters in the experiment can be referred to the work of Li et al., 2017.

After several initial simulation experiments based on the specified experiment setting, we consider the number of charging stations varying from 16 to 32. For every scenario of number of charging station, we run 5 random instances and obtain average simulation results. Four important output parameters are chosen to evaluate the performance of the B-AGV system, i.e., quay crane utilization, yard crane utilization, charging station utilization, and proportion of B-AGV waiting for charging. Table 2 presents the simulation results when the number of charging stations varying. The first column is the number of charging stations, and the following four columns are the performance parameters.

<table>
<thead>
<tr>
<th>Number of Charging stations</th>
<th>Quay crane utilization(%)</th>
<th>Yard crane utilization(%)</th>
<th>Charging station utilization(%)</th>
<th>Proportion of B-AGV waiting for charging(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>27.94</td>
<td>50.62</td>
<td>99.05</td>
<td>14.39</td>
</tr>
<tr>
<td>20</td>
<td>30.29</td>
<td>52.52</td>
<td>97.89</td>
<td>7.57</td>
</tr>
<tr>
<td>24</td>
<td>29.61</td>
<td>52.63</td>
<td>86.04</td>
<td>3.27</td>
</tr>
<tr>
<td>28</td>
<td>29.53</td>
<td>52.41</td>
<td>74.23</td>
<td>2.69</td>
</tr>
<tr>
<td>32</td>
<td>29.35</td>
<td>52.56</td>
<td>32.77</td>
<td>2.37</td>
</tr>
</tbody>
</table>

The first row in Table 2 shows the results when charging stations are insufficient. The charging station is under full work load and the B-AGVs need more time of waiting for charging. As the number of charging stations increases, the charging station utilization and proportion of B-AGV waiting for charging decrease. When charging stations is adequate, utilization of quay crane and yard crane have no significant change. The results show that for a given configuration, utilization of quay crane and yard crane is weakly related to charging stations. The capacity of charging station has significant influence on the B-AGVs. The more charging stations, the less proportion of the B-AGV waiting for charging. For the given configuration, the optimal number of charging stations is around 24. The final selection will be determined by port managers with consideration of cost and other issues.
5 CONCLUSIONS

Many mega ports plan to substitute the diesels AGV with battery-powered AGV considering zero pollution emission and stable electric price. Based on the current battery technologies, there are different choices on deploying charging stations for the B-AGVs in the terminal. As container terminal is a large-scale complex system, solving mathematical programming model is neither practical nor accurate. We presents a simulation framework for deploying charging stations for the B-AGVs in terminals. We show the main factors in capacity planning for charging stations and present the framework and main modules in the terminal simulation model. We also present some comparison results based on the simulation model. The proposed framework helps port managers to deploy the charging stations for the B-AGVs in terminals. Moreover, it also helps evaluate other configurations of the terminal in practice.

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REFERENCES


