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A simulation-based method for analyzing energy demands in container terminals under different arrival interval of ships

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Abstract. The contribution of this paper is to provide a simulation-based method to analyze the highly dynamic energy demands in container terminals under different arrival interval of ships. In order to overcome the complicated and stochastic operation processes in container terminals and obtain the energy demands at each time step, a simulation model is established. Then, various simulation models based on a container terminal in Northeast China are developed and carried out to study the impact of arrival interval of ships on energy demands. Finally, the energy demands in the container terminal are obtained and analyzed after running the simulation models. The results indicate that the energy demands represent a high randomness and large variations. When arrival interval changes from 5 h to 10 h, there is a sharp fall in the daily average energy demands, while as arrival interval changes from 15 h to 20 h, the daily average energy demands mainly concentrate between 0 MW and 1 MW. The obtained results and proposed method can provide references for power department policy making and balancing energy supply and demand in container terminals.

1. Introduction

Due to the heavy handling operation workload, container terminals make a major contribution to energy consumptions and play a key role in environmental issues. Efforts have been made to realize the goals of energy conservation and emission reduction from the perspective of green ports, such as quantitatively analyzing and evaluating the influence of mitigation measures on carbon emissions [1,2], optimizing energy supply structure for ports [3-6]. Among them, a promising avenue for constructing green ports is covering large shares of the energy demands in container terminals with renewable energy. However, due to the stochastic factors on operation processes in container terminals such as random arrival of ships, allocation and scheduling of handling facilities, energy demands represent highly dynamic and uncertain [7], and consequently there is a significant challenge in balancing energy supply and demand. Furthermore, for a real container terminal, it is costly and time consuming to collect real energy demands or energy consumption in handling operation processes. Therefore, an effective method for analyzing energy demands in container terminals is needed for energy supply and demand balances in the power system which provides required energy for handling operation.

Limited research has been devoted to analyzing energy demands in container terminals, and most of related works aim at minimizing energy consumption by optimizing the allocation and scheduling of the port resources, such as berths and handling facilities. Golias et al. [8] formulated the berth-scheduling problem as an optimization model to minimize fuel consumption and emissions of all ships, and developed a genetic algorithm to solve the model. Du et al. [9] presented a berth allocation model

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to reduce fuel consumption and ship emissions, and the results showed that carbon emission reduction of each ship could realize 49.58-143.22 tons on average under different allocation strategies. He et al. [10] optimized transportation energy consumption by presenting an integer-programming model for the internal truck assignment problem. Sha et al. [11] formulated the yard crane scheduling problem as an integer-programming model to minimize the total energy consumption of yard cranes. Chang et al. [12] developed an optimization model for integrating berth allocation and quay crane assignment in a container terminal with consideration of quay crane's energy consumption. He et al. [13] optimized the total transportation energy consumption in a container terminal through integrated scheduling of handling facilities, and obtained the optimal results under different scheduling strategies.

Through analysis of the researches mentioned above, most of the works always quantified the energy consumption of ships or handling facilities under a task or in a certain period firstly, and then took the energy consumption as an objective function or constraint conditions in optimization models for the resource allocating and scheduling problems. However, it is still a challenge to represent the dynamic characteristics of energy demands in container terminals and energy demands for a certain period, due to the interactive and stochastic operation system which is affected by many uncertain factors, such as weather conditions, resource allocation and scheduling. Such a complicated system is difficult or even impractical to be formulated and evaluated by analytical methods, which can be resolved by simulation methods [14].

Therefore, this paper firstly quantifies the required power of a ship during a stay at berth and the required power of handling facilities while handling containers, which is the basis of analyzing the energy demands in container terminals. Then, a simulation model is constructed to present the high uncertainties in the container terminal operation system. Finally, this paper carries out various simulation models to analyze the highly dynamic energy demands in container terminals during a certain period under different arrival interval of ships.

2. Problem description

For constructing simulation models, there are three problems that should be discussed more in detail, including required power of ships and handling facilities, operation systems in container terminals, and analysis on arrival interval of ships.

2.1. *Required power of ships and handling facilities*

Along with ship retrofitting and equipment reformation, container ships and handling facilities (i.e., quay cranes and yard cranes) are mainly supplied with on-shore power and electricity of port power system in the loading/unloading operation processes, respectively. The required power of ships and handling facilities can be defined as total energy consumption divided by each time step. For ships, energy consumption can be expressed as required powers multiplied by staying time at berth [15]. For handling facilities, energy consumption can be determined by the product of the number of handled containers and required electricity for performing each container [1].

Therefore, the energy demands in the container terminals at time step t are obtained by the following equation.

$$P_{R,t} = P_{ship,t} + P_{qc,t} + P_{yc,t} \tag{1}$$

where $P_{R,t}$ is the total energy demands, $P_{ship,t}$, $P_{qc,t}$ and $P_{yc,t}$ is the required power of ships, quay cranes and yard cranes, respectively, which is defined as equation (2)-equation (4).

$$P_{ship,t} = \Delta t^{-1} \cdot \sum_{i} P_{ship,i}^{aux} \cdot t_i \tag{2}$$

$$P_{qc,t} = \Delta t^{-1} \cdot \sum_{j} P_{qc,j}^{power} \cdot n_j \tag{3}$$

$$P_{yc,t} = \Delta t^{-1} \cdot \sum_k P_{yc,k}^{power} \cdot n_k \tag{4}$$

where Δt is the time interval of each time step, $P_{ship,i}^{aux}$ is the auxiliary power of ship *i* at time step *t*, $P_{qc,j}^{power}$ and $P_{yc,k}^{power}$ represent the energy consumption of quay crane *j* and yard crane *k* when handling a container, respectively. t_i is the spending time of ship *i* at berth at time step *t*, n_j and n_k is the number of the handled containers by quay crane *j* and yard crane *k* at time step *t*, respectively.

However, the parameters for quantifying the required power in container terminals, such as t_i, n_j and n_k as in equation (2)-equation (4), are random variables influenced by many stochastic factors, which can result in the large fluctuation of energy demands at different time steps. For example, the unloading efficiency of ships can be time-varying due to weather conditions and etc., which can result in the unpredictable fluctuation of t_i and n_j as in equation (2)-equation (3) at each time step, and consequently influence the energy demand at each time step. Therefore, there is a need to study the operation systems in container terminals to analyze the impact of inherent stochastic factors of the system on the energy demands in container terminals.

2.2. Operation systems in container terminals

The operation processes, including quayside operations, yard operations and gate operations, are always dynamic and interconnected in a container terminal, as shown in figure 1. Making an analysis on system characteristics in container terminals is the basis of developing the simulation models and obtaining the energy demands. The operation systems at least comprise four sub-systems that are dynamic and interconnected: *Ship entering the port and berth allocation* sub-system, *Ship sailing through waterway* sub-system, *Container handling* sub-system, and *Ship departing from the port* sub-system. All these sub-systems require shared resources in container terminals to handle and transport containers: berths, yard and handling facilities. Taking the unloading process as an example, the following specifically discusses the sub-systems.

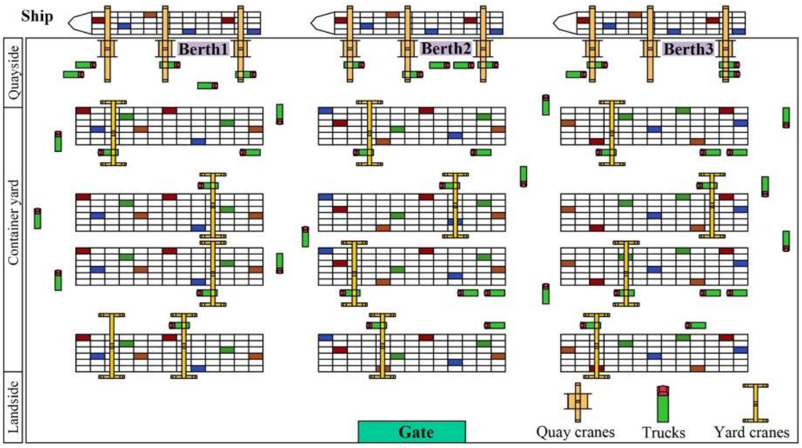

Figure 1. The general layout of a container terminal.

2.2.1. Ship entering the port and berth allocation sub-system. Ship entering the port and berth allocation sub-system consists of the creation of ships and berth allocation to ships. Firstly, ships with various attributions, such as length, tonnages, number of containers, auxiliary operation time and engine power, arrive at port. Then, berths are allocated to ships according to predefined allocation rules. When the berths are occupied, ships will wait in sequence for corresponding idle berths.

2.2.2. Ship sailing through waterway sub-system. In case the berths are idle, the waterway conditions, such as weather status, tide factors and traffic situations, are judged to figure out whether or not ships can sail through the waterway for berthing. When natural conditions, such as weather conditions, and traffic situations in sailing process are satisfied, ships sail through waterway, and moor at the allocated berths.

2.2.3. Container handling sub-system. In case the ship moors at berth and auxiliary work is finished, the assigned handling and transporting facilities begin to handle the containers. Firstly, quay cranes unload containers to the called trucks. Then, the trucks transport the containers to the deployed yard block to wait in queue to stack the containers by idle yard cranes. Finally, when the dispatched yard cranes are free, containers will be set down and stacked.

2.2.4. Ships departing from the port sub-system. After all the handling tasks are finished, the ship is arranged to depart from the port. The waterway conditions as mentioned in section 2.2.2 are still needed to judge before the ship leaves. If any of those conditions is not met, the ship has to stay at berth. And the ship can depart until all the waterway conditions are met.
From the analysis above, the interconnected sub-systems are complex and dynamic, which are impossible to be described by analytical methods. Therefore, this paper develops a simulation method to represent the uncertain and dynamic system characteristics in container terminals.

2.3. Analysis on arrival interval of ships in container terminals
The arrival interval of ships can influence the quantity of ships entering the container terminals and therefore affect the required energy for handling operation over a period of time. According to the data analysis, the arrival interval of ships implies with a certain type of probability distribution in ports [16]. In the long term, the arrival interval of ships in ports is time-varying and fluctuating, which is influenced by port scale, liner service schedule and etc.

When the expected arrival interval is large, which means that the quantity of daily arrival ships is small, low energy supply is adequate to meet the electricity demand for ships and handling facilities. However, with the expected arrival interval gradually decreasing, the quantity of daily arrival ships will increase and thus the quantity of handled containers will raise. There will be a great requirement on electricity for all handling tasks at each time step. From the analysis above, the arrival interval of ships has an important effect on the energy demands in container terminals, and there is a need to quantify the impact of the arrival interval on the energy demands.

3. Simulation model
One major purpose of the simulation model is to output the value of the parameters for quantifying the required power at each time step, such as t_i, n_j and n_k as in equation (2)-equation (4), and another is to represent the stochastic and dynamic operation processes in container terminals. The simulation model is developed by using ARENA 10.0 software, and the modelling process is discussed more in detailed as follows.

3.1. Model assumptions
The simulation model is developed and constructed under the following assumptions.

1) The handling facilities in ports are fully utilized.

2) All facilities work well without consideration of failure and maintenance work.

3) Ships occupy the idle berths by means of fixed berthing rule without regard to flexible berthing rule.

3.2. Model construction
According to the analysis of operation systems above, the simulation model in this paper simulates the whole environment in container terminals considering stochastic factors, and three sub-models by

using ARENA software are included, i.e., *Ship arriving at the port and berth allocating* simulation sub-model, *Container handling* simulation sub-model and *Ship leaving the berth and departing* simulation sub-model, as shown in figure 2.

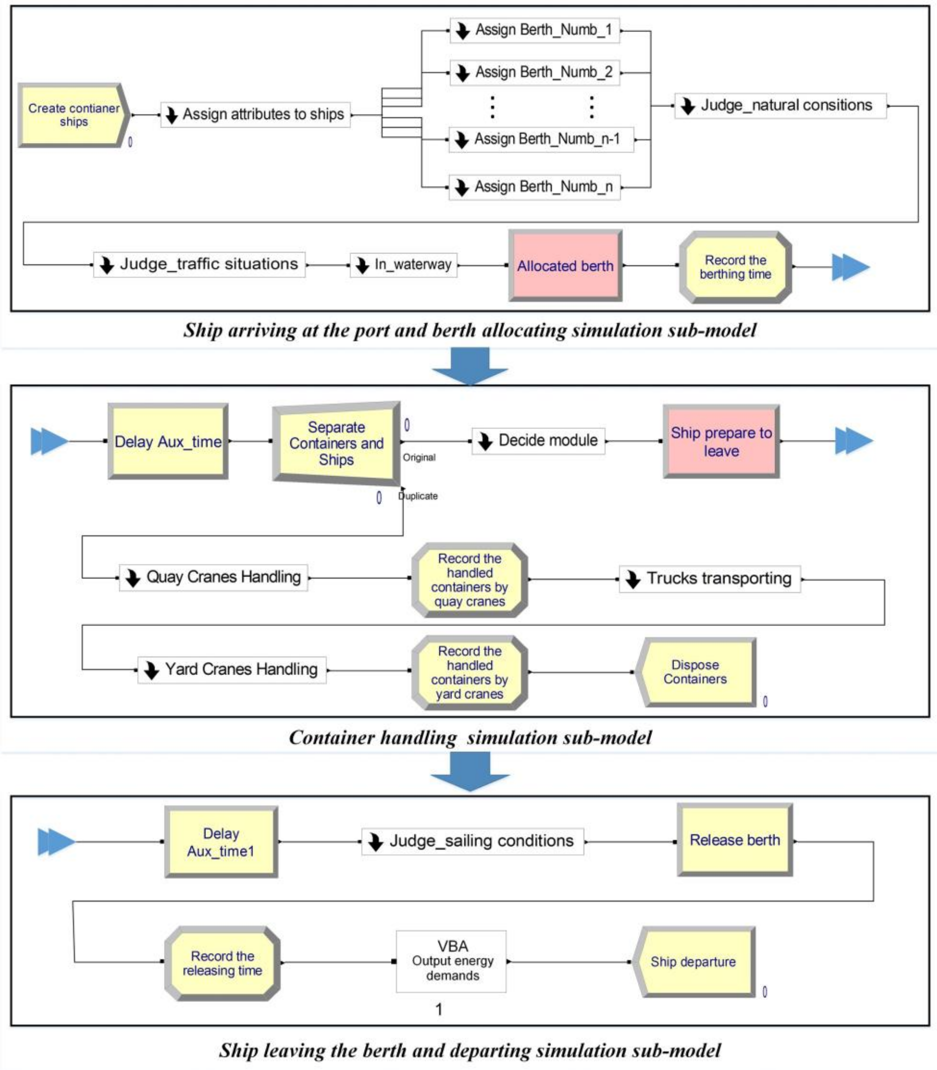

Figure 2. The developed simulation model of the operation system in container terminals.

3.2.1. Ship arriving at the port and berth allocating simulation sub-model. Within the Ship arriving at the port and berth allocating simulation sub-model, arrival ships are generated with arrival interval obeying a predefined distribution according to the real data. Meanwhile, the attributes, such as length, tonnages, number of containers, auxiliary operation time, engine power and etc., are assigned to the arrival ships. Then, the corresponding berths are allocated to ships according to the assignment rules users can define, and ships seize the assigned berth resources by the *Seize* module. Finally, when parallel conditions, i.e. weather status, tide factors and traffic situations in sailing process, are met, ships sail to the corresponding berths. Simultaneously, the berthing time of the ship is recorded in the sub-model, which along with the recorded releasing time is applied to output t_i as in equation (2).

3.2.2. Container handling simulation sub-model. In case the auxiliary preparation work is finished, the process of handling containers from ships begins. Firstly, *Separate* module is used to separate

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containers from ships. Then, containers enter into the handling module by *Duplicate* point, and ships enter into the *Decide* module by *Original* point to figure out whether or not the tasks of handling the containers of the ship is completed. In the handling module, the containers are unloaded by quay cranes, conveyed by trucks and stored by yard cranes, and the *Assign* module is used to output n_j and n_k as in equation (3)-equation (4). Finally, when the tasks of handling the containers of the ship is completed, the ship is arranged to leave the berth.

3.2.3. Ship leaving the berth and departing simulation sub-model. When the waterway conditions, such as weather status, tide factors and traffic situations, are satisfied, ships release corresponding berths through the *Release* module and the releasing time is recorded. Then, the *Assign* module is used to record the releasing time. Next, ships leave the berths, go through the waterway and depart. Finally, the *VBA* module is applied to output the energy demands at all time steps to the external Excel spreadsheet.

4. Case study

4.1. Parameter settings

In this study, a container terminal in Northeast China is taken as the simulation case. The container terminal has five container berths 1#-5#, and the layout diagram are illustrated in figure 3. The parameters of berths, such as berth number, tonnages and the assigned quantity of quay cranes, are presented in Table 1. And the handling efficiency of quay cranes is set as 30 TEU/h. Besides, the waterway is characterized by one-way navigation lane and 20 nm length. In addition, the navigation speed of ships is averaged set as 18.52 km/h. Moreover, the allocating and scheduling rule of resources and other initial input parameters in the simulation model are supplied by the port operators. Furthermore, one year is taken as the simulation time range for analyzing the energy demands, and the total number of all the time steps is equal to 8760. The parameters of ships and handling facilities are presented more in detail as follows.

Table 1. Parameters of Berths in the Container Terminal.

Berth number	Tonnage of berth *DWT* (ten thousand tonnage)	The assigned quantity of quay cranes to each berth
1#	1.5	2
2#	3.5	3
3#	3.5	3
4#	7.0	4
5#	7.0	4

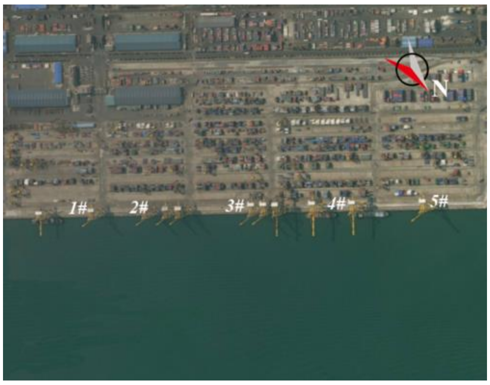

Figure 3. Layout Diagram of the container terminal in this case study.

4.1.1. Parameters of ships. According to the statistical analysis on the collected data in 2016, the arrival interval of ships implies with negative exponential distribution. Considering the influence of uncertain factors, such as port scale and liner service schedule, on the arrival of ships in the long term, this paper takes the expected arrival interval of ships as 5.0 h, 10 h, 15 h, 20 h to study the arrival interval of ships on the energy demands. Besides, the type combinations of ships are listed in Table 2, and the auxiliary operation time for each ship is set as 4.0 h.

Table 2. Type combinations of arrival ships.

Tonnage of ships *DWT* (ten thousand tonnage)	Proportion (%)	Power of auxiliary engines (kw)	Average quantity of handled containers (TEU)	Berth number for ship mooring
0.5	20	320	460	1#,2#,3#
1	20	430	500	1#,2#,3#
2	19.5	700	650	2#,3#
3	20	1260	855	2#,3#,4#,5#
5	10.5	1960	1200	4#,5#
7	10	2320	2400	4#,5#

4.1.2. Parameters of handling facilities. As discussed in section 2.1, the electricity required for performing each container is an essential parameter to calculate the energy demands of handling facilities. Based on the previous studies [1], the electricity consumption rate is set as 5.23 kWh/TEU and 3.02 kWh/TEU, respectively.

4.2. Results

In this section, after conducting the simulation models in the ARENA software platform, the energy demands in the port at all time steps are output and the influence of arrival interval on energy demands is analyzed.

4.2.1. Energy demands in the container terminal. According to the corresponding parameters shown in section 4.1, the energy demands at all time steps are obtained after operating the simulation model. Taking an arrival interval of 10 h as an example, energy demands in hourly time step for one week are as shown in figure 4.

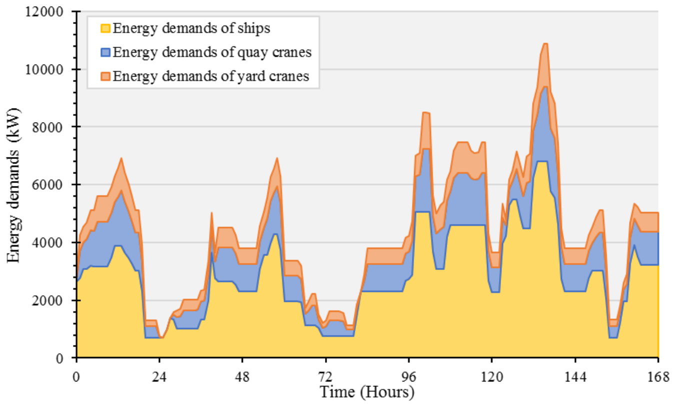

Figure 4. Energy demands in hourly time step for one week.

As illustrated in figure 4, the energy demands represent extreme fluctuation, ranging from 0.7 MW to 10.87 MW. Besides, ships receive the largest share of the total energy demands in the port, secondly by quay cranes and followed by yard cranes.

4.2.2. The impact of arrival interval of ships on the energy demands. For analyzing the impact of arrival interval of ships on energy demands, this paper conducts the simulation models with arrival intervals taken as 5.0 h, 10 h, 15 h, 20 h. Then the statistics of daily average energy demands under different arrival intervals are obtained according to the output results by the simulation model, as shown in figure 5.

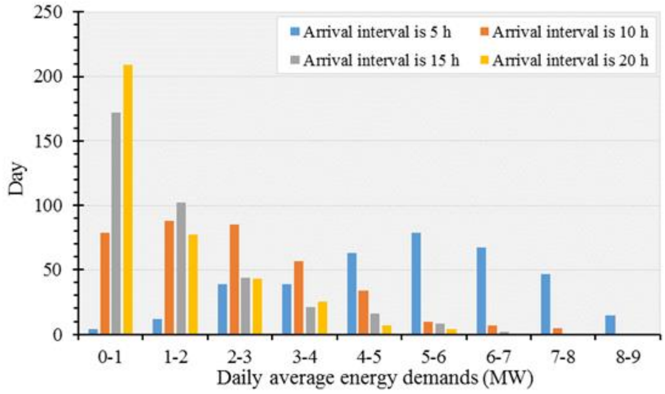

Figure 5. Daily average energy demands under different arrival intervals.

As shown in figure 5, when arrival interval is set as 5 h, the daily average energy demands mainly concentrate between 4 MW and 8 MW. When arrival interval is set as 10 h, the daily average energy demands mainly range from 0 MW and 4 MW. Under arrival interval as 15 h and 20 h respectively, there are 172 days and 209 days when daily average energy demands are between 0 MW and 1 MW. The results indicate that when arrival interval changes from 5 h to 10 h, there is a sharp fall in the daily average energy demands, while when arrival interval changes from 15 h to 20 h, the daily average energy demands mainly concentrate between 0 MW and 1 MW.

According to the simulation method above, the obtained energy demands at all time step can be used to give a reference to schedule the energy supply for realizing the balance between energy demand and supply in port area. Besides, the energy demands under different arrival interval of ships can be used to give a reference for port operators to developing green ports, such as reasonably allocating the capacity of shore-to-ship power at each berth according to the energy demands of ships.

5. Conclusions

The contribution of this paper is to study the energy demands in container terminals by developing a simulation-based method with consideration of the complex and uncertain characteristics of the operation systems. In order to study the impact of arrival interval of ships on energy demands, this paper takes a container terminal in Northeast China as a case example to design and conduct various simulation models. Finally, the energy demands at all time steps are obtained and analyzed by carrying out the simulation models.

1) The proposed simulation model can be used and extended to analyze the energy demands in container terminals with the corresponding parameters about berths, ships and handling facilities and other parameters such as natural conditions, and energy demands represent an extreme fluctuation.

2) When arrival interval changes from 5 h to 10 h, there is a sharp fall in the daily average energy demands.

3) When arrival interval changes from 15 h to 20 h, the daily average energy demands mainly concentrate between 0 MW and 1 MW.

The obtained results and proposed method can give references for power departments to make policy for balancing energy supply and demand in container terminals. However, this paper only considers the influence of arrival interval of ships on energy demands. Future study should introduce a microscopic simulation model to achieve a higher output accuracy on the energy demands when relevant uncertain factors (e.g., schedule scheme of the port resources) are taken into account simultaneously.

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