

Article

A Method for Determining the Required Power Capacity of an On-Shore Power System Considering Uncertainties of Arriving Ships

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Abstract: The contribution of this paper is to provide a method for determining the required power capacity of an on-shore power system (OPS) considering the stochastic nature of arriving ships. In order to cope with such complicated and stochastic operation processes in container terminals, simulation models are established with arrival intervals of ships ranging from 1 to 100 h as inputs. Firstly, the mobile pattern of OPS adopted in the container terminal is introduced. Then, patterns of arriving ships are analyzed to explain why a simulation method is necessary. Next, a series of simulation experiments based on a container terminal in China are constructed and carried out. Finally, the required power capacity of an OPS under different arrival intervals is given when considering all berthed ships using an OPS. Besides, with the consideration of reducing environmental impact of ships at different levels, the required power capacity is provided with different proportions of arriving ships using an OPS. The results obtained, and the proposed method can be used to provide references for government policy making and green container terminal construction.

Keywords: green container terminal; OPS; emission reduction; simulation method.

1. Introduction

The consequent emissions of air pollutants and noise from ships at berth is one of the important components of total pollution in ports [1], since the electricity demand of ships at berth is satisfied by auxiliary diesel engines. Many efforts to reduce emissions of visiting ships inside ports have been made to realize the environmental goal of green ports [2–4]. An on-shore power system (OPS), also known as “cold ironing”, is one of the emission mitigation strategies by supplying electricity power from shore rather than the auxiliary engines, which can reduce the pollutant and noise emissions produced by ships during their mooring at berth [5]. For example, an OPS was implemented in the Venetian Harbor, leading to about a 30% reduction of carbon emissions [6]. Thus far, many ports have adopted an OPS to reduce emissions of ships in ports, such as Sweden (Göteborg, Stockholm, Helsingborg), Finland (Kotka, Oulu, Kemi), Belgium (Antwerp, Zeebrugge), and other ports [7]. However, regardless of shore-connected electricity standardization, a major issue that still influences terminal operators to carry out OPS technology in ports is how to decide the required power capacity of an OPS to meet electricity demand of all arriving ships. Besides, most existing ports lack effective methods for determining this capacity, which has a great influence on port costs. For instance, based on the data from Stora Enso 2008 [8], the investment costs of an OPS for a connected ship and ports are \$236,000

and \$589,000, correspondingly. The capacity of the OPS in the Port of Göteborg is decided by only considering the power utilization of several certain ships or specific kind of ships, such as ferries and ro-ro ships, without considering the stochastic nature of arriving ships and servicing all arriving ships to use shore power. Therefore, it is imperative to provide a method for determining the required power capacity of an OPS under the stochastic arrival of ships to meet electricity demand of all ships in ports, which is the problem we aim to solve in this paper.

Limited literature has studied how to determine the capacity of an OPS, and the capacity is decided by historical data of OPS construction and expert experience in most cases, e.g., Port of Lianyungang, which is located in China. In addition, few of the current international norms or standards give a determination strategy of OPS capacity for specific ports. For example, the *Technical Code of Shore-to-Ship Power Supply System* [9] gives the auxiliary power of different types of ships and regulates that the capacity of an OPS must satisfy the power demand of on-board equipment when ships moor at a berth, but how to calculate the capacity of an OPS is not provided by means of formulas or other methods.

Most existing research on OPS focus on electricity standardization, technical reformation, and policies. In terms of shore-connected electricity standardization, a joint international electrical standardization addressing the connection of shore power and ships was released in 2012, to promote a uniform system of OPSs [10]. Followed by this standardization, a series of literature [11–13] contribute to the power supply standard to ensure safe and reliable operation of an OPS. For technical reformation of the OPS, the studies mainly take efforts on protection equipment and control strategies to minimize the system damage [11,14], converter devices for high power connection [15,16], and cable connection for different types of ships provided by shore power [17]. Besides, Innes and Monios [18] analyze different configurations of an OPS to determine the most efficient, practical, and cost-effective system design, consisting of all the necessary components, and calculate the system cost and the emission savings under the specific configuration. Apart from the above technical requirements on an OPS, international and regional organizations and ports themselves have introduced a series of regulations to adopt shore power technology. For example, the European Commission issued a recommendation in 2006 directly on deploying an OPS in Europe [19]. Other relevant regulations proposed that most ships at berth use shore power [20,21], and carry out exemptions or reductions of electricity taxation to offset the disadvantage of an OPS for speeding up the development of shore power technology [22,23].

From the above analysis, without consideration of electricity standardization and technical reformation, the policies mentioned above support the implementation of an OPS in ports, and present the goal that most or all arriving ships can use shore power during their mooring at berth. Meanwhile, determining how the capacity of an OPS can meet that goal is still not resolved.

However, to satisfy the total power demand of all ships, the capacity of an OPS is affected by the number and pattern of arriving ships in ports. The different arriving pattern of ships (size, type, cargo, etc.) will lead to different impacts on the size of OPS installations, and on the costs and benefits of an OPS [24]. For patterns of arriving ships, the probability distributions have been widely applied to describe the stochastic nature of ship arrival [25]. For example, numerical research reveals that the number of daily arriving ships and the arrival intervals of ships generally obey a Poisson distribution, negative exponential distribution, and normal distribution, correspondingly [26–30]. Besides, other research on patterns of arriving ships mainly concentrates on prediction approaches, such as the neural networks model [31], logistic regression [32], support vector machines [33], etc.

The previous literature mainly focuses on probability description and prediction approaches on patterns of arriving ships. However, the research on how patterns of arriving ships affect the capacity of OPS installations are still lacking.

Another issue that needs to be discussed is the environmental benefits of an OPS, which is closely related to the capacity of the OPS adopted in ports. For example, a ship named China-Korea Star is provided with shore power in the Port of Lianyungang, for which fuel consumption is reduced by about 437 tons every year [17]. Sciberras et al. [34] indicated that it can realize zero emissions

from ships at berth when on-board auxiliary generators are switched off and power demands are provided by shoreside electricity. Zis et al. [35] indicated emission reductions of CO₂ (48~70%), SO₂ (3~60%), and NO_x (40~60%) by supplying shore power to ships from the perspective of net emissions considering energy mixture, respectively. Hall [36] obtained that provision of shore power could reduce emissions of CO₂, SO₂, CO, and NO_x by 25%, 46%, 76%, and 92%, respectively, when using shore power compared to on-board power generation.

The previous literature indicates that an OPS is effective technology to reduce the environmental impact of berthed ships in ports, if almost all ships are supplied by shoreside electricity. However, if the capacity of an OPS increases too much to meet the demand of all arriving ships, the investment costs of the OPS will raise rapidly. It is necessary to decide the required power of the OPS capacity to minimize cost and air pollution.

Therefore, the main contribution of this paper is to provide a method for determining the required power capacity of an OPS to adequately meet the electricity demand of all visiting ships under the stochastic arrival of ships. Besides, with consideration of the capacity limitation of the grid and reducing environmental impact of ships at different levels, the allocated capacity is provided by the method when different proportions of arriving ships use shore power. Numerical simulation experiments are conducted with consideration of the stochastic arrival and combination of ship types to obtain the required power capacity. The remainder of this paper is organized as follows. Section 2 focuses on materials and methods, including patterns of arriving ships and the simulation method. Then, the results under different arrival intervals of ships are presented in Section 3, followed by conclusions and discussions in Section 4.

2. Materials and Methods

This paper aims to solve the problem of how to determine the required power capacity of an OPS when considering the stochastic arrival of ships. Due to the complicated and stochastic operation system in container terminals, simulation technology was introduced to overcome problems under uncertainties. The problem and method will be explained more in detail in this section.

One problem that needs to be discussed firstly is the adopting pattern of an OPS in container terminals. In existing ports, there are mainly two patterns of OPSs which can be defined as a fixed pattern and mobile pattern. Under a fixed pattern of an OPS, the facilities of an OPS cannot be mobile along the quayside, while a mobile pattern allows facilities to move along the quayside, as shown in Figure 1. The general components of an OPS are illustrated in detail in IEC/ISO/IEEE80005-1 [10], consisting of a frequency converter, shore transformers, a berth-side switchboard, a shore connection switchboard, etc. According to IEC/ISO/IEEE80005-1 [10], a shore transformer is necessary for each berth-side connection while a frequency converter can service one or multiple berths. In this paper, a continuous quay was considered, and the mobile pattern of an OPS was adopted. One rule for using shore power by ships is introduced based on the mobile pattern of an OPS as shown in Figure 2, that is, shore transformers are fixed on the quayside at each berth, while the frequency converter is mobile along the quayside and can service all the berthed ships. For example, if on-shore power supply j is installed, the ships at berth from 1 to V can receive electricity simultaneously when the capacity of the OPS satisfies the total power demand of all ships. If the capacity is not enough to service all berthed ships simultaneously, ships can use shore power following previously user-defined rules, such as “first come, first service” rule and “large-tonnage ship, first service” rule.

The following concentrates on the problem of how patterns of arriving ships affect the capacity of OPS installations, as shown in Section 2.1. Besides, the method for determining the capacity of an OPS is illustrated in Section 2.2.



Figure 1. The patterns of an on-shore power system (OPS) adopted in existing ports. (a) The fixed pattern of an OPS in the Port of Los Angeles [37]; (b) The mobile pattern of an OPS in the Port of Shenzhen [17].

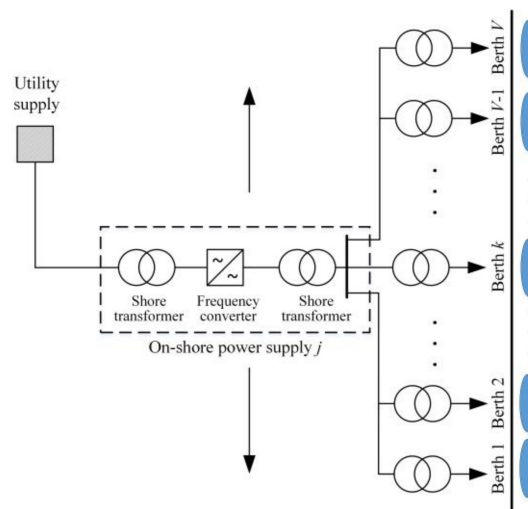


Figure 2. Mobile pattern of an OPS.

2.1. Analysis on Patterns of Arriving Ships

Generally, patterns of arriving ships can be described by arrival interval and combination of ship types. Considering that all arriving ships use shore power, the following focuses on how the required power capacity is influenced by patterns of arriving ships.

2.1.1. Arrival Interval of Ships

Affected by handling operations in port, weather conditions, and other stochastic factors, ships arrive at port randomly. Based on the frequency statistics of real data, the arrival interval of ships follows a certain kind of probability distribution, such as negative-exponential and gamma distribution [30]. When the expected arrival interval of ships is small, the number of daily arriving ships is large, and ships have to wait at anchorage for idle berths. Therefore, it is very likely to reach a point where all berths are occupied by ships simultaneously, as shown in Figure 3. Thus, to meet the electricity demand of ships, it is necessary to allocate a large capacity for the OPS. With the expected arrival interval of ships increasing gradually, the number of ships arriving daily will decrease, which can result in idle berths. Therefore, a small capacity can satisfy the power demand of all berthed ships. From the analysis above, the arrival interval of ships has an important effect on the allocated capacity of an OPS considering all berthed ships can receive shore power.

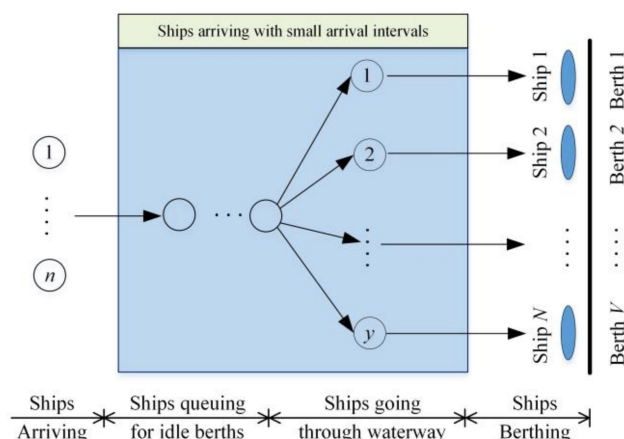


Figure 3. Influence of ships arriving with different intervals.

2.1.2. Combination of Ship Types

Combination of ship types, which can be described by the tonnage proportion of ships, is another factor affecting the required power capacity of an OPS. With the rapid development of the shipping industry, the tonnage of ships has improved greatly, and the electrical power demand for on-board equipment of berthed ships has increased to tens of megawatts for large ships. When large-tonnage ships arriving at the port account for a large proportion, there is a need for high capacity of the OPS to satisfy the electricity demand. Conversely, when small-tonnage ships make up a large proportion, a small capacity may meet the electricity demand. Thus, there is a particular capacity for each kind of type combination under constant arrival interval.

From the above analysis, the OPS allocation is influenced by patterns of arriving ships. Besides, the operation system in ports consists of many interconnected subsystems, such as ships going through the waterway, ships being handled by equipment, containers being transported by trucks, etc., and the system is affected by many stochastic factors: natural conditions, sailing speed of ships, working efficiency of equipment, etc. Such a complex and stochastic system in ports is nearly impossible to describe by just a series of formulas; this can be resolved by the simulation method presented in this paper.

2.2. Simulation Method

Recently, with the development of the OPS installation, how to determine the required power capacity of the OPS to meet electricity demand of all arriving ships has been an unresolved problem. Therefore, this paper presents a simulation method for solving that issue. Firstly, a simulation model to represent the total operation system of ports under uncertainties was constructed, taking arrival interval of ships, combination of ship types, and other parameters as inputs, and taking the total shore power provided to all berthed ships as outputs. Then, the shore power provided to ships varying with simulation time was obtained after running the simulation model. Finally, the required power capacity of the OPS in this paper was defined as the largest shore power gained by all berthed ships.

Before simulation models were established, a logic model was firstly developed, as shown in Figure 4. Generally, there are two dynamic operation processes in container terminals opposed to each other: loading and unloading. The following takes the unloading process as an example to describe the logic model, and details about simulation models are discussed in subsections below.

Based on the logic model, ARENA 10.0 software (Rockwell Automation, Milwaukee, USA) was applied to construct a complicated process-oriented simulation model to simulate the stochastic operation process in container terminals. The whole simulation model consists of four sub-models: *Ship creating and berthing* sub-model, *Shore power allocated to ships* sub-model, *Ship handling operation* sub-model, and *Ships departing* sub-model.

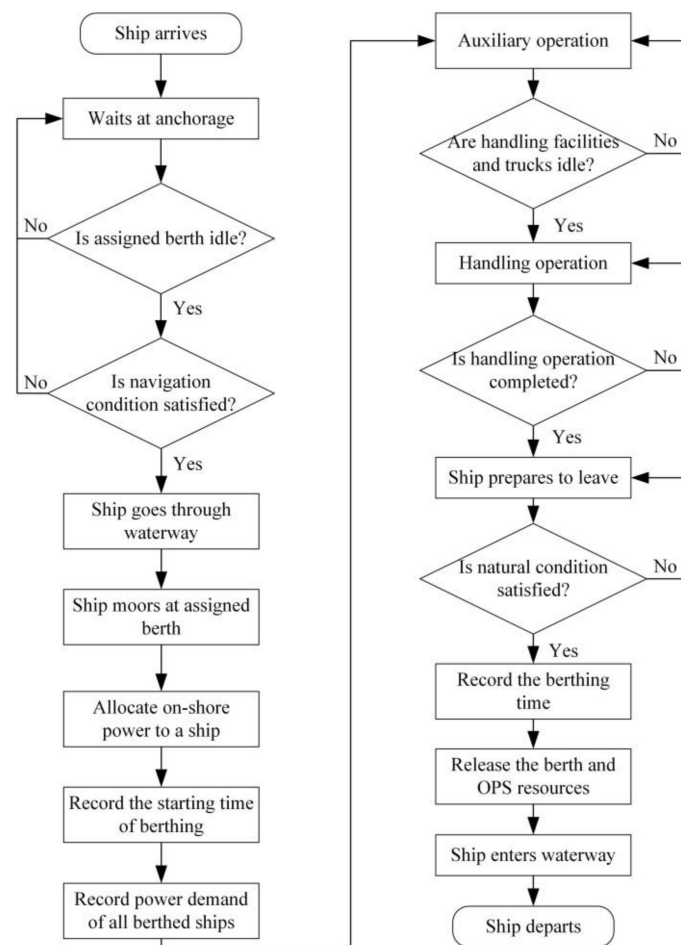


Figure 4. The logic model of simulation experiments.

2.2.1. Model Assumptions

- There are no accidents and interferences happening during a simulation run.
- Regardless of power standardization between shore and ships, all ships arriving at port can utilize shore power during their mooring at berth.
- The shore-connected electricity supply system works well without considering its maintenance and repair.
- The handling facilities are taken full use of, and the number of facilities for handling operation is adequate.

2.2.2. Ship Creating and Berthing Sub-Model

In the *Ship creating and berthing* sub-model, a ship sequence was firstly created by *Create* modules with a certain distribution and specific arrival interval. Then, the attributes of ships were recorded in the *Assign* module, such as combination type, the power of auxiliary engines, the number of handled containers, the navigation speed in the waterway, and auxiliary operation time etc. Next, the matching berths were assigned to arriving ships, as shown in the *Assign Berth_Numb* module. If the berth is idle, the ship will seize the berth resource, otherwise ships have to wait at anchorage for corresponding idle berths. Finally, when the navigation conditions consisting of weather conditions and traffic conditions in the waterway are satisfied, the ships go through the waterway and moor at the assigned berths, as shown in Figure 5.

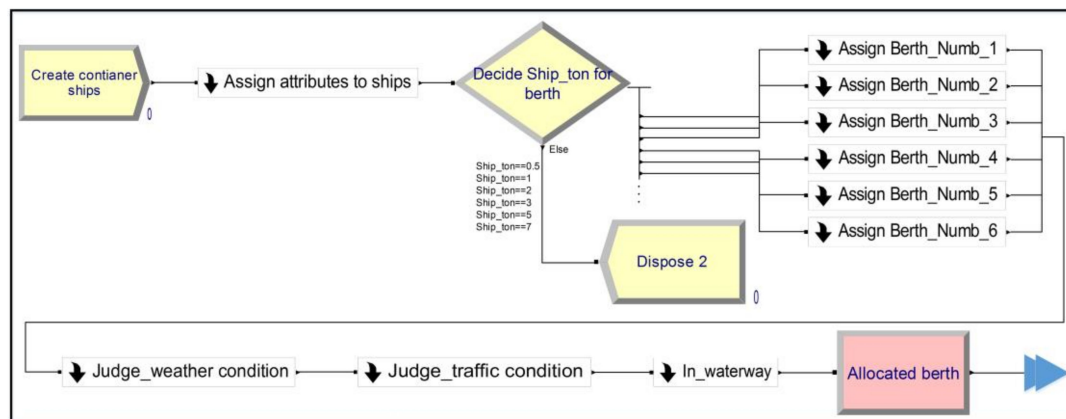


Figure 5. Ship creating and berthing sub-model.

2.2.3. Shore Power Allocated to Ships Sub-Model

After mooring at berth, the entities go into the *Shore power allocated to ships* sub-model. In this model, the start time of berthing of ships was firstly recorded by the *Record* module. Then, the shore power resource was allocated to each berthed ship in the *Allocate shore power* module to meet electricity demand for on-board equipment. Finally, the total shore power gained by all berthed ships was recorded in the *Statistics* module, which can be used to calculate the required power capacity of the OPS, as shown in Figure 6.

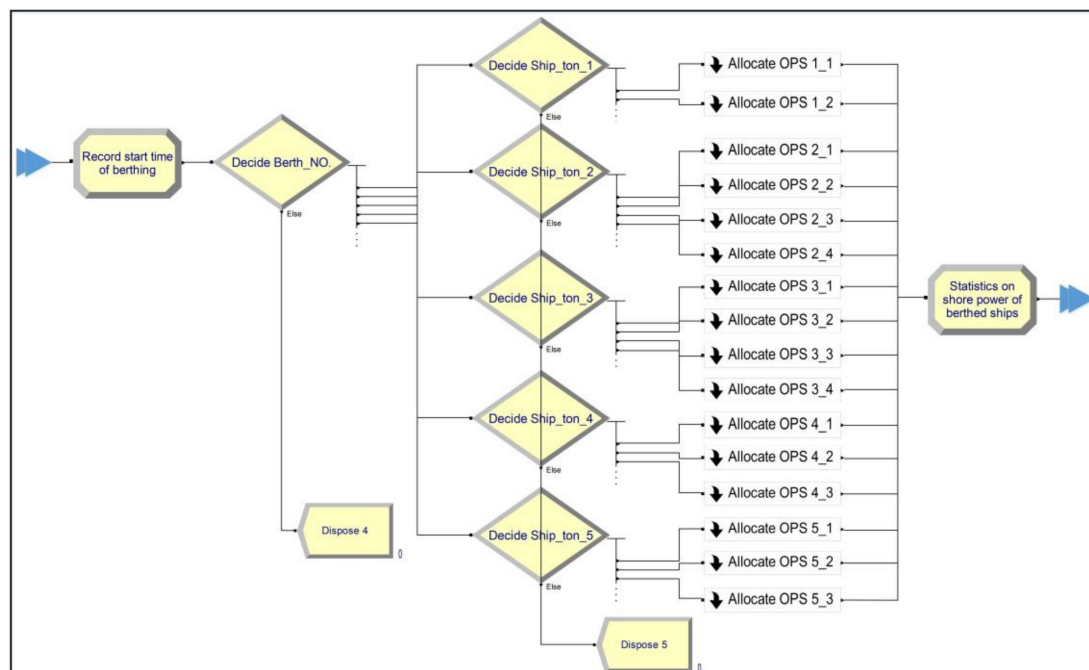


Figure 6. Shore power allocated to ships sub-model.

2.2.4. Ship Handling Operation Sub-Model

After shore power allocation and the auxiliary operation, the process of handling operations begins. As shown in Figure 7, containers separated from ships were created in the *Separate* module and sent to the *Cranes handling* module through the *Duplicate* exit point for handling operations. In the process of handling operations, containers were handled by quay cranes from ships onto empty trucks in the *Cranes handling* module. Then, trucks assigned to quay cranes transport containers to yard blocks to wait for idle yard cranes in the *Trucks transportation* module. Next, yard cranes stack

containers at the assigned block in the *Yard handling* module. Finally, the *Decide* module was used to judge whether handling operations were completed.

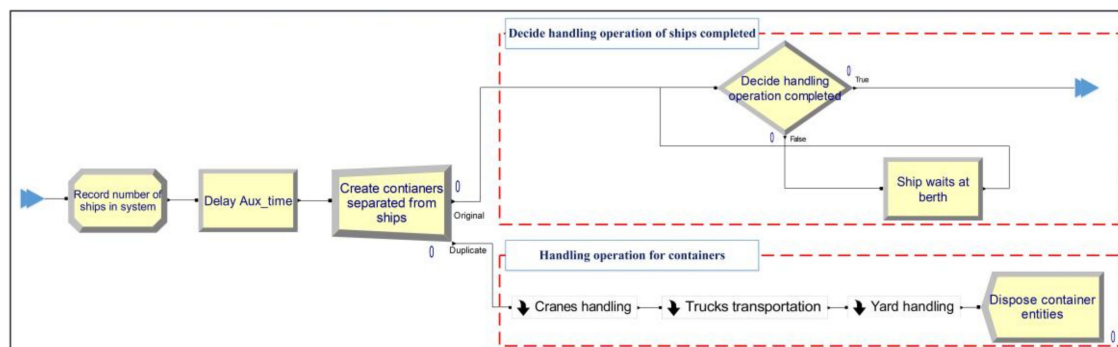


Figure 7. Ship handling operation sub-model.

2.2.5. Ships Departing Sub-Model

Once handling operations were finished, ships prepared to leave the port. As shown in Figure 8, after the navigation condition was satisfied, ships release shore power and berth resources by the *Release* module, and go through the waterway to leave the port via the *Out_waterway* module. Then, the berthing time for each ship, which consists of the auxiliary working time, the time for handling operation of ships, and the waiting time for leaving the port, can be obtained. After ships depart, the shore power provided to all berthed ships and the berthing time for each ship can be written to the external Excel spreadsheet by the *VBA* module with the simulation clock moving.

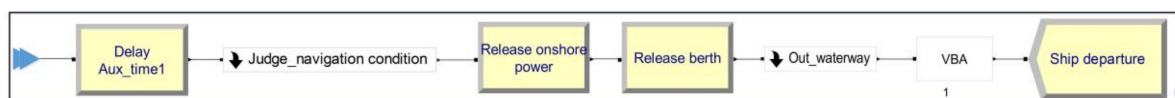


Figure 8. Ships departing sub-model.

3. Results

3.1. Data Collection

The method for determining the required power capacity of an OPS was illustrated by taking a container terminal in China as a simulation case and taking a full calendar year as an example study.

The terminal is 1847 m long, with five container berths and sixteen quay cranes along the quayside, as shown in Figure 9. Besides, the waterway is 20 nm long with one lane, and the navigation speed of ships in the waterway is 18.52 km per hour. Initial parameters of the simulation inputs such as natural conditions, operation days, etc., were provided by the port company in 2016. The following focuses on the parameters of ships, berths, and the OPS.

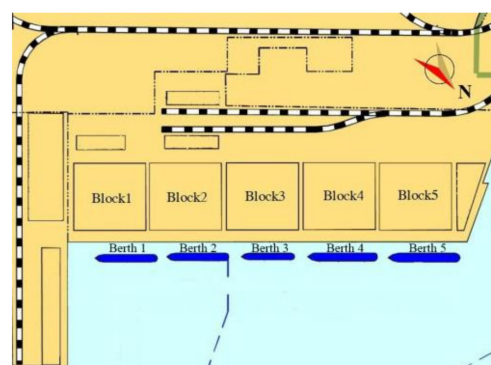


Figure 9. The general layout of the container terminal.

3.1.1. Parameters of Ships

(a) Arrival interval of ships

Ships arrive at the container terminal with an arrival interval obeying a negative exponential distribution according to the frequency curve fitting of real operation data in 2016. To determine the required power capacity of the OPS under different expected arrival intervals, this paper set the expected arrival interval ranging from 1 to 100 h stepped by 1 h.

(b) Combination of ship types

As previously mentioned in Section 2.2, the combination of ship types is another aspect indicating the stochastic nature of ships arriving at ports, which can also affect the required power capacity. The categories of ship types can be categorized according to the code [38]. The combination of ship types obtained by the real data, such as tonnage and proportion, along with the number of average handled containers and berth number for each ship mooring, are listed in Table 1. According to the code [38], the auxiliary working time consists of the time for preparative work, assessment work, and joint inspection, which are set as 0.75–1.00 h, 1.50–2.00 h, and 1.00–2.00 h, respectively. Therefore, the auxiliary working time for ships in this paper was set as 4.0 h around the average.

Table 1. Combination of ship types in container terminals.

Tonnage of Ships DWT (Ten Thousand Tonnage)	Proportion (%)	Cumulative Frequency (%)	Power of Auxiliary Engines (kW)	The Number of Average Handled Containers (TEU)	Berth Number for Ship Mooring
0.5	20	20	320	460	Berth 1, Berth 2, Berth 3
1	20	40	430	500	Berth 1, Berth 2, Berth 3
2	19.5	59.5	700	650	Berth 2, Berth 3
3	20	79.5	1260	855	Berth 2, Berth 3, Berth 4, Berth 5
5	10.5	90	1960	1200	Berth 4, Berth 5
7	10	100	2320	2400	Berth 4, Berth 5

Note: DWT is the abbreviation of “Dead Weight Tonnage”, and TEU is the abbreviation of “Twentyfoot Equivalent Unit”. The layout of Berth 1–5 is shown in Figure 9.

3.1.2. Parameters of Berths

The assignment of berth resources has a great influence on the berthing time and position of arriving ships, which closely influences the number of ships berthing simultaneously, thereby further affecting the required power capacity for meeting the total electricity demand of all berthed ships. The parameters of berths, such as berth number and tonnages of berthed ships, along with the allocated number of quay cranes, are shown in Table 2. In this paper, the number of quay cranes was fixed, and the quay cranes assigned to each berth could only move along their assigned berth and could not move around between adjacent berths.

Table 2. Parameters of berths in the container terminal.

Berth Number	Tonnage of Berth DWT (Ten Thousand Tonnage)	Tonnage of Berthed Ships DWT (Ten Thousand Tonnage)	The Number of Quay Cranes for Each Berth
Berth 1	1.5	0.5, 1	2
Berth 2	3.5	0.5, 1, 2, 3	3
Berth 3	3.5	0.5, 1, 2, 3	3
Berth 4	7.0	3, 5, 7	4
Berth 5	7.0	3, 5, 7	4

Note: The layout of Berth 1–5 is shown in Figure 9.

3.1.3. Parameters of the OPS

The mobile pattern of the OPS was adopted in the container terminal, which could service all berthed ships, as illustrated in Section 2.1. To satisfy the total electricity demand of all ships during their mooring at berth, an adequate shore power was set in the OPS. Thereby, the total shore power

gained by all berthed ships, which changes over the simulation time, could be obtained to calculate the required power capacity of the OPS. Besides, the usage rule of shore power for arriving ships complies with the “first come, first service” rule.

3.2. Analysis of Simulation Results

In this section, a series of simulation experiments were carried out to determine the required power capacity of the OPS for meeting electricity demand of all berthed ships under different arrival intervals. In addition, the comparison between the results of the simulation experiments and those added by the largest electricity demand of ships at each berth, illustrates economy and effectiveness of the method for determining the required power capacity. Besides, considering the capacity limitation of electricity provided by the grid, the capacity of the OPS is also respectively provided when 20%, 40%, 60%, and 80% of arriving ships use shore power.

3.2.1. Required Power Capacity of the OPS Under Different Arrival Intervals

To determine the required power capacity under different arrival intervals, the required power capacity of the OPS was firstly decided under a certain arrival interval. Taking the scenario with the arrival interval set as 7 h for example, the total shore power gained by all berthed ships changing with the simulation time was obtained after running the simulation model by one year, as shown in Figure 10.

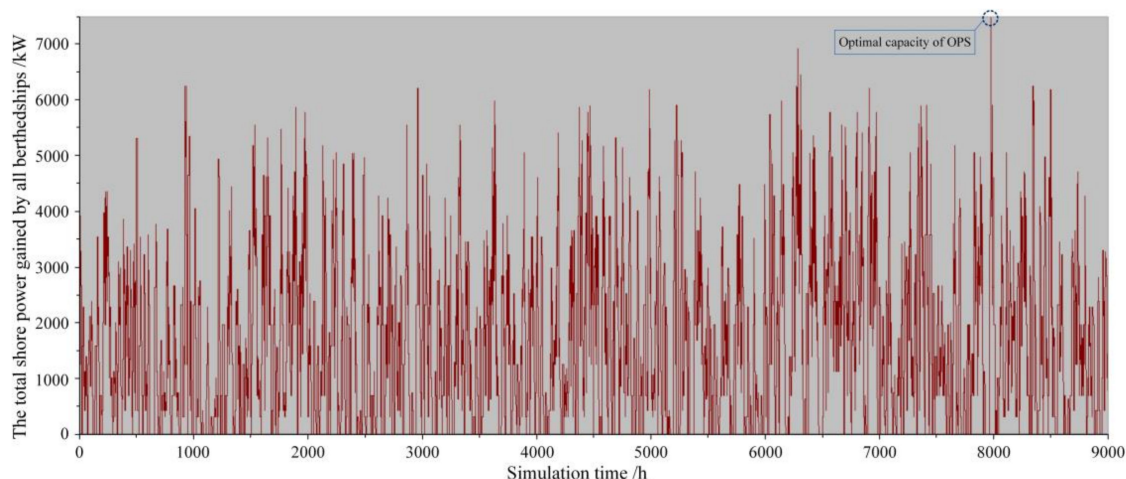


Figure 10. The total shore power gained by all berthed ships during one year.

As illustrated in Figure 10, the shore power used by ships varies randomly, which depends upon the number of berthed ships and the auxiliary power of ships at one moment. In this paper, the required power capacity of the OPS was defined as the largest shore power provided to ships. Therefore, the required power capacity was reached when the simulation time was around 8000 h.

Then, a total of 100 simulation scenarios with arrival intervals changing from 1 to 100 h stepped by 1 h were conducted for 80 runs by ARENA software. Thus, after running all the simulation models, the required power capacity of the OPS for each arrival interval scenario was obtained, as shown in Figures 11 and 12.

As shown in Figure 11, when the arrival intervals of ships range from 1 to 10 h, the required power capacity of the OPS is the largest, which lies between 6000 and 7000 kW. With the arrival intervals increasing gradually, the required power capacity of the OPS reduces correspondingly, and the capacity was between 3000 and 5000 kW with the arrival interval increasing from 20 to 60 h. When the arrival interval of ships was between 60 and 100 h, the required power capacity of the OPS remains stable around 2300 kW. Figure 12 shows the trend of required power capacity in detail with the arrival interval changing. Considering a situation where each berth is occupied by the largest-tonnage ships

simultaneously, the needed power capacity of the OPS is 7590 kW to meet the total electricity demand. The power capacity is larger than the results obtained by the simulation experiments, which means that the situation rarely happens with the arrival interval increasing, and there is no need to allocate such a high capacity to the OPS.

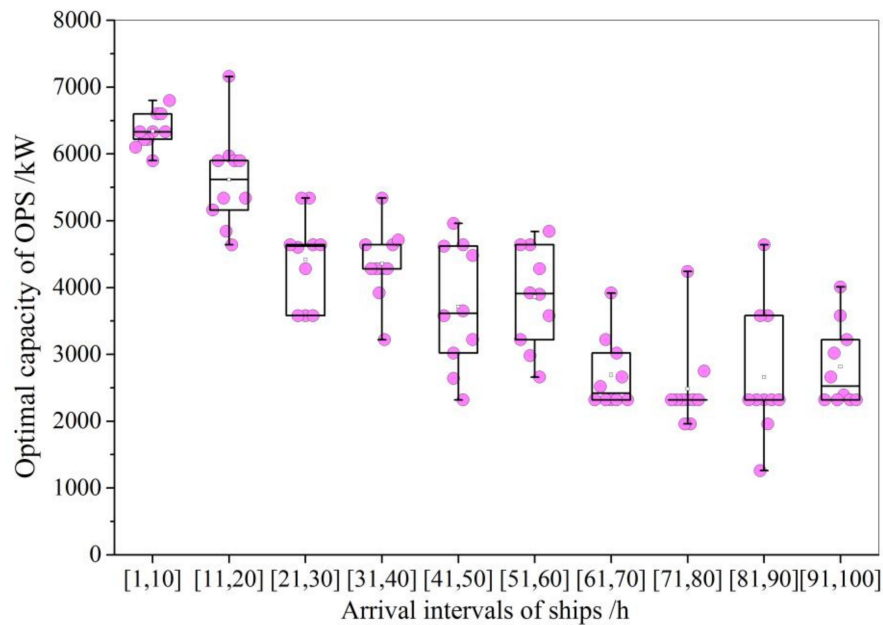


Figure 11. The required power capacity of the OPS under different arrival intervals.

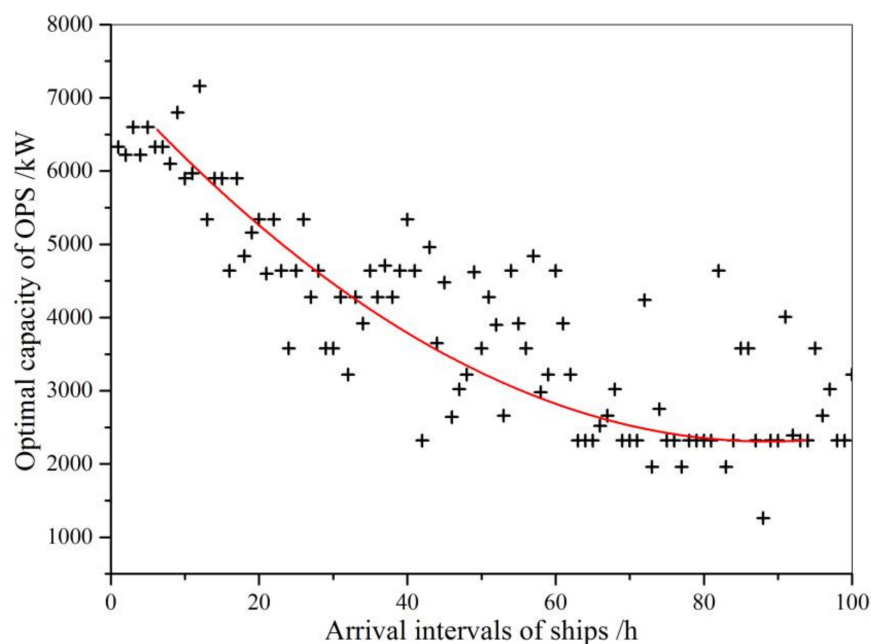


Figure 12. The trend of required power capacity under different arrival intervals.

To analyze the environmental benefits of the OPS, the carbon emissions from ships at berth were calculated considering the electricity of all ships was provided by auxiliary engines. Then, the emission reductions are shown in Table 3.

Table 3. Environmental benefits of the OPS when all ships use shore power.

Group Number	The Range of Arrival Intervals (Hour)	The Average Emission Reductions (Thousand Tons)
1	(1,10)	14.1
2	(11,20)	4.7
3	(21,30)	2.9
4	(31,40)	2.0
5	(41,50)	1.6
6	(51,60)	1.3
7	(61,70)	1.1
8	(71,80)	1.0
9	(81,90)	0.9
10	(91,100)	0.8

3.2.2. The Capacity of the OPS Under Different Proportions of Ships Using the OPS

With consideration of the capacity limitation of the grid and reducing environmental impact of ships at different levels, it was necessary to study the allocation strategy of the OPS when only a proportion of arriving ships use shore power. Therefore, this paper set the expected arrival interval as 7 h according to real data from the port company in 2016, and implemented numerical simulation models to obtain the allocated capacity and carbon emissions when 20%, 40%, 60%, and 80% of arriving ships used shore power.

Considering the port area as the system boundaries, it can realize zero direct emissions from auxiliary diesel generation of ships during their mooring at berth if the electricity demand was supplied by shoreside electricity, without respect to lifecycle carbon emissions. The emissions consisting of CO₂, SO₂, and NO_x from ships when consuming fuels at berth, can be calculated according to ISO 14064-1 (2006) [39] and Intergovernmental Panel on Climate Change (IPCC, 2006) [40], as follows.

$$W = F \times w_f \quad (1)$$

$$F = \sum_i F_i^{ship, berth} = \sum_i l^A \times (P_i^A \times R^A) \times t_i^{berth} \quad (2)$$

where W represents the emissions from ships, kg; F represents the total diesel consumption of all ships consuming fuels at berth, kg; w_f represents the emission coefficient of diesel, kg/kg; $F_i^{ship, berth}$ represents the diesel consumption of ship i at berth, kg; l^A is the load coefficients of auxiliary engines, which is set as 0.5; P_i^A is the power of auxiliary engines of ship i , kW; R^A is the diesel consumption rates of auxiliary engines, kg/kWh; t_i^{berth} is the berthing time of ship, h.

The power of auxiliary engines is shown in Table 1, and the berthing time can be obtained by the simulation model as shown in Section 2.2. In order to quantify emissions of ships, the emission coefficient of diesel for CO₂, SO₂, and NO_x were set as 3.16 kg/kg [40], 0.35 kg/t [41], and 47.6 kg/t [41], respectively.

After running the simulation model, the capacity of the OPS and the emissions were obtained and are shown in Figure 13.

As shown in Figure 13, with the proportions of ships using shore power increasing gradually, the allocated capacity of the OPS grows correspondingly, and reaches the peak point (6330 kW) as all berthed ships use shore power. When the proportion rises from 80% to 100%, the allocated capacity has great growth from 1800 to 6330 kW, due to the high electricity demand of large-tonnage ships. Besides, the emissions comprising CO₂, SO₂, and NO_x from ships at berth decrease with the capacity of the OPS increasing.

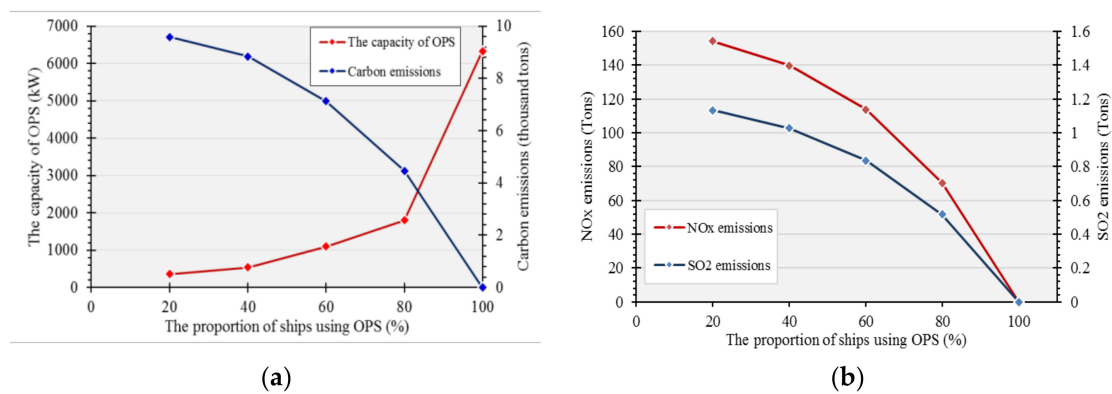


Figure 13. The capacity of the OPS and emissions of ships under different proportions of ships using the OPS. (a) The capacity of the OPS and CO₂ emissions under different proportions of ships using the OPS; (b) The SO₂ and NO_x emissions under different proportions of ships using the OPS.

3.2.3. The Capacity of the OPS Considering Combination of Ship Types Using the OPS

Due to the long time period of handling operations and high power demand for large-tonnage ships, the emissions from large ships account for a major proportion of emissions from all berthed ships. To reduce environmental impact of all berthed ships, there was a need to study the capacity allocation of the OPS when only large ships were provided with shore power. Therefore, this paper divided arriving ships into six groups according to their tonnages, and determined the capacity of the OPS separately for each group which were only supplied with shore-connected electricity. The capacity of the OPS and emission reductions are shown in Figure 14.

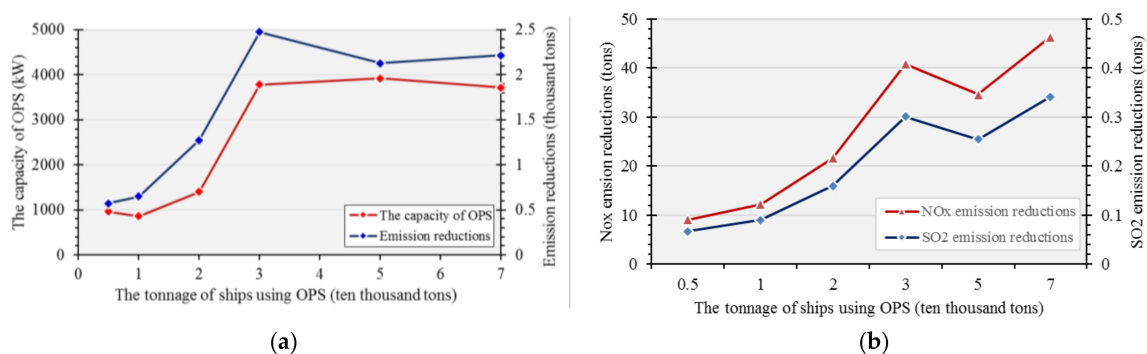


Figure 14. The capacity of the OPS considering combination of ship types using the OPS. (a) The capacity of the OPS and CO₂ emission reductions considering combination of ship types using the OPS; (b) The SO₂ and NO_x emission reductions considering combination of ship types using the OPS.

As shown in Figure 14, emission reductions can be realized when supplying shore power to large-tonnage ships (30,000, 50,000, and 70,000 tons) compared to small ships. However, due to the high electricity demand of large ships, the capacity of the OPS allocated in ports ranges from 3000 to 4000 kW, which is much larger than the capacity satisfying small ships.

3.2.4. The Key Performance Indicators (KPIs) of the OPS System Under Different Capacities

In order to compare the key performance indicators of the OPS under different capacities, this paper selected the proportion of ships using shore power and the usage time of the OPS divided by one year to reflect the KPIs. The results under different capacities were obtained after running the simulation models, as shown in Figure 15.

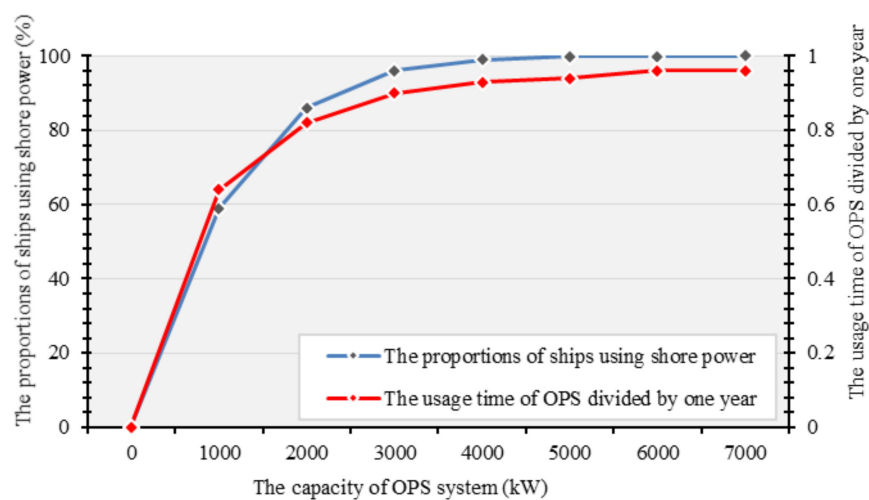


Figure 15. The key performance indicators of the OPS under different capacities.

As shown in Figure 15, when the allocated capacity of the OPS increases, the proportion of ships using shore power will raise, and the usage time of the OPS divided by one year will also increase. When the capacity of the OPS was 4000 kW, the proportion of ships using shore power reached the point of 99%, which means that only large-tonnage ships cannot connect to the shore power.

4. Conclusions and Discussion

This paper was concerned more about how to determine the required power capacity of the OPS to meet total power demand of all arriving ships, considering the stochastic nature of arriving ships. Therefore, this paper does not consider the power standardization between the shore and ships and introduces the hypothesis that the OPS and handling equipment works well in operational stages. Based on the previous hypothesis, and to cope with such complicated and stochastic operational processes in container terminals, numerical simulation models were established with the arrival interval of ships ranging from 1 to 100 h stepped by 1 h. Finally, the simulation experiments based on a container terminal in China were carried out. Results are represented as follows.

- (1) Considering all arriving ships use shore power, the required power capacity of the OPS reduces correspondingly with the arrival intervals of ships increasing. When arrival intervals range from 1 to 10 h, the allocated capacity is the largest, which lies between 6000 and 7000 kW. When the arrival intervals of ships are between 60 and 100 h, the required power capacity remains stable around 2300 kW.
- (2) The proposed simulation method can determine the capacity of the OPS when considering different proportions of arriving ships using shore power. When 20%, 40%, 60%, 80%, and 100% of arriving ships were provided with shore power, the allocated capacity was 360, 540, 1100, 1800, and 6330 kW, correspondingly; the carbon emissions from auxiliary diesel generation of ships at berth were 9600, 8800, 7100, 4500, and 0 tons; the SO₂ emissions from auxiliary diesel generation of ships at berth were 1.1, 1.0, 0.8, 0.5, and 0 tons; and the NO_x emissions from auxiliary diesel generation of ships at berth were 154.1, 139.8, 113.8, 70.3, and 0 tons.
- (3) This paper divided arriving ships into six groups by their tonnages, and the allocated capacity was provided by the simulation method considering when only a group was supplied by shore power. Emission reductions can be realized when providing shore power to large ships compared to small ships.

The results and proposed method can be applied to build a green container terminal and determine the required power capacity of an OPS according to the arrival intervals of ships. Besides, the capacity of the OPS was provided by the proposed simulation method when considering different proportions

of arriving ships using shore power. However, this paper focused on capacity allocations of OPSs, regardless of the standardization of shore-connected electricity. Future study should focus on the connection standardization between ships and the OPS.

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