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Simulation based Estimation of Power Consumption of Reefers at Container Yards

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Abstract

The power consumption and peak demand will greatly increase when a large amount of reefer containers arrive at container terminal and are stored in the container yard. To estimate the power consumption and temperature fluctuations of reefers, we propose to apply agent-based simulation to simulate the stochastic operation process of reefers at the container terminal. The model considers the influence factors of power consumption, especially dynamic variations of solar radiation, ambient temperature, and stack effect. Moreover, this study designs three kinds of simulation experiments that are optimal unloading sequence and continuous and intermittent power supply modes of refrigerated power rack to study the improving effect of peak power demand and total cargo loss rate. It has a certain reference value for reducing pollution and energy costs at the reefer yard.

Keywords: Agent-based modeling; Reefer container Yard; Power Consumption; Green Port.

1. Introduction

Reefers are the main power consumption equipment of container terminal, which account for about half of the total power consumption and 30-35% of the total energy consumption of ports (Geerlings and van Duin, 2011). When a large number of reefers is plugged-in at the terminal, peaks in energy consumption occur. The peak power is then applied in the billing for the next 12 months for the terminal. Averagely, the peak power cost is about 25-30% of the total monthly energy cost. Moreover, if the grid cannot cope with such high peak power, the electrical power system will be unstable or even paralyzed. To reduce port operation cost and environmental pollution, it is necessary to estimate the power fluctuations of the reefers at the container terminals.

Related studies have applied the experimental analysis and simulation to estimate the reefers' power consumption. For example, Fitzgerald et al. (2011) quantified the carbon emissions of reefer transportation based on the data of power consumption of reefers and fuel consumption of ships. Budiyanto and Shinoda (2018) collected the data of a 40ft high reefer to analyze the influence of solar radiation on the power consumption of reefers. Budiyanto and Shinoda (2017) studied the influence of stacking on the surface temperature and power consumption of three level reefers. Budiyanto et al. (2019) estimated power consumption of reefers by modeling heat transfer processes (heat conduction, heat convection and solar radiation) and heat load process based on the IES Virtual Environment (IESVE) platform. Budiyanto et al. (2018) applied fluid dynamics to conduct thermal simulation of the heat transfer process on the reefer wall respectively with and without sunshades. These studies focus on the estimation of power consumption of individual reefer considering the impact of solar radiation. To estimate the peak consumption of container terminals, van Duin et al. (2018) established a simulation model to evaluate the power consumption of reefers at the container yard. However, their dynamic variations and stack effect are not described.

Simulation is a good method to describe the dynamic variation and randomness. Most current studies focus on the energy consumption of Electrical equipment at container terminal by the operation simulation, mainly including quay crane (QC), yard crane (YC) and automatic guided vehicle (AGV), but no reefers. For example, Cao et al. (2019) built a 3D simulation model to model the operation process of QCs, YCs and AGVs at automatic container terminal on AnyLogic software. Ma, et al. (2021), and Xiang and Liu (2021) presented a simulation approach to make the battery performance evaluation and management of charging stations and AGVs at automated container terminal. Li, et al. (2021) studied the several layouts in automated container terminals by the operation simulation of QCs, YCs and AGVs from efficiency, economic and environment perspectives. Therefore, based on previous studies, this study proposes a simulation-based estimation of power consumption with time of reefers at container yard considering dynamic variations and stack effect. Through simulating the operation process of reefers at the container terminal, the power consumption of reefers is estimated according to these variables (operation state and position of each reefer, solar radiation, and ambient temperature). This will provide support for analyzing the possibility of peak shaving and cargo loss reduction.

The rest of the paper is organized as follows. Section 2 describes reefer operation in the container terminal, the influence factors, and Section 3 presents the simulation model to estimate power consumption of reefers at the container terminal. The proposed model is applied and tested at a container terminal with output results and discussions in Section 4. The conclusions are presented in Section 5.

2. Problem Description

2.1. Reefer operation process

van Duin et al. (2019) divides the root cause factors of reefers' power consumption into six categories according to the 6 Sigma principle: Manpower, Machine, Environment, Method, Measurement, and Materials, as shown in Figure. 1. There are many influencing factors, which are not only related to the property of the reefer, but also closely related to the operation process of the reefers at the terminal.

The reefer operation process at container terminal is divided into six stages, as shown in Figure 2.

Stage 1: On ship. All reefers are unplugged by the crews before vessel arrival at the assigned berth and are at off mode. When the reefer is unplugged (t_0) depends on the ship berthing time (t_1) and the availability of crews.

Stage 2: Unload. Quay crane (QC) unloads the unplugged reefer from the ship after berthing and loads it to the internal truck (IT) at time t_2.

Stage 3: Transport. The IT transports the unplugged reefer to the yard and arrives at the target bay at time t_3.

Stage 4: Load. Yard crane (YC) first loads the unplugged reefer into the cold storage rack at time t_4.

Stage 5: Storage. The reefer is stored in yard and plugged in by the staff until it is picked up by external truck (ET). The time when the reefer is plugged (t_5), depends on the time t_4, and the availability of staff. During storage, the cooling compressor used to regulate the mode switches on and off to save energy. When the internal temperature of the reefer is within the allowed bandwidth of set temperature, the reefer is in the switched off mode, and only the circulating fans operate by means of auxiliary power. Otherwise, the reefer starts the cooling/heating at on mode. The auxiliary power and the cooling/heating power are used to restore to the set temperature.

Stage 6: Pick up. The reefer is unplugged by the staff at time t_6 before the arrival of the ETs at time t_7. Then the unplugged reefer is loaded to the ET by the YC at time t_8 and transported to hinterland at time t_9. When the reefer is unplugged (t_6) depends on the ET's arrival time (t_7) and the availability of staff.

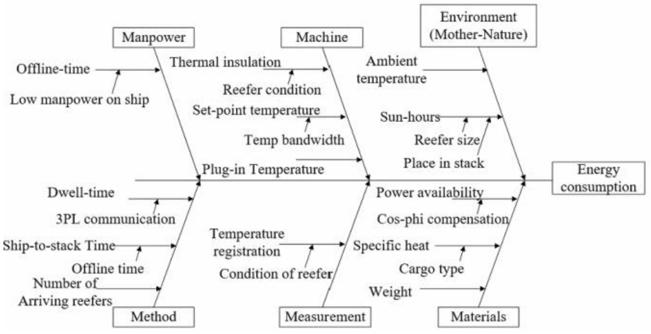


Figure 1. Influencing factors of reefer energy consumption

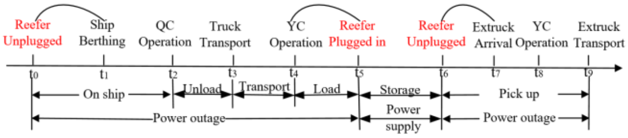


Figure 2. The process of reefer operation at the terminal

2.2. Temperature fluctuation estimation

As seen in Figure 2, the reefers are plugged out at all stages other than Stage 5, there is a rapid increase in their temperature. Thus, the power demand will greatly increase when a large number of reefers arrive at container terminal. To explore the possibility of peak shaving and cargo loss reduction, the values of performance indicators need to be estimated according to the temperature fluctuation estimation.

(a) **Peak power**: the maximum power of all reefers at the reefer yards.

(b) **Cargo loss rate**: the rate of the number of reefers whose temperatures are beyond the the allowed bandwidth of set temperature.

Based on the literature study (van Duin et al. 2018), the most comprehensive equations to model the temperature fluctuations at on/off mode are defined as follows:

$$\Delta T_{off}(t_{off}) = \Delta T_{ambient} - \Delta T_{ambient} * e^{\frac{-A*K*t_{off}*(1+S)}{m*C_p}} \tag{1}$$

$$S_i = \frac{j_i*A_i}{J_0} \tag{2}$$

$$S = \sum_i S_i \tag{3}$$

$$\Delta T_{on}(t_{on}) = Q * t_{on}/(m * C_p) \tag{4}$$

Where:

$\Delta T_{off}(t)$: Temperature fluctuation at off mode (℃);

$\Delta T_{ambient}$: Temperature difference between ambient temperature and internal temperature of reefer (℃);

A: Surface area of reefer (m²);

K: Thermal insulation of reefer (W/m²·℃);

t_{off}: Time at off mode(s);

S: Exposed sun intensity (no dimension);

m: Mass of cargo (kg);

C_p: Specific heat of cargo (kJ/kg·℃);

i : Reefer wall direction, 0-left, 1-right, 2-front, 3-back, 4-top;

S_i: Exposed sun intensity of i-wall (no dimension);

j_i: Sun intensity of i-wall (W/m²);

A_i: Area of i-wall (m²);

J_0: The total maximum amount of sun intensity received on all surfaces of a reefer in summer (W);

$\Delta T_{on}(t)$: Temperature fluctuation at on mode (℃);

Q: Cooling/Heating power (W);

t_{on}: Time at switch-on mode(s).

As seen, the equations cover different types of factors affecting the power consumption of reefers. For example, the key time points of each reefer unplugged and plugged-in needs to be determined, which are closely related to the dynamic and complex operation process of the reefers as shown in Figure 2. Moreover, the ambient temperature and exposed sun intensity depends on the geographic positions considering the stack effect. Thus, to evaluate the power demand and temperature fluctuations of reefers, it is necessary to determine the time-space operation situations of reefers in each stage.

Container terminal operation system is a complex dynamic system, traditional analytical method is difficult to describe the reefer container operation process. Therefore, we propose to apply agent-based simulation to simulate the stochastic operation process in Section 2.1, to estimate the power consumption and temperature fluctuations of reefers.

3. Simulation Model

This study uses AnyLogic software to establish a simulation model to simulate the reefer operation process at container terminal, and output the energy consumption of reefers, and the energy consumption and temperature fluctuations of each reefer.

3.1. Main agent

The Main agent is the basis of the simulation model, which has the following functions. (a) It generates terminal layout (e.g., function zones and road network), and port resources (agents of Berth, QC, YC, and ITs); (b) It realizes agent creation, activation, and interaction. Main agent creates the agents of Ship and ET at the scheduled arrival time, actives the agents of port resources and establishes the interactions between each agent; (c) It summarize and analyse the simulation results, outputs the values of peak powers and cargo loss rates of reefers.

3.2. Ship and Berth agents

As shown in Figure 3, the Ship agent simulates various behaviors of ships from arrival to departure, and the Berth agent simulates the occupancy and release of berth with interactions with the Ship agent.

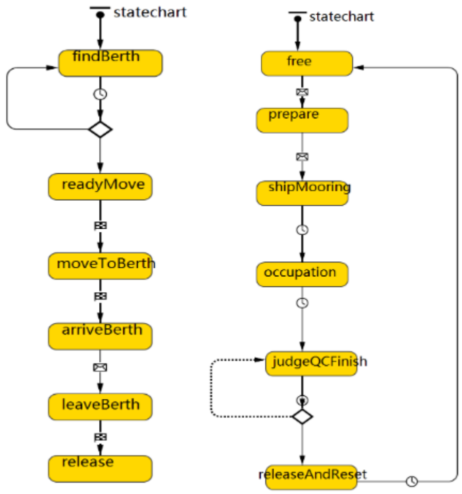


Figure 3. The state charts of Ship and Berth agents

Step **1:** The Ship agent generated by Main agent enters the State "*Statechart*" and waits at anchorage until a berth is assigned (State *findBerth*).

Step **2**: The Ship agent enters the State "*readyMove*", and the Berth agent starts to schedule QCs and ITs to the ship (State *prepare*).

Step **3:** The Ship agent sails to and arrives at the assigned berth (States *moveToBerth* and *arriveBerth*). Then, the Berth agent performs mooring operation (State *shipMooring*) and records the ship berthing time

(t_1) and sends it to Energy agent to determine reefer unplugged time (t_0).

***Step* 4:** After berthing, the Berth agent enters the "*occupation*" state, and activates the assigned QC agents to handle the ship. Meanwhile, the Berth agent checks whether the handling operation is completed (State *judgeQCFinish*).

***Step* 5:** When finished, the ship releases the Berth agent and leaves. While the Berth agent enters the State "*releaseAndReset*" and restore to idle state.

3.3. QC agent

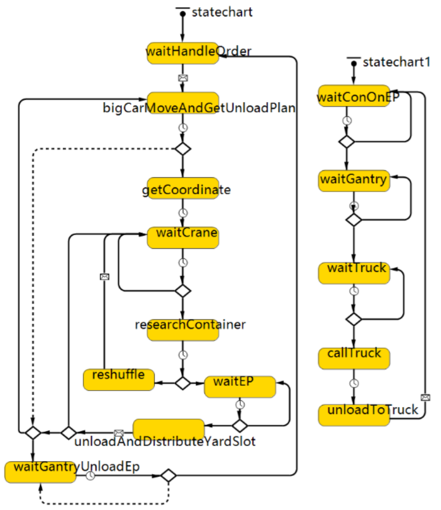
Figure 4 and Figure 5 show the implemented state charts and flow charts of QC agent with the main trolley and gantry trolley. The QC agent simulates all movements of the QC. These movements include acceleration, deceleration, hoisting, and lowering.

***Step* 1:** The QC agent waits for the loading and unloading tasks (State *waitHandleOrder*) until it receives a task from the Berth agent. It moves to the assigned destination and obtains its operation plan (State *bigCarMoveAndGetUnloadPlan*).

***Step* 2:** The QC agent gets its coordinate of the reefer and waits until the main trolley is idle (States *getCoordinate*, *waitCrane* and *researchContainer*). The main trollet carries out the operation of "*load conatiners from ship*" to obtain the target reefer by and determine its task type as shown in Figure 5.

(a) If the type is "reshuffle" (State *reshuffle)*, the operations for the main trolley (*reshuffle containers to ship* in Figure 5) is carried out.

(b) If the type is "unloading", the QC agent waits until the exchange platform (EP) has free slot (State *waitEP*). Then, the operations for the main trolley (*load containers to EP* in Figure 5) are carried out. After that, the QC agent enters next cycle (State *unloadAndDistributeYardSlot)*.



(a) Main trolley (b) Gantry trolley

Figure 4. The state charts of QC agent

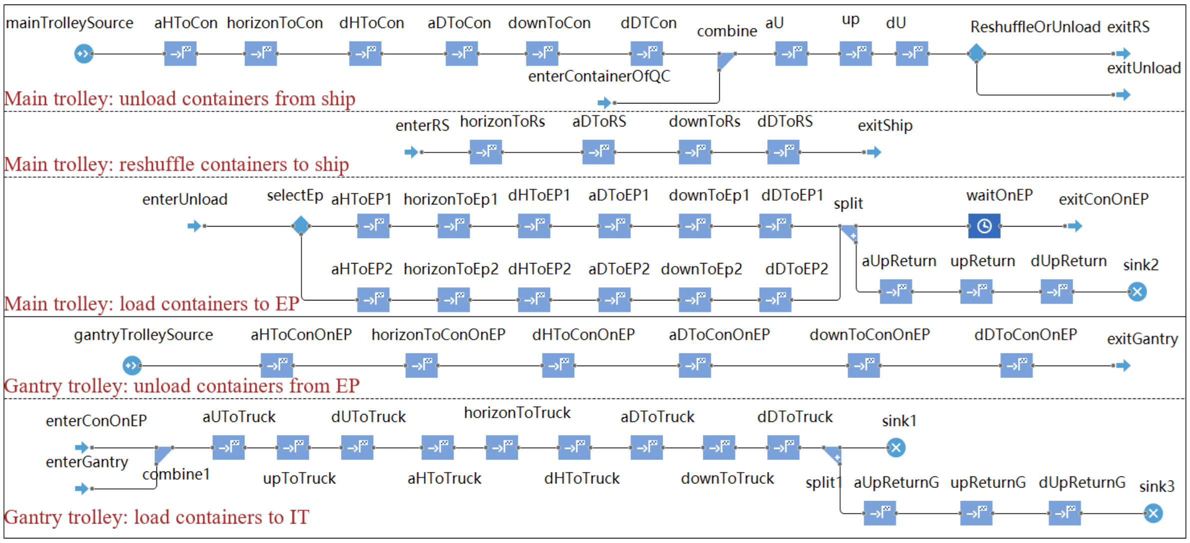


Figure 5. The flow charts of QC agent

3.4. YC agents

Figure 6 and Figure 7 show the implemented state charts and flow charts of YC agent with the stacking operation and pickup operation.

***Step* 1:** The YC agent waits until it receive a task from the IT agent (State *waitCon*).

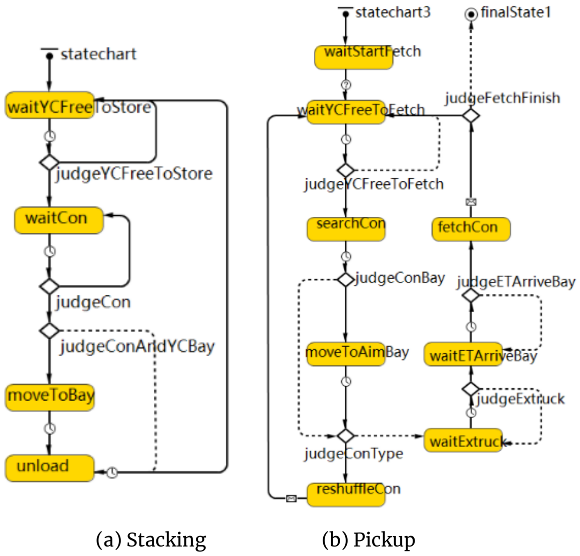
***Step* 2:** If the YC agent is not located at assigned destination, it firstly moves to the destination and starts the unloading operation (States *moveToBay*). Otherwise, it starts the unloading operation (State *unload*) and the YC trolley carries out the operation of "*unload containers from truck*", "*load containers to yard*" and "*trolley return*" in Figure 7. After that, record the YC unloading operation time (t_4) and send it to Energy agent to determine plugged-in time (t_5).

***Step* 3:** When receiving the task from ET agent (State *waitStartFetch*), the YC agent must finish its current task (State *waitYCFreeToFetch*).

(a) If the YC agent is not located at assigned position (States *searchCon* and *judgeConBay*), it moves to the assigned position (State *moveToAimBay*). Otherwise, it starts the operation according to the operation type (State *judgeConType*).

(b) If the type is "reshuffle" (State *reshuffleCon*), the YC trolley carries out the operation of "*unload containers from yard*" and "*reshuffle containers to yard*" as shown in Figure 7.

(c) If the type is "unload", it waits until the ET agent arrives (States *waitExtruck and waitETArriveBay*). Then, the ET arrival time (t_7) is recorded and sent it to Energy agent to determine the reefer unplugged time (t_6). Finally, the YC trolley unloads the container to the ET (*unload containers from yard* and *load containers to ET* in Figure 7).



(a) Stacking (b) Pickup

Figure 6. The state diagram of YC agent

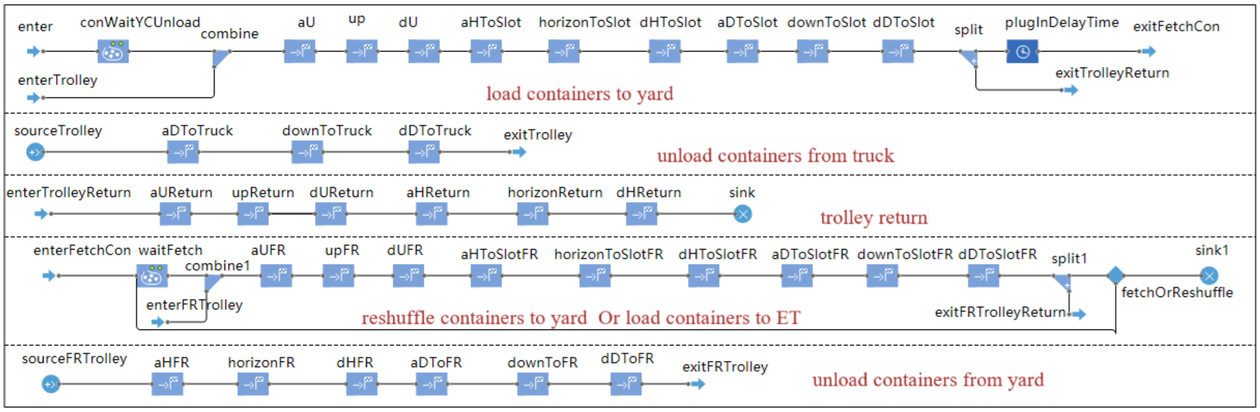


Figure 7. The flow chart of YC agent

3.5. IT and ET agents

Figure 8 shows the flow chart of IT agent, which simulates the containers transportation between QC and YC via roads within the container terminal. The process include *Initialization*, *Moving to QC and be served*, *Transporting containers to YC*, *Being served by YC*, and *Moving to parking lots/QC*.

Figure 9 shows the flow chart of ET agent. ETs randomly arrive at container terminal according to the time of ships' arrivals and departures. Then they move to the assigned bay after entrance permission, are served by the YC, and leave the port finally.

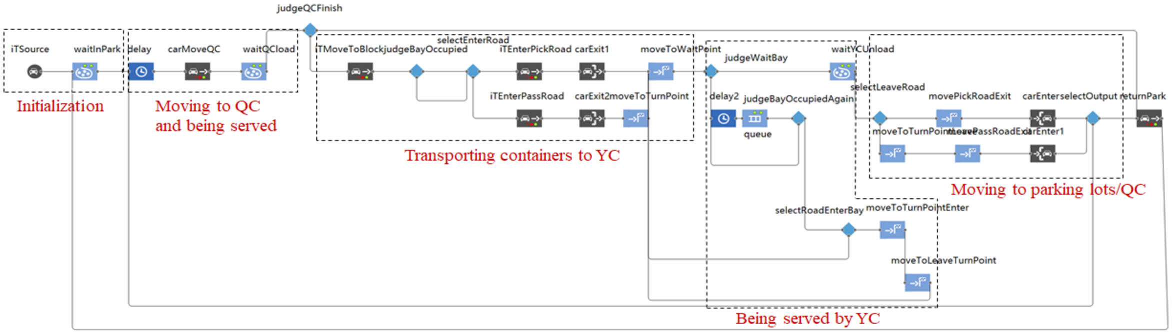


Figure 8. The flow chart of IT agent

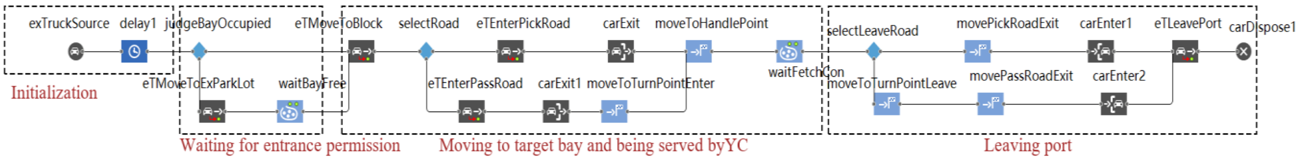


Figure 9. The flow chart of ET agent

3.6. Energy agent

The Energy agent is to calculate power consumption and temperature fluctuations over time of reefers.

***Step* 1:** For each reefer, the agent identifies which walls (up, left, right, front, and back) are receiving solar radiation, and the ambient temperature at each moment and the solar radiation intensity in each direction are obtained. As shown in Figure 10, for example, R1 has 2 walls (up and back), and R2 has 3 walls (up, left, and back) with sun lights.

***Step* 2:** If the reefer is in the cooling/heating mode, both the auxiliary power and cooling/heating power are supplied. Otherwise, only the auxiliary power is used for the compressor, fan, controller, etc.

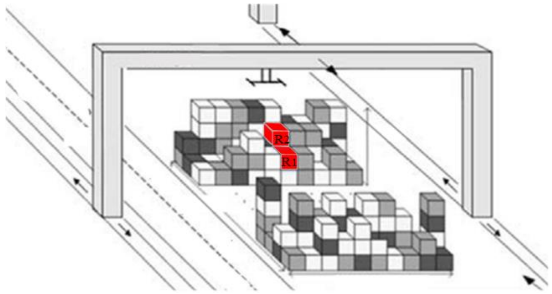


Figure 10. The walls with sunlight for reefer at yard

***Step* 3:** Estimate the times of when unplugged and plugged of each reefer according to the key time points (t_0, t_5, t_6) and (t_1, t_4, t_7). It depends on the availability of staff or crew and this study assumes the time difference is 0.5h, i.e., $t_1 - t_0 = t_5 - t_4 = t_7 - t_6 = 1.0h$.

***Step* 4:** Calculate power consumption and temperature fluctuations of all reefers at the terminal over time based on formula (1)-(4).

In ***Step* 3**, the Energy agent implements two modes: continuous and intermittent power supply.

(1) Continuous power supply mode (CPSM). In the CPSM mode, when the internal temperature of the reefer is within the allowed bandwidth of set temperature, the auxiliary power is used. Otherwise, the reefer starts the cooling/heating power, and the auxiliary power plus the cooling/heating power will be supplied to restore to the set temperature.

(2) Intermittent power supply mode (IPSM). The power rack usually supplies power to reefers on both sides (as shown in Figure 11). In the IPSM mode, the power rack supplies cooling/heating power to reefers on one side of rack at a time and supplies auxiliary power to reefers on the other side. After a certain interval, the supply power of the two sides will be exchanged. When cooling/heating power is supplied, the reefer intermittently starts the cooling/heating power until reaching to set temperature if the internal temperature of the reefer exceeds the allowed bandwidth of set temperature.

Figure 11. The simulated power consumption of 100 reefers

4. Model Verification

To verify the simulation model, this study simulates the power consumption of 100 reefers at yards in 120h, as shown in Figure 12. Compared with the actual data (Figure 13), their trends in changes of power consumptions are consistent, in which the power demand tends to increase first and then decrease in a day. Moreover, due to the uncertainties on the ambient temperature and solar radiation, the actual peak power is 400kW, while the simulated peak power is about 490 kW. Although, the gap of peak power exits, the simulation model is an important tool to support for analyzing the possibility of peak shaving.

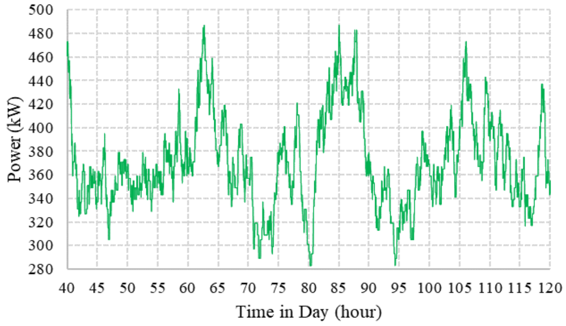


Figure 12. The simulated power consumption of 100 reefers

5. Case Study

This study takes a 70,000 DWT berth of a container terminal as an example. The reefers are classified into 6 classes and the properties of each reefer are generated randomly according to the Appendix in (Nafde, 2015). The properties include cooling power and auxiliary power, set temperature, the allowed bandwidth of set temperature, specific heat of cargo, thermal conductivity related to its service life, and the mass of goods varying from 5 to 23 tons. As the radio of each class of reefers changes with the seasons, we consider three ratios (R1, R2 and R3) as listed in Table 1. So, the peak power consumption and cargo loss rate of reefers are evaluated for S1, S2 and S3.

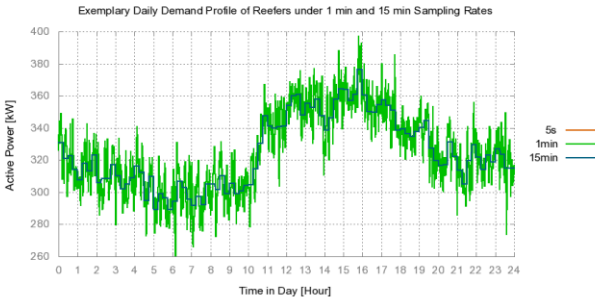


Figure 13. The actual power consumption of 100 reefers (Tao et al., 2014)

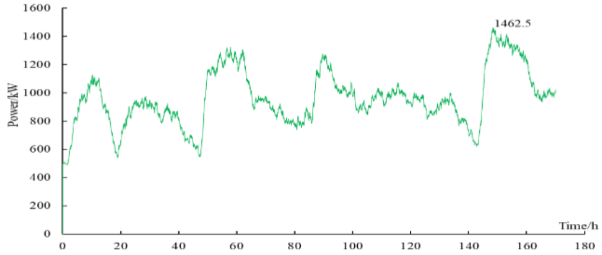
Table 1. Three ratios of 6 classes of reefers

No.	R1	R2	R3
Deep-Frozen	0.02	0.02	0.03
Frozen	0.7	0.16	0.35
Chilled	0.1	0.5	0.3
Pharmaceuticals	0.06	0.2	0.2
Banana	0.1	0.1	0.1
Musical instruments, paintings	0.02	0.02	0.02

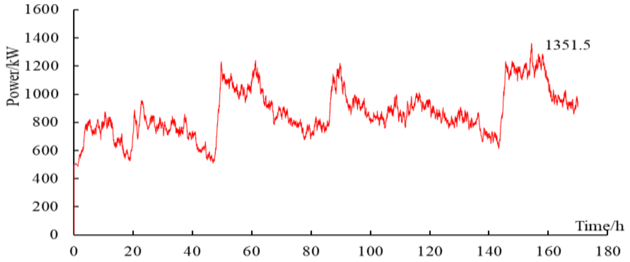
5.1. Benchmark case

The benchmark cases (S1, S2 and S3 in Table 2) select the CPSM mode to run the simulate model and simulate the operation process of the container terminal for a week. And Figure 14 shows the power consumption changes of reefers for S1, S2, and S3. The different ratios of 6 classes of reefers have a certain influence on the peak powers and cargo loss rates. For example, the peak powers for S1, S2 and S3 are 1452.5kW, 1351.5kW and 1364kW respectively. In addition, the cargo loss rates for S1, S2 and S3 are 9.3%, 16.8%, and 12.5% respectively. Moreover, the results in Figure 14 show that the power consumption of reefers will increase sharply after each ship arrival and then decrease slowly over time, which results in several peaks.

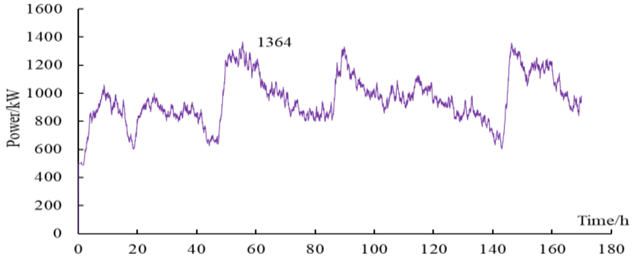
The peak power is caused by the increasing number of reefers stacked at yard when ship arrival, and most of them switch to cooling/heating mode simultaneously once storing at yard due to previous long-time outage. The outage duration (t_5-t_0) at Stage1-4 is so long that the internal temperature of reefer is beyond the allowed bandwidth. Moreover, the unplugged duration of each reefer is related to its own unloading sequence, and the earlier the unloading, the shorter the outage duration.



(a) S1



(b) S2



(c) S3

Figure 14. The power of reefers with three ratios

5.2. Improvement strategies

To improve the performance on the power consumption and cargo loss rate, we explore a series of improvement strategies as listed in Table 2.

Table 2. Simulation experiment schemes

Strategy	Power supply mode		Reefer unloading sequences		Ratio
	CPSM	INTE	Ran	IMP	
S1	✓	×	✓	×	R1
S2	✓	×	✓	×	R2
S3	✓	×	✓	×	R3
SB1	✓	×	×	✓	R1
SB2	✓	×	×	✓	R2
SB3	✓	×	×	✓	R3
SC1-t	×	✓	✓	×	R1
SC2-t	×	✓	✓	×	R2
SC3-t	×	✓	✓	×	R3

1. Reefer unloading sequences

To ensure as many reefers as possible being within the allowed temperature bandwidth, the reefers with a rapid temperature change should be prioritized during the stages of "On ship" and "Unloading". Thus, we propose to make reefer unloading sequences based on the time required to exceed the allowed temperature bandwidth (t_e, unit: s). The value of t_e is calculated by formula (5) considering the reefers' properties and environmental factors. So, the improved unloading plans are obtained by the ranking the values of t_e for all reefers.

$$t_e = -\frac{m*C_P}{A*K} \ln\left(\frac{\overline{T}_{ambient} - T_{setTemp} - \Delta T*0.9}{\overline{T}_{ambient} - T_{setTemp}}\right) \tag{5}$$

$T_{setTemp}$: Reefer setting temperature (℃);

$\overline{T}_{ambient}$: Mean ambient temperature (℃);

ΔT : The allowed temperature bandwidth (℃), the degree to which these fluctuations are allowed depends on the type of products.

2. IPSM mode

IPSM mode is another way to reduce the power consumption and cargo loss rate by decreasing the number of cooling/heating reefers at the same time. As the timeslot of IPSM mode (t) is the key factor, t=5min, 10min, and 15min are considered.

After running simulation experiment for all improved strategies, the results are given in Table 3.

(a) Improved unloading sequence has little effect on power consumption of reefers, but significantly reduces cargo loss rate from more than 10% to 2%.

(b) IPSM mode does reduce peak power consumption of reefers, decreased by 4.7%-9.6%. With the increasing timeslots of IPSM mode, the peak power decreases, but the cargo loss rate increases.

(c) Generally, IPSM mode and improved unloading sequence can both lead to varying degrees of cost savings. But the cost will increase if port don't choose the proper time interval for IPSM mode, such as SC1-15 and SC3-15.

Table 3. Simulation results

Scheme	Peak power (kW)	Decrease (%)	Cargo loss rate (%)	Cost Change (CNY/Day)
S1	1462.5	——	5.0	——
SB1	1492.5		1.6	-364.05
SC1-5	1347.5	7.8	9.4	-671.51
SC1-10	1321	9.6	11.7	-518.32
SC1-15	1341	8.3	16.9	+1026.70
S2	1361.5	——	6.2	——
SB2	1280		1.9	-2271.70
SC2-5	1297.5	4.7	8.2	-472.00
SC2-10	1277.5	6.2	8.7	-650.00
SC2-15	1252.5	8	11.4	-366.20
S3	1364	——	4.8	——
SB3	1360		1.7	-793.37
SC3-5	1241	9	8.8	-898.71
SC3-10	1276.5	6.4	10.2	-35.01
SC3-15	1263.5	7.4	13.3	+503.35

In conclusion, the proposed simulation model can model the power consumptions and temperature fluctuations with time of reefers at container yard through simulating the terminal operation process. Analyzing the results of a series of experiments, we find that improved reefer unloading sequence has a significant effect on cargo loss reduction, while IPSM mode can decrease the number of cooling/heating reefers at the same time and realize peak shaving.

6. Conclusions

This study establishes a simulation model of reefer operation process to evaluate the power consumption and temperature fluctuations of all reefers at the container yard. The model considers dynamic variations of solar radiation, ambient temperature, stack effect, and the reefer properties including cooling/heating power and auxiliary power, set temperature, the allowed temperature bandwidth, specific heat of cargo, thermal conductivity related to its service life, and the mass and type of goods. Through simulating the terminal operation process, we get the key operation time and storage position of each reefer more accurately to calculate the power consumption and cargo loss rates according to solar radiation and ambient temperature. The improved reefer unloading sequences is designed based on the time required to exceed the allowed temperature bandwidth. Two power supply modes (CSPM and ISPM mode) are implemented in Energy agent. Analyzing the results of a series of experiments, the improved reefer unloading sequences can improve the quality assurance of reefers, and ISPM can reduce the peak power of reefers but increase the cargo loss ratio with increasing timeslot of IPSM mode. Therefore, when port staff make the schedule plan of unloading the ship, it is important for cargo loss reduction to take the temperature change of reefer into account. In addition, it currently suggests that power supply in batches is applied at reefer yard under the condition of selecting an appropriate timeslot, as the case may be. In the future, the IPSM mode may have a chance to develop into the Intelligent power supply control for each reefer based on itself temperature and the real time peak power, rather than for a group of reefers. This will solve the cargo loss due to intermittent power supply.

This study provides supports in estimating the power consumptions and cargo loss rates. However, there are still some improvements. For example, the staff scheduling optimization problem is not considered, which assumes the operation duration is a fixed value. In the future, the staff scheduling optimization will be integrated with power management of reefers.

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