Simulation-based emission calculation method for container terminal production operation system

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Abstract. The emission calculation method based on actual energy data and mathematical analytical models have the disadvantages of time-consuming and high cost, and therefore it is necessary to study a system simulation-based method for calculating the emissions of container terminal production operation systems. This paper develops a simulation model of container terminal production operation systems based on the Arena simulation platform. Emission calculation formulas are embedded into the simulation model, which can calculate and output the energy consumption and emissions of ships and handling equipment. To validate the system simulation-based emission calculation method, a container terminal is taken as the research object and a series of simulation experiments are conducted. The main results show that (1) NOx is the main air pollutant and the CO2 and NOx emissions mainly come from ships, which are 90.7% and 80.4%, respectively, and (2) CO2 and NOx emissions during navigation of ships in the waterway are the main part of ship emissions and account for 60.7% and 53.9%, respectively.

1. Introduction

Energy saving and environmental protection have attracted wide attention of the international community. Environmental pollution and climate change pose threats to human survival, society, economy and environment. As one of the key nodes of shipping industry, green and low-carbon ports have attracted more and more attention. Container transportation has become a major mode of water transportation due to its advantages, such as safety, efficiency and economy. At the same time, the problem of energy saving and emission reduction of container terminals has become more and more prominent. A container terminal is a complex random system, which brings together lots of large-scale mechanical equipment such as ships, quay cranes, yard cranes and horizontal transportation vehicles. In the process of container terminal production operations, mechanical equipment emits a large amount of air pollutants and greenhouse gases, which is an important source affecting the global air quality. Moreover, the connection between production links and equipment is very complicated. Changes in one link or device will not only affect the direct emissions of this link, but also emissions generated by other links and devices.

At present, relevant studies are mostly based on actual measurement data and mathematical analytical models to estimate emissions of container terminal production systems. Peng [1] summarized the port carbon emission statistical and analytical methods formulated by China, and compared the carbon emission intensity of domestic and foreign container terminals. Wang et al. [2] proposed a theoretical formula for calculating the carbon emissions of container terminals, which is
based on analysing the energy consumption indicators of various mechanical equipment and other influencing coefficients. Fan et al. [3] established the emission lists of ports in the Pearl River Delta through fuel consumption estimation and statistics on the basis of field survey. Dong et al. [4] built a carbon emission model for container terminal handling equipment and technological processes under different collection and distribution modes, and used numerical examples to quantitatively analyse container terminal carbon emissions.

From the above analysis, most of the existing studies estimate carbon emissions of container terminals by using the actual energy data of ports and mathematical analytical models, which have the disadvantages of time-consuming and high cost. Thus, it is necessary to study a system simulation-based method of calculating the emissions of container terminals, which can simulate container terminal operations and calculate emissions in time. To this end, this paper builds a simulation model for the container terminal production operation system based on the Arena simulation platform, simulates container terminal operations and outputs the total emissions, which provides a theoretical basis for the construction of a green port.

2. Emission calculation methods of ships and handling equipment

In order to fully quantify the emissions from diesel and electricity consumption by container ships and handling equipment, a life-cycle evaluation method is adopted, which fully considers carbon emissions and air pollution generated by diesel and electricity at all stages of the life cycle such as mining, transportation, refining and consumption. The unified calculation formula for carbon and air pollution emissions is as follows.

\[
Emissions = \text{energy consumption} \times \text{emission coefficients}
\]  

(1)

The calculation methods for energy consumption of ships and handling equipment are as follows.

2.1. Calculation method for fuel consumption of ships

\[
F_{\text{ship,}j} = F_{\text{sail,}j} + F_{\text{anchor,}j} + F_{\text{berth,}j}
\]

(2)

Where \(F_{\text{ship,}j}\) is the total fuel consumption of ship \(i\) in the port, kg; \(F_{\text{sail,}j}\) is the fuel consumption of the ship sailing; \(F_{\text{anchor,}j}\) and \(F_{\text{berth,}j}\) are the fuel consumption of the ship waiting at the anchorage and berth, respectively.

The fuel consumption calculation formula of the ship sailing is as follows:

\[
F_{\text{sail,}j} = \left[ P^M_i \cdot R^M \cdot I^M \left( \frac{v_j^o}{v_j^d} \right)^3 + n_i \cdot P^A_i \cdot R^A \cdot I^A \right] \cdot t_{\text{sail,}i}
\]

(3)

where \(P^M_i\) and \(P^A_i\) are the power of the main and auxiliary engines of ship \(i\), respectively, kW; \(R^M\) and \(R^A\) are the diesel consumption rates of the main and auxiliary engines, respectively, kg/kWh; \(I^M\) and \(I^A\) represent the load coefficients of the main and auxiliary engines, respectively; \(v_j^o\) and \(v_j^d\) are the actual speed and the designed speed of the container ship in the port area, respectively, nm/h; \(n_i\) represents the number of auxiliary engines; \(t_{\text{sail,}i}\) represents the sailing time, h.

The fuel consumption calculation formulas of the ship waiting at anchorages and berths are as follows:

\[
F_{\text{anchor,}j} = l^A \cdot (P^A_i \cdot R^A) \cdot t_{\text{anchor,}i}
\]

(4)
where $t^\text{anchor}_i$ and $t^\text{berth}_i$ represent the waiting time at anchorage and berth of ship $i$, respectively, h.

2.2. Calculation method for electricity consumption of quay cranes

$$F^k_{QC} = P'' \cdot t'' + P' \cdot t' + P^d \cdot t^d$$

where $F^k_{QC}$ is the power consumption of quay cranes, kWh; $P''$ is the power of lifting motors, kW; $P'$ is the power of trolley motors, kW; $P^d$ is the power of bridge motors, kW; $t''$ is the working time of lifting motors, h; $t'$ is the working time of trolley motors, h; $t^d$ is the working time of bridge motors, h.

2.3. Calculation method for energy consumption of yard cranes

$$F^k_{YC} = C_{YC} \cdot \gamma^k_{YC}$$

where $F^k_{YC}$ is the energy (diesel or electricity) consumption of yard cranes; $C_{YC}$ is the amount of containers (equal to $C_{QC}$ in numerical value) for the handling operations of yard cranes; $\gamma^k_{YC}$ is the energy consumption rate of yard cranes for handling one container, kg/TEU or kwh/TEU.

2.4. Calculation method for energy consumption of horizontal transport vehicles

$$F^m_{\text{vehicle}} = R^m_{\text{vehicle}} \cdot v^m_{\text{vehicle}} \cdot t^m_{\text{vehicle}}$$

$$F^m_{CT} = R^m_{CT} \cdot v^m_{CT} \cdot t^m_{CT}$$

where $F^m_{\text{vehicle}}$ is the energy consumption of vehicles in the port; $F^m_{CT}$ is the energy consumption of the external trucks; $R^m_{\text{vehicle}}$ is the energy consumption rate of internal vehicles in state $s$; $R^m_{CT}$ is the energy consumption rate of external trucks in state $s$; $s=1$ means the internal vehicle with a heavy load and $s=0$ means the vehicle is empty; $v^m_{\text{vehicle}}$ means the driving speed of vehicles in the port in state $s$; $v^m_{CT}$ means the driving speed of external trucks in state $s$; $t^m_{\text{vehicle}}$ and $t^m_{CT}$ represent the driving time of internal vehicles and external trucks in state $s$, respectively.

In this study, CO$_2$, SO$_2$, NO$_X$, CO, and HC emissions are considered. The emission coefficients for diesel and electricity are determined as follows:

According to the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" [5], assuming that diesel is fully burned, the carbon emission coefficient of diesel is 3.16 kg/kg.

According to the "Technical Guidelines for Compiling Emission Inventory of Air Pollutants from Non-road Mobile Sources" [6], air pollution emission coefficients of diesel consumed by ships and handling equipment are different, as shown in table 1. The sulfur content of diesel is 0.35g/kg.

| Pollutant        | NO$_X$ | CO   | HC   |
|------------------|--------|------|------|
| Ship             | 47.60  | 23.80| 6.19 |
| Handling equipment | 32.79  | 10.72| 3.39 |

The carbon emission coefficient of electricity is taken from the baseline emission coefficient of China Power Grid published by the Department of climate change, national development and Reform
Commission. SO\textsubscript{2} and NO\textsubscript{X} emission coefficients are taken from the "Annual Development Report of China Electric Power Industry in 2018" [7].

| Pollutant | Emission coefficient (g/kWh) |
|-----------|------------------------------|
| CO\textsubscript{2}   | 810                          |
| SO\textsubscript{2}  | 0.26                         |
| NO\textsubscript{X} | 0.25                         |

3. Emission calculation simulation model of container terminal production operations
The quantification of greenhouse gases and air pollution emissions in the container terminal production operation system is based on the operation data of various facilities, which is difficult to obtain directly in the production operations. Therefore, an emission calculation simulation model of container terminal production operations is established to simulate the process of container terminal production operations and output emissions.

3.1. Logical model
This section illustrates a logical model of container terminal production operations, which provides a model framework for the construction of the simulation model, as shown in Figure 1.

Figure 1 divides the container terminal production operation system into four subsystems, namely ship arrival subsystem, ship entering and leaving the port subsystem, handling operation subsystem, and external truck operation subsystem.

Figure 1. The logical model of container terminal production operations.
3.2. Emission calculation simulation model

Based on the processes of container terminal production operations, with the aid of Arena simulation software, the emission calculation simulation model of container terminal production operations is constructed, including ship arrival sub-model, berth assignment sub-model, ship entering the port sub-model, handling operations sub-model, ship leaving the port sub-model, and emissions output sub-model as shown in Figure 2.

The ship arrival sub-model is used for generating container ships according to the rules and attributes of ships arriving at the port. The berth assignment sub-model is used for allocating berth resources for arriving ships. The ship entering the port sub-model is used for simulating weather conditions and judging navigation conditions, while the ship leaving the port sub-model is opposite. The handling operations sub-model is used for completing quay crane operations, internal yard truck operations, yard crane operations and external yard truck operations. Besides, in order to calculate the emissions of container terminal production operations, the emission calculation formulas are embedded into the emissions output sub-model, which can not only calculate the energy consumption and emissions of ships and handling equipment, but also output them through the output module. Considering that the length is limited to display all the simulation models, this paper takes QC, YT, YC, and external truck operation simulation sub-models as examples for demonstration, as shown in Figure 3.

![Figure 2](image2.png)

**Figure. 2** The emission calculation simulation model of container terminal production operations.

![Figure 3](image3.png)

**Figure. 3** Handling operations sub-model.

4. Case study

4.1. Parameter setting

The numerical experiments are set according to a container terminal in North Africa. Several simulation experiments for emission calculation of the container terminal production operation system
are carried out. There are 10 berths at the terminal, and each berth corresponds to 8 container yards. Berth parameters are shown in Table 3. The waterway is 20 nautical miles long, and the average speed of ships is set as 10 knots. The average auxiliary operation time is set as 4h. The quay cranes are single 40-foot trolleys, and the average operation efficiency is set as 30 TEU/h. The number of quay cranes is three times that of yard crane, and the average operation efficiency of yard cranes is set as 35 TEU/h. The average speed of container trucks is set as 22.5 km/h.

Table 3. Berth parameters.

| Berth number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Berth tonnage (10000 tons) | 5   | 5   | 7   | 7   | 7   | 10  | 16.5 | 20  | 2   | 2   |
| Number of quay cranes | 3   | 4   | 4   | 4   | 4   | 5   | 5   | 5   | 2   | 2   |

Ship parameters are set as follows:
(1) Ship arrival rules
Based on the analysis of arrival data, it is found that the number of arriving ships obeys the Poisson distribution, which means that arrival time intervals obey a negative exponential distribution. The average time interval is 4.612 h. Other ship parameters are shown in Table 4. The diesel consumption rates of main engines and auxiliary engines are 0.206 kg/kWh and 0.211 kg/kWh respectively.

Table 4. Type combination of ships.

| Ship tonnage (10000 tons) | 2   | 3   | 5   | 7   | 10  | 12  | 15  | 20  |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Proportion (%)            | 34  | 25  | 17  | 11  | 10  | 1   | 1   | 1   |
| Design speed (nm/h)       | 18.67 | 22.3 | 24.3 | 25 | 24.7 | 25.3 | 25.38 |
| Container capacity (TEU)  | 875 | 1000 | 1800 | 3400 | 4800 | 6000 | 7950 | 10050 |
| Main power (kW)           | 11769 | 18411 | 48617 | 51500 | 58344 | 72240 | 72360 | 72360 |
| Auxiliary power (kW)      | 700 | 1260 | 1960 | 2320 | 2760 | 3320 | 3850 | 4000 |
| Number of auxiliaries     | 3   | 3   | 3   | 3   | 4   | 4   | 4   | 4   |

(2) Ship berthing rules
The available berths of each ship are shown in Table 5. When choosing berths, the smaller tonnage berths are preferred among all available berths.

Table 5. Available berth for each ship.

| Berth tonnage (10000 tons) | 2   | 5   | 7   | 10  | 16.5 | 20  |
|---------------------------|-----|-----|-----|-----|------|-----|
| Ship tonnage (10000 tons) | 2   | 2,3,5 | 2,3,5,7 | 3,5,7,10 | 5,7,10,15 | 7,10,15,20 |

4.2. Result analysis
By conducting the above simulation experiments, the emissions of CO$_2$, NO$_X$, CO, CH and SO$_2$ at the container terminal are obtained as shown in Table 6. It shows that the emission of CO$_2$ is the most, and NO$_X$ is the main part of air pollution.
Table 6. Emissions of CO2 and air pollution.

| CO2 Emissions (ton) | NOx | CO | CH | SO2 |
|---------------------|-----|----|----|-----|
| 86013.52            | 1134.72 | 548.31 | 144.5 | 19.5071 |

In addition, in order to analyse the proportion of emissions generated by various parts of the container terminal production operation system, the proportions of CO2 and NOx from ships, quay cranes, yard cranes and vehicles are counted as shown in table 7 and table 8. It can be seen that CO2 and NOx mainly come from ships, and the emissions during ship navigation are the main part of ship emissions. The NOx emission coefficient of electricity is very small, and the NOx emission of quay crane accounts for a small proportion as quay cranes are driven by electricity.

Table 7. CO2 emission proportion.

| Source           | Quay crane | Yard crane | Vehicle | Ship |
|------------------|------------|------------|---------|------|
| CO2 emission (ton)| 6764.59    | 4649.92    | 5405.41 | 3503.07 | 46332.24 | 19358.30 |
| Proportion (%)    | 7.86       | 5.41       | 6.28    | 4.07  | 53.87    | 22.51    |

Table 8. NOx emission proportion.

| Source       | Quay crane | Yard crane | Vehicle | Ship |
|--------------|------------|------------|---------|------|
| NOx emission (ton) | 2.09 | 47.81 | 55.57 | 287.95 | 52.11 | 689.19 |
| Proportion (%) | 0.18 | 4.21 | 4.90 | 25.38 | 4.59 | 60.74 |

5. Conclusions

In order to promote the construction of green port, a container terminal is taken as the research object in this paper, and a simulation model of the container terminal production operation system based on Arena is developed aiming for calculating emissions. The total emissions of the container terminal production operation system are obtained by simulating the container terminal production process. The main conclusions are listed as follows:

1. NOx is the main air pollutant during the operation of container terminal. The CO2 and NOx emissions at the container terminal mainly come from ships in port, which are 90.7% and 80.4% respectively in numerical experiments. CO2 and NOx emissions during navigation of ships in the waterway are the main part of ship emission and account for 60.7% and 53.9% respectively.

2. For problems of high cost and long computing time when using mathematical analytical model to estimate emissions, simulation method proposed in this paper can be applied to solve these problems with actual energy data efficiently and provides theoretical basis for the construction of green port in future.

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