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Optimal Management and Simulation of Harbor Resources Given Uncertain Conditions and Low Carbonization

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Abstract

This paper proposes a multi-objective optimization model for collocation of shoreline resources under uncertain conditions. By incorporating carbon emissions and TCO (Total Cost of Ownership), an optimization scheme for shoreline resources in its operation period is further defined here. The proposed simulation model can effectively measure the service indicator and operation mode at the harbor. The results from correlational studies show that since the low-carbonization retrofit at the harbor, the environmental benefit around the harbor has been greatly improved, and the production cost has also been reduced significantly. A simulation algorithm is proposed here for low-carbonization retrofit of the yard crane, which implements relevant reconstruction strategies for yard crane at different service ages. Besides, a kind of low-carbonization retrofit strategy, which does not affect the normal operation of harbor, is also developed for single facility. A dynamic programming model in question is constructed to effectively reduce the overall carbon emissions at the harbor, thus achieving a good effect on harbor multi-objective optimization. If the limit of funds is not tight, the revamping workloads of facilities in the harbor will be greatly increased. The service indicator in the harbor can be pushed to the limit of low carbonization retrofits. The verification results from project instances show that the simulation model proposed in this paper features high precision and is superior to others.

Key words

Collocation of shoreline resources, Multi-objective optimization, Uncertainty, Low-carbonization, Simulation.

1. Introduction

With the advent of the trade globalization, the international logistics industry also gets a constant development. Unlike the trains, aircrafts and other transport means, the large ship can carry a huge load at the marine transport, and with advanced harbor operation system and other unparalleled advantages, it takes up a dominant position in the whole logistics industry. However, in recent years, the international economic situation becomes more complex, and the costs for ship transport and dispatching shoreline resources continue to increase. In order to ensure the sustainable development of dispatching system for shoreline resources, it is an irresistible trend to transform the scientific technology and reduce production cost in the future development of harbor [1-4].

The previous studies focused on harbor container berth, rood truck transport route limit, and optimal working efficiency at container deport and other jobs in relation to collocation of shoreline resources and logistics optimization [5-8]. They integrated all harbor resources as a whole, and relocated one or two or even more types of resources in the system [9-14]. However few studies have been done on low carbonization collocation of shoreline resources under uncertain environment.

In recent years, the global climate gets warmer. To reduce CO_2 emissions, it is a compulsory policy that every country has enacted for all sectors to establish the low-carbon industries. For the low-carbon harbor, there are some studies which have focused on CO_2 emissions discharged by various resources as consumed and by individual logistics chains such as quantitative transmission, rood truck, quay crane. These studies have never involved the life cycle of the low-carbon logistics system after retrofit and the environmental cost-benefit after low carbonization [15-19].

It is a more urgent need to meet the challenges that the collocation of shoreline resources based on uncertainties has presented before us. As a harbor with intensive resources, it is vulnerable to impacts from external environment and human factors. A quantitative risk assessment, uncertainty of operating systems and so on are all important pledges for reducing the production costs of harbor and improving the economic efficiency [20-25].

This paper proposes a multi-objective optimization model for collocation of shoreline resources under uncertain conditions. By synthesizing carbon emissions and TCO (Total Cost of Ownership), an optimization scheme for shoreline resources in operation period is further defined. The proposed simulation model can effectively measure the service indicator and operation mode at the harbor. The results concluded in this paper provide a theoretical reference for improving collocation of shoreline resources at related harbors.

2 Concepts on Multi-Objective Optimization Model

2.1 Measurement of Carbon Emission

A low-carbon emission harbor means the abandonment of traditional construction technology. The new energy resources and technologies must be adopted in the early planning, construction, official operation and maintenance processes, thereby reducing carbon emissions, achieving sustainable development of harbor. This paper mainly explores the methodology of carbon reduction and resource allocation in the operation phase of the harbor.

Carbon emissions contain direct CO_2 and secondary CO_2 from facilities which operate using electric and heat energies. There are carbon emissions mainly discharged from ships and facilities involved with harbor resources as consumed.

The direct CO_2 emissions, $W^{sa}{}_{fuel}$, during the voyage of ship is calculated as

$$W_{fuel}^{\text{sail}} = C_{fuel} \cdot \bar{\omega}_{fuel} \cdot \left(\sum_{j=1}^{n^{\text{ME}}} P_j^{\text{ME}} \cdot V_j^{\text{ME}} + \sum_{j=1}^{n^{\text{AE}}} P_j^{\text{AE}} \cdot V_j^{\text{AE}} \right) \cdot \frac{d_{\text{ship}}}{v_{\text{ship}}} \tag{1}$$

C_{fuel} is the carbon emission coefficient; w_{fuel} is the fuel consumption rate; P_j and V_j are separately the power and fuel consumption of the engine j; n is the number of engines; d_{ship} is the sailing distance.

The quay crane at the harbor is generally a power-driven type, the annual carbon emission of quay crane i, $W_{fue}{}^{qc}$, is counted as follows

$$W_{fuel,i}^{\text{qc}} = EF_{fuel} \cdot N_i^{\text{qc}} \cdot \left(\frac{2 \cdot H_i^{\text{u}} \cdot p_i^{\text{u}}}{v_i^{\text{u}}} + \frac{\left(R_i^0 + D_i\right) \cdot p_i^{\text{l}}}{v_i^{\text{l}}} \right) \tag{2}$$

N_i^{qc} is annual working times; H_i^u, p_i^u is the height the quay crane rises or descents and the motor power; R_i^o is the outstretching distance of quay crane.

Carbon emission from rood truck in the container arear is

$$W_{fuel}^{\mathrm{ct}} = \sum_{i=1}^{n^{\mathrm{ct}}} W_{fuel,i}^{\mathrm{ct}} = \sum_{i=1}^{n^{\mathrm{ct}}} E_{fuel} \cdot \rho_{fuel,i}^{\mathrm{ct},s} \cdot v_i^{\mathrm{ct}} \cdot t_i^{\mathrm{ct}} \tag{3}$$

E_{fuel} is the carbon emission coefficient; s is the state of rood truck (full or empty); v_i^{ct} is the driving speed of rood truck; t_i^{ct} is the driving time of rood truck.

Annual carbon emission of gantry crane in the harbor container area is

$$W_{fuel}^{\mathrm{RMG}} = \sum_{i=1}^{n^{\mathrm{RMG}}} W_{fuel,i}^{\mathrm{RMG}} = \sum_{i=1}^{n^{\mathrm{RMG}}} EF_{fuel} \cdot Q_i^{\mathrm{RMG}} \tag{4}$$

2.2 Uncertainty of Harbor Resource Collocation

The resource allocation system at the harbor is a large complex system. For the logistics system there, the uncertainty of the shipping network refers to the natural disasters such as windstorms, typhoons, etc., and man-made accident disasters such as fire, explosion, ship collision; the uncertainty of harbor resource allocation refers to job problems that occurred in the whole process of operating system, e.g. arrival or departure of the rood truck at or from the harbor, faults occurred on the handling and transport facilities, unloading time of container, etc. The number of ships arrived daily or monthly, the arrival time interval of ships and other factors are all uncertainties the system involves.

3. Harbor Resource Optimization Model Based on Uncertain Condition and Low Carbon Environment

3.1 Modelling

Suppose the following conditions when modelling:

(a) Low-carbon adjustment is made for the traditional collocation of harbor resources within 2 years;

(b) Ship container handling takes the principle of first come, first served, in accordance with the process of unloads preceding loads;

(c) Container haul trucks must be dispatched to ensure a shortest route;

(d) The carbon emissions cycle spans any one operation stage at the harbor.

There are two objective functions for the model built here, i.e. the lowest carbon emission and the lowest production cost. The objective function set is

$$\min F(\mathrm{X}) = \left[f_1(\mathrm{X}), f_2(\mathrm{X}) \right] \tag{5}$$

$$\min f_1(\mathrm{X}) = \sum_{EQ=1}^{N^{\mathrm{EQ}}} W_{EQ}(t) = \sum_{EQ=1}^{N^{\mathrm{EQ}}} \sum_{i_{EQ}=1}^{n_{EQ}} W_{i_{EQ},fuel}(\mathrm{X}), \forall t = 1, \ldots, T^{s1} \tag{6}$$

$$\min f_2(\mathrm{X}) = \sum_{EQ=1}^{N^{\mathrm{EQ}}} Z_{EQ}(t) = \sum_{EQ=1}^{N^{\mathrm{EQ}}} \sum_{i_{EQ}=1}^{n_{EQ}} Z_{i_{EQ},fuel}(\mathrm{X}), \forall t = 1, \ldots, T^{s1} \tag{7}$$

The constraint condition of objective function is

$$\sum_{EQ=1}^{N^{\mathrm{EQ}}} \sum_{i_{EQ}=1}^{n^{EQ}} C_{i_{EQ},fuel}^{EQ}(\mathrm{X}) + I_{i_{EQ},fuel}^{EQ}(\mathrm{X}) \le B_t \tag{8}$$

X is the decision vector for harbor resource optimization; T^{sl} is the time spent in low-carbonization retrofit of equipment used at the harbor; B_t is the total capital limit for the harbor; the two entries on the left side of the equation 8 are the cost of low carbon retrofit of the equipment and the cost of the new resources, respectively.

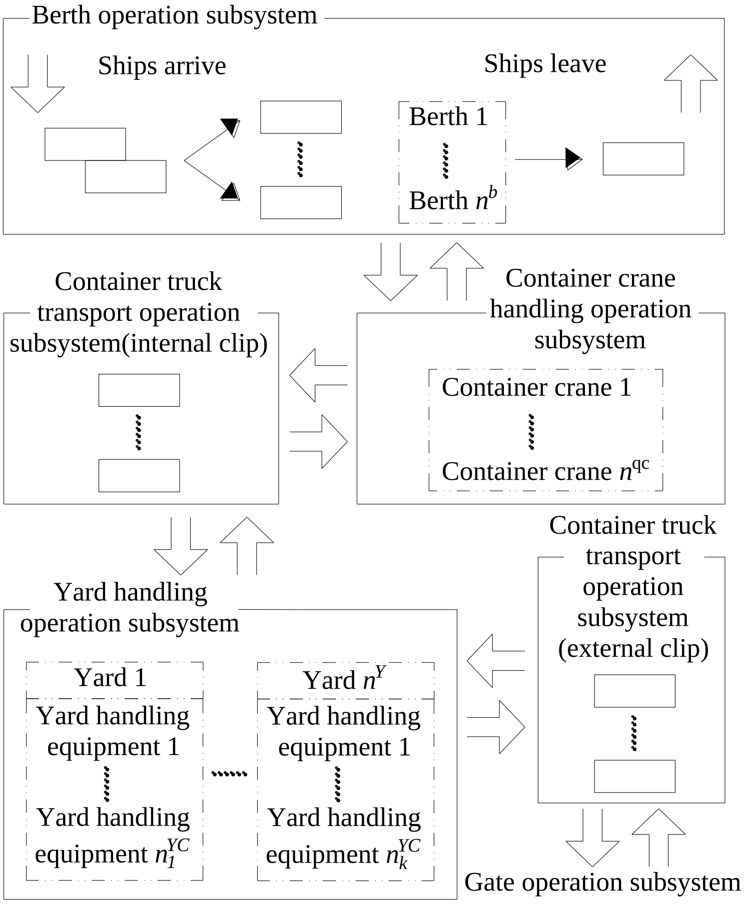

Fig.1. The Resource Allocation of Operation System in Container Terminal Production

The queuing theory is imported to construct the optimal schedule model for overall production of the harbor systems. The Arena software is used for modelling. Harbor resource allocation system can be considered as an aggregation of multiple operation subsystems. The whole logistics chain is shown in Fig. 1.

As shown in Fig. 1, the model includes five subsystems, i.e. the berth, which serves for berth relevant works of ships, the rood truck, which handles the container truck and arranges transport route; the quay crane, used for handling operation of ships; the stack yard, used for temporary stacking of containers; the gate, including entrance gate and exit gate.

A correlation exists among the subsystems of resource allocation system at the harbor, by which they are coupled into an organic whole. Each subsystem in the system must be molded, e.g. handling the container stack yard and rood truck transportation system, as shown in Fig. 2. After the ship accesses to the harbor, the rood truck conveys the containers into the stack yard for temporary storage. The different types of containers are stored separately according to its numbers.

When the rood truck arrives at the designated site, the free yard crane will be used for loading and unloading services. The rood truck is not allowed to departure until all jobs have been completed.

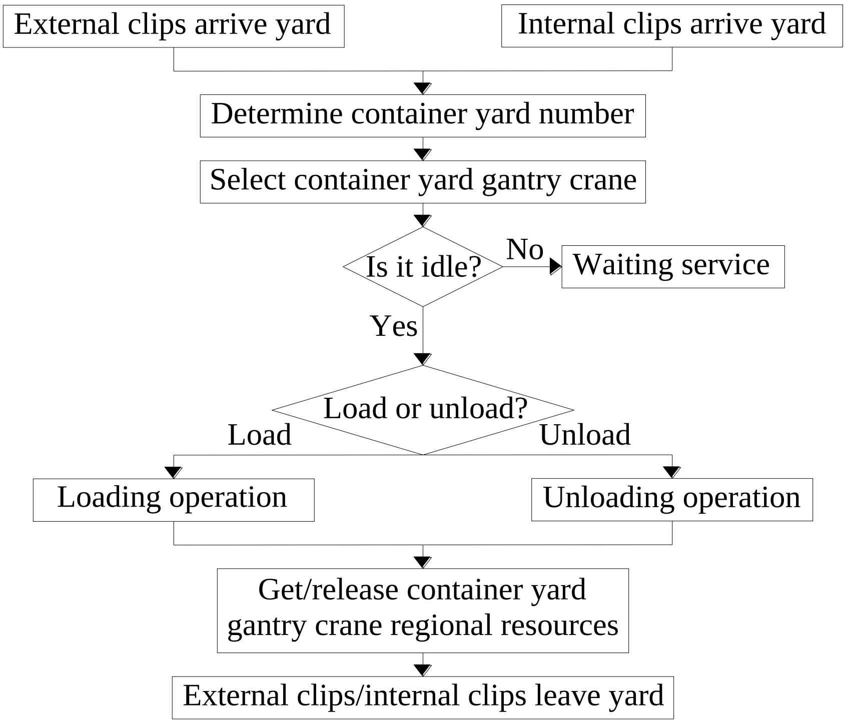

Fig.2. The Design of Yard Operation System Logical Sub-model

The optimal allocation of shoreline resources is a multi-objective optimization process. A Pareto optimum solution will be available if the relevant parameters of the model can be evaluated. Harbor service indicator S is defined to be a comprehensive evaluation index of production systems at the harbor:

$$S = \frac{AWT}{AST} \tag{9}$$

AWT is the average standby time after the ship accesses to the harbor; AST is the average handling time of container. In general, S falls between 0.1-0.5.

The model optimization scheme is imported into the Arena software for simulation solution, and the optimal solutions are evaluated for the two objective functions, i.e. the minimum carbonation level and the lowest operating cost is available by multiple iterations. The optimal model for harbor resource allocation process is shown in Fig. 3. The interval between adjacent arrivals as propagated is defined in line with a certain rule. The Create module can be used to construct the ship entity, which is assigned with the appropriate attributes. When the berths idle, the Berth module is used to dock the ships, while in the Quay Crane module, the container and other entities can be generated. An appropriate attribute is assigned to the quay crane; the Yard Truck module simulates rood transport and design the shortest route for rood truck.

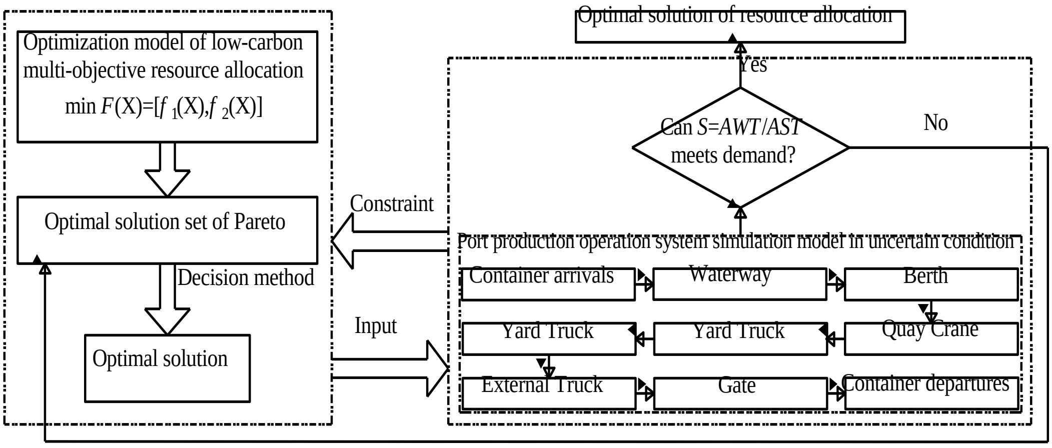

Fig.3. The Solution Process of the Simulation Optimization Model of the Allocation of Harbor Resources

Take a year as a cycle, if there is a fund limit for the total production cost, the multi-objective allocation of shoreline resources is improved. The optimal strategy is evaluated by the following procedure:

(1) Initialize the model parameters, use NSGA-Π algorithm to evaluate the Pareto optimal solutions for multi-objective optimization model of shoreline resources;

(2) Sort the optimal solutions as evaluated based on TOPSIS multi-target decision, and select the best solution from option;

(3) Set the best solution to X， perform the simulation, and then calculate the S value;

(4) Make sure whether the S value reaches the harbor service indicator, if so, the best solution is called the ultimate result; if not, return to the step 2 and delete the best solution.

3.2 Feasibility Test on Simulation Model

The statistical results of the simulation model are compared with the theoretical calculation values of the queuing theory. After the simulation model runs 15 times, the statistical average is evaluated. The theoretical calculation results are that the average waiting time for ship to be berthed is 5.18h, and the number of ships waiting for berth is 0.337; the simulation test shows that the average waiting time of the ship to be berthed is 5.31h, and the number of ships waiting for berth is 0.314. The theoretical calculation results are roughly consistent with the simulation results. It is proved thereby that the simulation model is highly accurate.

The actual statistical results from a large harbor are compared with that from the simulation model. The statistical period for actual harbor is 11 months. Fig. 4 shows the actual statistical histogram and simulation fitted curve for the number of ships arriving at the harbor daily. As can be seen from the figure, whether the simulation results or actual statistical results, the number of ships daily arriving at the harbor is subject to the normal distribution rule, and the maximum of probability is 10-12 ships.

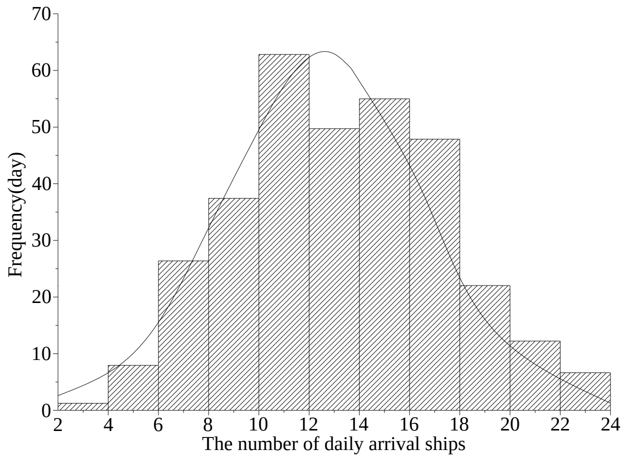

Fig.4. The Number of Daily Arrival Ships of Actual Statistical Results and Simulation Curve

Figure 5 shows the fitted curve for the statistical scatters and the simulation results of the annual container throughputs at the harbor. As can be seen from the figure, when the container throughput takes 4.95 million TEU, the harbor service index is 0.385. it is roughly consistent with the actual statistical results. It is hereby proved that the simulation model described in this paper can well simulate the actual production process of the harbor and capture the harbor service indicator accurately.

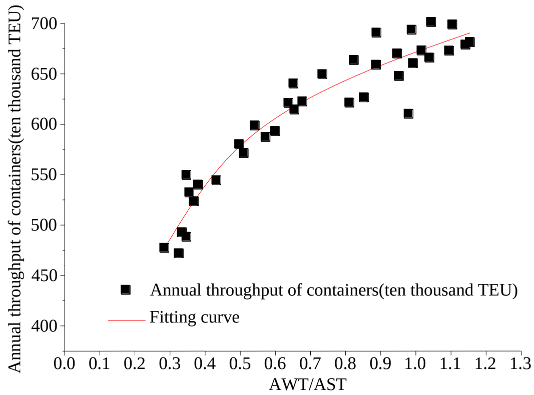

Fig.5. The Relationship Between AWT/AST and Annual Containers

4. Case Analysis

The statistics data in above section is still used to verify the model built in this paper. The energy consumption of equipment in the harbor is about 80% of the total, so that the optimal allocation of shoreline resources is a key factor for consideration in the simulation process.

In the process, the model first analyzes the optimization of shipping network resources, and by incorporating berth resources and low carbon reconstruction technology of yard crane, explores improvement of the economic and environmental benefits of post-reconstruction harbor. There are five giant berths, 300m - 400m long, on the selected harbor, one of which is 40,000 tons and the remaining four are 50,000 tons. The quay cranes, yard cranes and rood trucks are distributed by various types according to different container throughputs, and the number of quay crane fall in between 12-16 units; yard cranes between 24-64, rood trucks between 36-112.

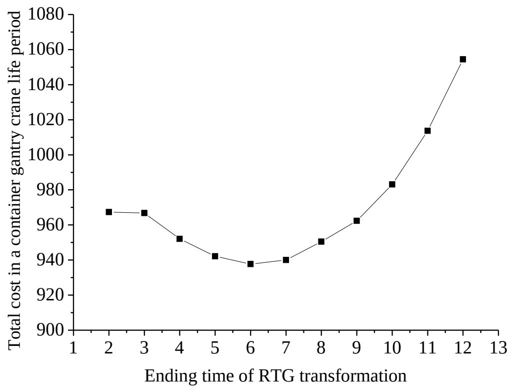

Fig.6. Relationship Between Ending Time of RTG and Container Gantry Crane Cost

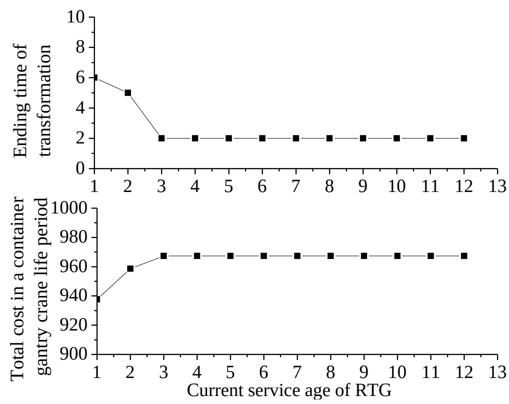

Fig.7. Comparison Curve of Current Service Age of RTG and Ending Time Transformation and Total Cost

Yard crane (RTG) is the core for handling operation at the harbor. It is of great significance for optimizing the energy usage of RTG to harbor low-carbon transformation. Assume that the service age of the RTG at the harbor, S_h^{YC}, is a year, the relation between the total cost and the completion time of the yard crane in its service life is shown in Fig. 6. Low-carbon transformation is first performed for RTG. When the transformation time of RTG lasts for 6 years, the total cost of yard crane in the service life reaches the minimum; when the transformation time further extends, the cost will grow greatly. Fig. 7 shows the relationship between the completion time of RTG low carbonation and the total cost spent when the optimal strategy is used in the simulation model. If S_h^{YC}=2 = 2, as we can see from the figure, RTG reconstruction is completed at the end of the forth year in the case of the optimal strategy.

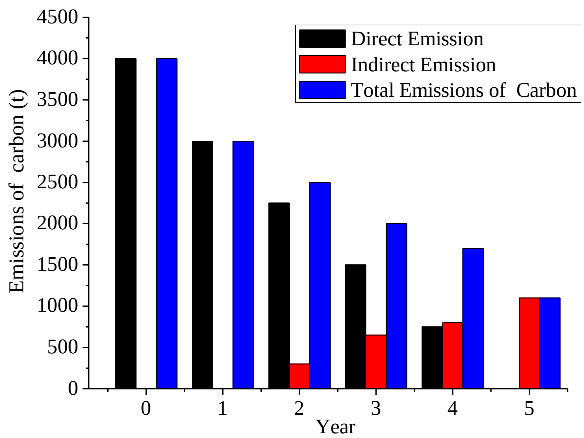

Fig.8. The Trend of Yearly Carbon Emissions for Yard Cranes

Figure 8 shows the annual carbon emissions of yard crane which works for years after it has been reconstructed. As can be seen from the figure, the carbon emissions of the yard crane after the transformation diminish year by year, and the total carbon emissions in the fifth year are all indirect, only 1/4 of that of the pre-reconstruction. The direct carbon emissions have been eliminated, the cost of carbon tax is then reduced.

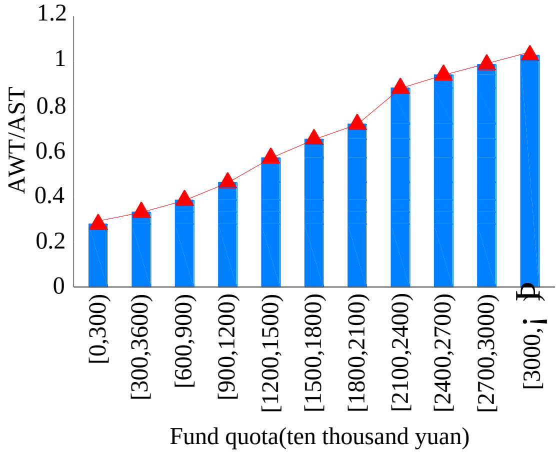

Fig.9. Comparison Curve of the Investment Amounts and Service Indicator

Figure 9 shows relation between the funds limit and the service indicator in the case of the optimal simulation model. As can be seen from the figure, the greater the funds limit, the higher the service indicator at the harbor increases gradually. When the funds limit is less than 3 million, the yard crane can not get a low-carbon reconstruction due to lack of funds. And when the funds limit exceeds 30 million, all yard cranes can be rebuilt for low-carbon operation. Based on the statistics in the figure, we know that the amount employed in low-carbon reconstruction of harbor facilities shall be limited below RMB 9 million. In this way, we can guarantee a normal operation of the system at the harbor.

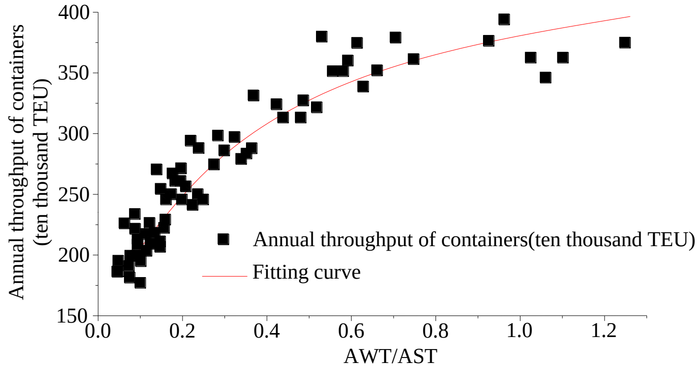

Fig.10. Comparison Curve of Throughput and Service Indicator of a Harbor

Figure 10 shows actual statistical scatters and fitted curve for the total throughput of the harbor wharf and the service indicator. As can be seen from the figure, when the S value is between 0.1 and 0.5, the annual throughput of the harbor container fall in 1.9 million TEU - 3.3 million TEU. When the throughput is more than 3.3 million TEU, the proposed optimal allocation scheme fails to reach the service indicator of the harbor. In this case, the suboptimal solution in the Pareto shall be used to calculate.

Conclusion

This paper proposes a multi-objective optimization model for collocation of shoreline resources under uncertain conditions. By synthesizing carbon emissions and TCO (Total Cost of Ownership), an optimization scheme for shoreline resources in its operation period is further defined. The proposed simulation model can effectively measure the service indicator and the operation mode at the harbor. The relevant conclusions are deduced as below:

(1) After the low-carbon reconstruction, the environmental benefit around the harbor has been improved significantly, and the production cost is reduced greatly.

(2) A simulation algorithm is put forward for low-carbonization retrofit of the yard crane, which implements relevant reconstruction strategies for yard crane at different service ages. Besides, a kind of low-carbonization retrofit strategy, which does not affect the normal operation of harbor, is also developed for single facility. A dynamic programming model in question is constructed to effectively reduce the overall carbon emissions at the harbor, thus achieving a good effect on harbor multi-objective optimization.

(3) If the limit of funds is not tight, the revamping workloads of facilities in the harbor will be greatly increased. The service indicator in the harbor can be pushed to the limit of low carbonization retrofits. The verification results from project instances show that the simulation model proposed in this paper features high precision and is superior to others.

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