# Research on Smart Port Theory and Countermeasures Based on Internet of Things Technology

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**ABSTRACT**

With the development of Internet, the global economy has spawned intelligent-shipping, thus driving the rise and development of smart ports. First, after reviewing the development status of smart ports supported by information technology and Internet of Things (IoT) technology, this paper carries out theoretical research on the integrated platform of smart port based on the IoT. By establishing a multi-objective optimization model and designing an intelligent optimization algorithm, the ship schedule coordination problem in port and shipping scheduling is explored. Secondly, in order to close to practical application, the influence factors of ship navigation such as big data, ship characteristics and navigation environment are fully considered. Data mining technology and machine learning algorithm are used to generate ship passage plan. Furthermore, the theory has been verified by practical promotion, and the "the integrated platform of smart port" based on theory has been developed and improved. The stage development, construction and iteration from the smart port version 1.0 of Shanghai Port to the smart port version 2.0 of Nantong Port are realized. Finally, the paper puts forward countermeasures and suggestions to promote the development of IoT in the smart ports.

## 1. Introduction

The development of economic globalization has promoted the innovation and application of various technologies. At the moment of international trade becoming digital and service-oriented, Internet technology plays an increasingly important role in the shipping industry. As a key hub node in the shipping industry, ports need to assume the role of logistics centers in integrated transport. In addition, it is necessary to continuously expand its own service advantages and expand relevant business functions. With the help of Internet, it develops to a multi-functional, comprehensive and digital value-added service center. Building a set of intelligent port information platform based on Internet technology.

## 2. Development status

### 2.1 Smart port construction and development status

Smart port is formed by the gradual evolution of port development since modern times. Reviewing its development process, it can be summarized as: port enterprises based on existing infrastructure, with the help of a new generation of information technology, such as the Internet of Things, cloud computing, big data, so as to give full play to the advantages of port business in modern port transportation new format. At present, the world port has been in the high-end development and application stage of port information, and has experienced three stages of port information construction, comprehensive application, expansion and upgrading. Nowadays, it is comprehensively integrating regional information and material resources to build a comprehensive application platform. With the help of information technology and intelligent application, the port realizes the seamless connection and collaborative linkage of various resource elements in the port. Through comprehensive perception, deep mining and maximum utilization of information resources, the scientific decision-making intelligent control of port operation is realized, and the intelligent, efficient, green and safe modern port is built.

China' s smart port started slightly later, but the development momentum is strong. The most representative ports are Xiamen Port, Qingdao Port, Shanghai Port and Tianjin Port. Hairun container terminal of Xiamen Port is the first to implement the intelligent transformation and innovation project of traditional container terminals in the country, involving the whole port area and the whole operation chain. Since 2021, the joint commissioning and commissioning of the first batch of transformation equipment in the full intelligent transformation project has been successful. Complete the "Super Brain" -independent development of container terminal intelligent operating system (TOS) core research and development, artificial intelligence leads the port upgrade. On November 28, 2019, Qingdao Port emerged as the world's first 5G intelligent terminal, with six independent research and development, integrated and innovative scientific and technological achievements in the world's first hydrogen power automatic rail crane and the world's first 5G automation technology. The application of hydrogen energy makes the single container of rail yard crane reduce 3.5 kg carbon dioxide emissions. The self-developed application of AGV dual transportation mode reduces the energy consumption of equipment by 20 %. The original dual-container operation mode of high-speed rail yard crane increases the proportion of dual-container operation by 50 %, the yard operation efficiency by 30 %, and the energy consumption of single-container operation by 10 %. In December 2017, the Yangshan IV container terminal of Shanghai Port was put into operation. The terminal is the largest and most intelligent container terminal in the world, and is the construction benchmark of the container terminal of the global smart port. On June 25,2021, Shanghai International Port Group (SIPG) first realized ultra-remote control of large equipment operations in global ports.

The construction of smart port is a long-term and continuous task. With the development of social needs and technological progress, the connotation of smart port is constantly enriched. In addition, the establishment of smart port construction standard system and evaluation system should be actively promoted. Moreover, information technologies such as the Beidou Navigation System, the IoT, cloud computing and big data should be utilized to continuously promote the mutual development of smart ports and smart shipping.

### 2.2 Development trend of port IoT technology

The IoT refers to the use of information sensing equipment to connect objects through the network, and to exchange and communicate information through objects, so as to communicate between people and things. Smart port application layer is the combination of IoT technology and the needs of intelligent ports. In the process of informatization, it can realize the goal of intelligent communication and accurate management between all aspects of port management system. First of all, with the increase of international trade volume, the pressure of port cargo transportation is also increasing year by year. IoT technology helps ports carry out efficient supply chain management, and reflects the advantages of smart ports by establishing port information platforms based on big data. Second, the IoT technology for each independent operation of the platform for comprehensive information integration. It not only strengthens the coordination and cooperation between various departments, but also improves the efficiency of logistics informatization in port operation. Subsequently, the IoT technology has the function of intelligent identification, positioning, tracking and supervision. It not only improves the monitoring of the infrastructure, but also locates items in a timely manner. It can help port enterprises and customers clearly grasp the real situation of goods, but also help to strengthen the interaction and contact between ports.

It can be seen that the development of port IoT technology can realize information sharing and dynamic collaboration between things. Thus improve the efficiency, accuracy and visualization of port operations. Finally, a safe and smooth, environmentally friendly and efficient modern smart port will be formed.

## 3. Theoretical research on smart port integrated management platform based on IoT

### 3.1 Consider the theoretical basis of game theory and intelligent optimization

#### 3.1.1 Global analysis

The application scenarios of the platform are analyzed from both macro and micro levels. Firstly, at the macro level, the game theory is used to study the decision-making of port enterprises, shipping companies, tugboat companies and the equilibrium of such decisions. Specific analysis of the conflict of interest between ports, shipping-related enterprises during ship coordination. It is necessary to coordinate the main body of the alliance in a complex alliance environment, so as to obtain shipping schedule. Secondly, at the micro level, a multi-objective optimization model is established from the perspective of optimization, which considers the constraints such as alliance conditions and speed, and aims at maximizing the individual income of relevant enterprises. NSGA-II is used to solve the mathematical model, and the ship arrival and departure time and berthing position are obtained by decision. Finally realize the port, shipping related enterprises win-win Pareto optimal situation.

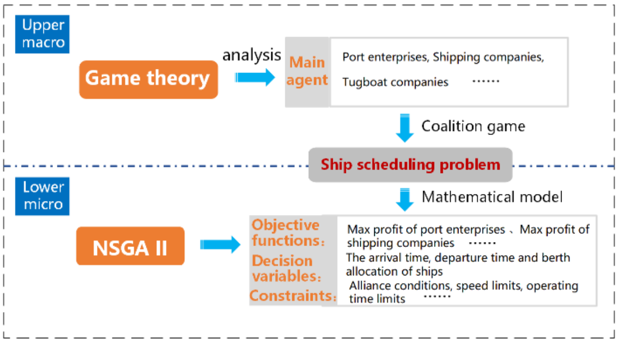


Fig. 1 Theoretical basis

From the point of view of game theory, the alliance game in cooperative game theory is considered. The integration and competition within the alliance can be viewed as the game process of alliance and non-alliance among the member enterprises, which can reveal the nature of the internal relations between ports and airlines. The analysis shows that the shipping schedule coordination between port and shipping enterprises needs to coordinate the conflict of interests of alliance subjects in the complex alliance environment. In fact, it is the embodiment of the cooperative game problem of Hong Kong and aviation related enterprises.

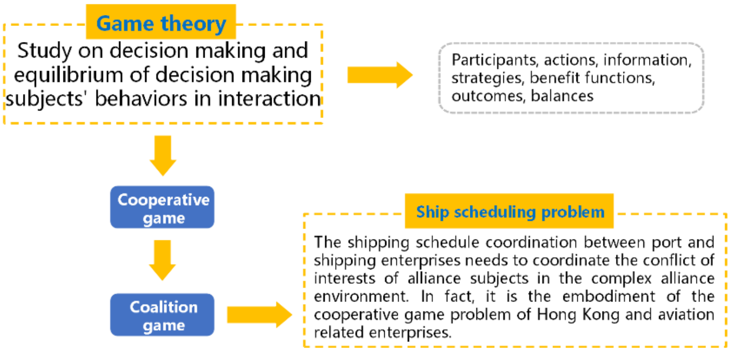


Fig. 2 Game theory analysis

From the perspective of intelligent optimization, considering that alliance is essentially a kind of transportation capacity integration, cooperation can improve the efficiency and overall benefits of logistics system. Based on the specific situation of shipping schedule coordination among port and shipping related enterprises, the revenue model of port and shipping related enterprises is constructed. In order to stabilize the alliance, port and shipping related enterprises negotiate the shipping schedule, so as to maximize their respective interests. The shipping schedule coordination and optimization problem of port and shipping related enterprises includes the arrival and departure time and berthing position of ships, and finally realizes the Pareto optimal situation of win-win situation of port and shipping related enterprises. Port and shipping related enterprises should cooperate effectively in capacity, information and organization, and give play to their respective advantages and functions. Coordinate and balance port, ship, cargo, loading, transportation, unloading and other major links, share information on ship, loading and unloading operations, cargo organization and management, and maximize the overall economic benefits.

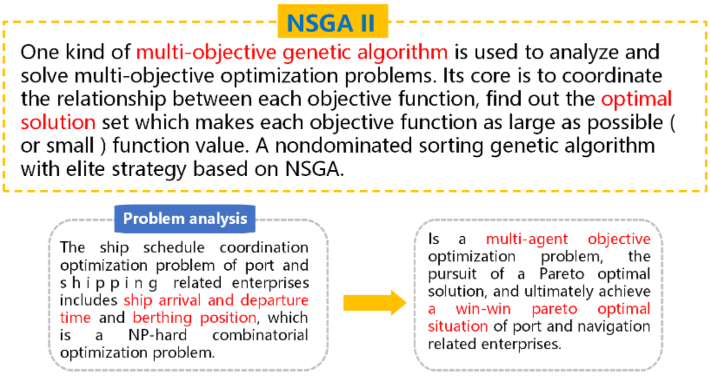


Fig. 3 Intelligent optimization analysis

### 3.1.2 Modeling of ship scheduling coordination problems

(1) Model assumption

①The amount of cargo handled by each route at this port is known.

②Port berth quay crane resources are limited.

③Ships do not affect the original operation plan of other ships in the port.

④If the expected revenue of either party is not reached, the revenue of both port and shipping is 0.

(2) Notations definitions

①Parameters

$I$: set of arrival ships during the planned period, $i \in I$, $i$ represents any ship of the shipping company, $i'$ represents ships other than $i$, $i \neq i'$ and $i' \in I$;

$B$: set of berth at ports, $j \in B$, $j$ represents the berth at ports;

$d_{12}$: distance from upstream port to downstream port;

$d_1$: distance from upstream port to union port;

$d_2$: distance from union port to downstream port;

$r$: basic rate;

$m_i$: forecast of freight demand on route;

$n$: port handling rates;

$g_i$: port management fees;

$p$: fuel price;

$e$: handling efficiency of quay crane;

$v_i$: actual speed of ship $i$;

$v_{i'}$: economic speed of ship $i$;

$v_i^{min}$: minimum speed limit for ship $i$;

$v_i^{max}$: maximum speed limit for ship $i$;

$u_i$: fuel consumption per mile of ship $i$ related to speed; $u_i = g_i(v_i)$ represents the relationship between fuel consumption rate and speed;

$u_{i'}$: economic fuel consumption per mile of ship $i$;

$t_i^1$： time of ship $i$ to leave upstream port；

$t_i^2$： time of ship $i$ to leave downstream port；

$c_1$： start-up cost of each quay crane operation；

$c_2$： operating cost per hour of quay crane；

$q_i$： number of quay cranes allocated to ship $i$；

$q_i^{min}$： minimum number of quay cranes available for ships $i$；

$q_i^{max}$： maximum number of quay cranes available for ships $i$；

$P_1$： expected profit of shipping company；

$P_2$： expected profit of port company.

②Decision variables

$\alpha_i$： planned arrival time of ship $i$；

$\beta_i$： planned departure time of ship $i$；

$x_{ij}$： if ship $i$ is assigned berth $j$, $x_{ij} = 1$, otherwise 0.

(3) Model formulation

①Maximizing revenue of shipping companies

The time of the ship in the port mainly considers the planned arrival time and planned departure time of the ship. The shipping company undertakes the marine transportation business of container goods, and its total income is the total cost of container transportation. Ship costs mainly include: a) fuel costs related to speed. On the premise of meeting the transport time limit, reducing the speed can reduce fuel consumption, thereby saving fuel costs. b) Port cost. If the port is attached and the operation plan is arranged, the corresponding handling and fixed attachment costs are incurred. Therefore, the objective function of the model based on the maximization of the revenue of shipping companies is as follows:

$$max f_1 = \sum_i \sum_j x_{ij} r m_i - \sum_i \sum_j x_{ij} p u_i (d_1 + d_2) - \sum_i \sum_j (1 - x_{ij}) p u_i d_{12} - \sum_i \sum_j x_{ij} (n m_i + g_i) \quad (1)$$

Constraints：

$$f_1 \geq P_1 \quad (2)$$

$$v_i^{min} \leq v_i \leq v_i^{max}, \ \forall i \in I \quad (3)$$

$$v_i = \begin{cases} \frac{d_1}{\alpha_i - t_i^1} or \frac{d_2}{t_i^2 - \beta_i}, & \sum_j x_{ij} \neq 0, \ u_i \prec u_{i'} \\ \frac{d_{12}}{t_i^2 - t_i^1}, & \sum_j x_{ij} = 0, \ u_i \prec u_{i'}, \ \forall i \in I, \ \forall j \in B \\ v_{i'}, & u_i \geq u_{i'} \end{cases} \quad (4)$$

$$t_i^1 + \frac{d_1}{v_{max}} \leq \alpha_i \ , \ \forall i \in I \quad (5)$$

$$t_i^2 - \frac{d_2}{v_{min}} \leq \beta_i \ , \ \forall i \in I \quad (6)$$

Constraint (1) indicates that the difference between shipping revenue minus fuel cost and port cost is the largest. The first is shipping income, the second is fuel costs at the time of the port being attached, the third is fuel costs at the time of the ship being unable to berth, and the fourth is the cost of the port being attached. Constraint (2) means that the shipping company ' s revenue must not be less than its expected revenue, before the alliance. In order to simplify the calculation and fully consider the various costs of the ship, the expected revenue includes the fixed cost of the ship. Constraint (3) is the speed limit of the ship. Constraint (4) represents the relationship between the actual speed of the ship and whether it is attached to the port, the voyage distance, the arrival and departure time of the ship and the economic speed. Constraints (5) and (6) respectively indicate that the arrival and departure time of the ship should meet the constraints of the earliest arrival time and the latest departure time under the transportation time limit.

②Maximizing revenue of ports

The core business of the port is to serve the liner, providing berthing, loading and unloading, storage and other services. To simplify the calculation, the port revenue in this paper mainly includes: a) the revenue from providing stevedoring services. b) port management income, including tonnage tax, pilotage fee, berthing fee, etc., collected from ships by port enterprises according to relevant regulations. The shipping schedule will affect the berth quay crane scheduling plan of the port, so the port cost mainly considers quay crane cost, including the ship operation quay crane start-up cost and loading and unloading operation cost. The objective function of this paper based on the maximization of port income is as follows:

$$max f_2 = \sum_i \sum_j x_{ij} n m_i + \sum_i \sum_j x_{ij} g_i - \left[ c_1 \sum_i \sum_j x_{ij} q_i + c_2 \sum_i \sum_j x_{ij} \frac{m_i}{e} \right] \quad (7)$$

Constraints:

$$f_2 \geq P_2 \quad (8)$$

$$\sum_j x_{ij} \leq 1 \ , \ \forall i \in I \quad (9)$$

$$\sum_i x_{ij} \leq 1 \ , \ \forall j \in B \quad (10)$$

$$\frac{x_{ij}(\beta_i - \alpha_i) + x_{i'j}(\beta_{i'} - \alpha_{i'})}{2} \leq \left| \frac{\beta_i + \alpha_i}{2} - \frac{\beta_{i'} + \alpha_{i'}}{2} \right| \ , \ \forall i, i' \in I, \ \forall j \in B \quad (11)$$

$$\beta_i - \alpha_i > \frac{m_i}{e q_i} \ , \ \forall i \in I \quad (12)$$

$$q_i^{min} \leq q_i \leq q_i^{max} \ , \ \forall i \in I \quad (13)$$

$$x_{ij} \in \{0,1\} \ , \ \forall i \in I, \ \forall j \in B \quad (14)$$

Constraint (7) indicates that the difference between the loading and unloading income of the port and the management income minus the cost of the quay crane is the largest, that is, the port income is the largest. Constraint (8) indicates that the port's revenue must not be less than its expected revenue before the alliance. In order to simplify the calculation and fully consider the various costs of the port, the expected revenue includes the fixed cost of the port. Constraint (9) indicates that each ship will berth once or cannot berth. In order to simplify the calculation, when the ship cannot berth, the "port rejection" operation will be carried out, and the shipping company reschedules and arranges the route. Constraint (10) ensures that at most one ship per berth. Constraint (11) ensures that the ship berthed at the same berth is within different time limits for handling operations. Constraint (12) indicates that the ship can leave the port after completing the loading and unloading task. Constraint (13) indicates the number limit of quay cranes available for ship i. Constraint (14) specify the binary decision variable.

**3.1.3 NSGA-II algorithm**

In this paper, we designed a two-dimensional NSGA-II. Chromosome encoding is in the form of two-dimensional matrix. In order to construct the non-dominated solution set, we used a fast-sorting method proposed by Konak et al. In addition, the crowding distance is sorted, and the elite strategy is introduced. At the same time, binary tournament selection, simulated binary crossover and polynomial mutation are used to effectively obtain optimal solutions.

(1) Input and initialization of basic data

Read shipping company ship navigation plan data, as well as container terminal layout data and equipment operation data.

(2) Encoding

According to the characteristics of decision variables, this paper adopts the coding method of real number coding combined with two-dimensional matrix. In order to ensure the diversity of population, random generation is used. Generate

$n \times 3$ chromosomes, each $n$ gene represents the arrival time, departure time and berth of the ship. As shown in chromosome 1 in Fig. 4, it represents that the ship will be docked. During the planning period, 11h arrived at the port, 28h left the port, arranged to dock in berth 2. According to the rules of chromosome coding, the initial population satisfying the constraint condition is generated randomly.

| | 1 | 2 | 3 | ... | n |
|---|---|---|---|---|---|
| Ship arrival time | 11 | 29 | 45 | ... | 79 |
| Ship departure time | 28 | 46 | 53 | ... | 93 |
| Ship berth number | 2 | 5 | 3 | ... | 1 |

Fig. 4 Chromosome

(3) Non-dominated sorting

The objective function $f1/f2$ can be non-dominated sorted. For any two chromosomes $u$ and $k$ in the population can establish a relationship as follows: if $fu1 < fk1$ and $fu2 > fk2$, $u$ dominates $k$, that is, $u$ is better than $k$ for all objective functions; and if the solution of $u$ is not dominated by $k$, then u is not dominated by $k$, that is, u and $k$ are solutions on Pareto.

(4) Crowding-distance sorting

The crowding degree is calculated by the local crowding distance between each point in the target space and two adjacent points in the same layer, which can keep the diversity of individuals.

(5) Genetic operator (selection, crossover, and mutation)

The purpose of selection operation is to prevent the loss of effective genes and filter out ineffective individuals. The optimization process is carried out in the direction of Pareto front solution, keeping excellent individuals and making them evenly distributed. Thus, we adopted the tournament selection with high utilization rate. In the iterative evolution process of NSGA-II, the alternation of crossover and mutation is helpful to improve the search performance of the algorithm. After the comparation through using different methods of crossover and mutation, and characteristics of chromosome, we adopt a simulated binary crossover and polynomial mutation operation to effectively obtain optimal solutions.

(6) Elitist strategy

The elitist strategy is to keep the excellent individuals in the parent generation and enter the offspring directly. It is a necessary condition for NSGA-II to converge with probability 1. According to the Pareto rank and crowding distance of the individuals, the population recombined by the parents and the offspring is screened again to form a population for the next generation evolution.

**3.2 Research on platform algorithm based on data mining**

This paper considers data preprocessing, data mining analysis, cloud data reading, adaptive matching of navigation environment, ship route generation and data classification management. Three key technologies of cloud data and local data cleaning, ship berth clustering and navigation path generation are focused on. In the data cleaning process, Chebyshev theorem and linear interpolation are used to filter and repair the abnormal speed information and data completion. In the clustering of ship berths, the K-means algorithm is used to cluster the ship berths according to the index range, so as to calculate the average position of various track points. In the generation of navigation path, after using the vector cross multiplication algorithm to detect the path navigability, the mid-latitude navigation method is used to calculate the path weight, and finally the A* algorithm is used to generate the optimal route. Based on the comprehensive integration of cloud data center and local data center, the algorithm cleans and mines the data. After in-depth study of the berthing points in the ship ' s habitual route, the optimal route of the ship is calculated according to the latest road conditions. It not only improves the utilization rate of public resources in the navigation process, but also better supervises and serves the port and shipping related enterprises, which will effectively break through the port and shipping data barriers.

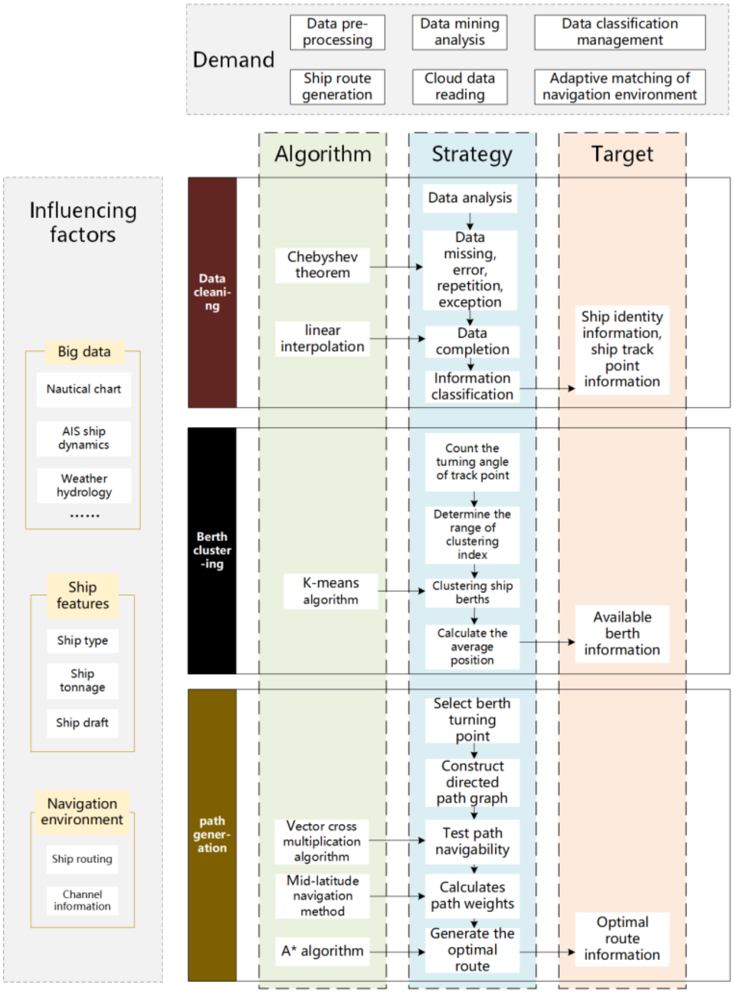

Fig. 5 Algorithm research

## 4. Application and popularization

Achieved from the Shanghai Smart Port 1.0 version, to Nantong Tongzhou Smart Port 2.0 version of the phased development, construction, iteration, completed the development of the “Port intelligence integration” platform. The system relies on the “land, sea and sky” total factor perception system, using basic data sources, superimposed real-time data. It scientifically formulates management rules according to actual needs. The high integration of port and shipping safety and production is realized through the global perception, full control and resource sharing. Realize “See, hear, shout”, build “A screen view of the world, a network management of the whole region” of the full elements of “Port and shipping intelligence integration” platform.

The establishment and application of this platform can realize the whole process control and trajectory tracking of the water-related ships. Ships in and out of the port are convenient and orderly. It can not only meet the requirements of government safety supervision, but also improve the speed of ship entry and exit, port handling turnover rate, greatly improve the efficiency of production and operation. Based on the smart port platform, information and advice on how to facilitate timely arrival of ships are provided to the port and shipping sectors and maritime administrations. Optimize ship voyage and port operation process, provide customers with the best logistics sustainable solution, improve the efficiency of port and shipping integration. At present, relying on the algorithm model, it participates in the construction of “Global Smart Port” project of Shanghai Shipping Exchange.

## 5. Suggestions on promoting the development of IOT in smart ports

### 5.1 “Create the directory”

The data directory and resource open platform for the IoT development of smart ports are constructed to realize the collection, circulation, coordination and sharing of basic data of smart ports. The research combs the whole port data system, so as to open up all aspects of data and build a smart port data port. Establish an open platform for sharing big data resources to realize the collection, circulation, coordination and sharing of basic data in smart ports.

**5.2 "Establish the standard"**

Establish data governance and safety standard system of smart port, and promote vertical data standardization of upstream and downstream industrial chain. The smart port data standard committee is established to comprehensively sort out the business, perception, documentation and regulatory data system on the data chain around the standard requirements of smart port data governance and data security. Establish standards and norms for public master data to form and provide catalogues and exchange channels of industrial data resources for the development of IoT in smart ports. Thus, leading the voice of global shipping logistics data standards.

**5.3 "Promote the application"**

Promote the application of big data technology in smart port, and create a batch of big data products, services and applications with full dimension, full technology, full mode and full chain. Build four application platforms, such as the digital twin platform integrating perception, integration and simulation; the port management platform for waterway, water and rail multimodal transport; the integrated guarantee platform for port operation integrating production and safety; the smart port data pool and capacity open platform.

**5.4 "Set up mode"**

Exploring the innovative mode of sustainable development of big data in smart port. The sustainable big data supply chain of shipping logistics with smart ports as the hub is constructed with commercial logic. Taking the digital hotspots such as port intelligence and business online as the starting point, the multidimensional resource advantages of the whole chain of the shipping industry are gathered. Focus on all aspects of the chain, mobilize all parties to build a big platform for smart port big data resources, technology and scheme.

**5.5 "Strengthen the leading"**

Activate the shipping industry digital engine power, make Shanghai become the global wisdom port technology and industrialization highland. Through various measures to activate the digital innovation vitality of smart port industry. Promote the wide application of mobile Internet, intelligent terminals, big data and cloud computing in the field of smart ports. Commercial logic mode is used to promote the ecological digitalization of port platform. To realize the important goal of accelerating the development of modern shipping industry in Shanghai by digitization, and further strengthen the ability of Shanghai International Shipping Center to gather internal and external radiation.

## 6. Conclusion

Based on the analysis and summary of the development status of smart port and IoT, this paper takes operational optimization and game theory as the breakthrough point, and conducts theoretical research and analysis from the perspective of port and shipping related enterprises. By establishing a mathematical model, using intelligent algorithm and data mining technology, the ship scheduling coordination problem in port and shipping scheduling is studied. To this end, the development of the "Port and shipping intelligence integration" platform has been applied in Shanghai port and Nantong port. It verifies that the Internet of Things of smart port is the future development trend.

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**Author's Biography**

Hu Xiaoyuan, female, PhD, major in logistics engineering and management, is currently working in CTTIC Smart Data Co., Ltd., responsible for the company' s related research work. The research directions are mainly port operation and operation, underground logistics system design and operation planning, and operation research optimization. Several papers were published by the first author and the author of communication in the journals of Computers & Industrial Engineering, Advanced Engineering Informatics and other SCI regions. Presided over Shanghai Maritime University 2021 graduate top innovative talent training project. During the doctoral period, she received two national scholarships for doctoral students, and many times received the second and third prizes of the National Graduate Mathematical Modeling Contest.