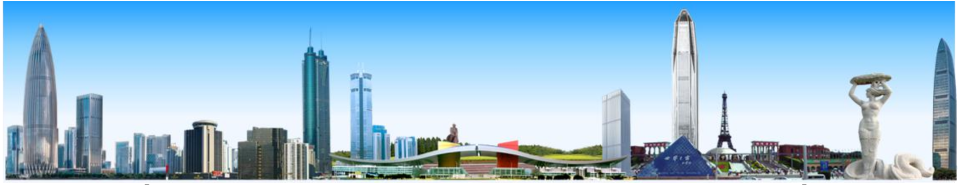

Resource efficiency optimization-oriented digital twin unmanned warehouse system

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Abstract: *With the gradual popularization of unmanned warehouse applications, resource allocation and optimization has become the key to cost control and improve customer satisfaction, especially the uncertainty of goods order arrival and the difficulty of real-time monitoring and scheduling of equipment status. In order to improve the accuracy of order forecasting and the efficiency of resource optimization, a new method of digital twin system based on an unmanned warehouse is proposed based on physical virtual fusion technology and digital twin technology. Firstly, a digital twin model suitable for a complicated warehouse system has been constructed. After that, the resource efficiency of unmanned warehouses is optimized by using the visualization technology of the model and optimization algorithm. Finally, an enterprise case is used to verify the effectiveness of this method.*

Keywords: *digital twins; unmanned warehouse; resource optimization; real-time monitoring*

1 Introduction

According to figures from the China Federation of Logistics and Purchasing (CFLP), the cost of warehousing reached 4.6 trillion yuan, which accounts for 5.1 percent of GDP in 2018. With the development of e-commerce, new retail and high-end manufacturing in China, the demand for high-standard warehousing is further increasing. Therefore, research on the problem of high cost, low service level and low efficiency is very important to improve customer satisfaction and reduce the inventory cost and the warehouse cost. In comparison with the traditional warehouse, the unmanned warehouse has the following advantages: low labor cost, minor personnel safety hazard and low risk of goods damage. So, it is very important to study the unmanned warehouse system to make the enterprise transform into information and intelligence. The unmanned warehouse system can realize the unmanned process of goods entering, tallying, storing, sorting, leaving the warehouse and order receiving.

For the problems of precise scheduling and resource optimization, the traditional solution is to consider the Problem as a Flexible Job-shop Scheduling Problem (FJSP) and solve it using immune genetic algorithms (Shi D et al. 2020), artificial bee colony algorithms (KZ Gao et al., 2016), artificial genetic algorithms (NSGA) (Ahmadi, E. et al., 2016) and other heuristic(Zhu and Zhou, 2020). By transforming the complex multi-objective optimization problem into a single-objective optimization problem (Wang et al., 2019), or treating the transportation equipment as a resource together with the three-dimensional shelf and the inspection equipment and using the genetic algorithm based on the elitist strategy to solve the problem (Ba L et al., 2016). Nevertheless, this algorithm also has some issues in solving resource allocations. The Algorithm's solution ability is limited and the degree of flexibility is not enough which cannot ensure the multi-frequency uncertain quantity goods arrived dispatch very well. The service capacity and efficiency of warehouses is restricted by the configuration of resources such as shelves, AGVs and forklifts. As a frontier and hotspot in the field of intelligent manufacturing (Schluse M et al., 2018; Xi Vincent Wang and Linhui Wang, 2019; Tao F et al, 2017; Tao F et al, 2019), digital twin (Grieves and Vickers, 2017; Glaessgen and Stargel, 2012) is introduced into the field of unmanned warehouse in this paper. At present, there is little research on the application of digital twins in unmanned warehouses, represented by the five-dimensional model of digital twins proposed by Tao Fei et al. (2018) and its application plan in the field of warehouses. But in the manufacturing field, application is many, may take the model. Tongue X et al. (2019) applications of digital twin technology, for production and processing data is difficult for real-time interaction, based on an intelligent multi-mode Terminal Solution. Based on the digital twin 3D Model, Pai Z etc. (2020) proposed a general product-level digital twin development method in a smart manufacturing environment and validated it with 3D printing technology. Chao L et al. (2020) proposed network-based digital twin modeling and remote-control network physical system combining cyber-system and digital twin technology.

In the process of resource scheduling and efficiency optimization, the traditional genetic optimization algorithm can only optimize a single problem because of the difficulty in programming. The choice of parameters in the operator is mostly based on experience, which seriously affects the quality of the solution. Therefore, using the application of digital twin in manufacturing for reference, digital twin technology can be combined with unmanned warehouses to solve multi-resource scheduling and efficiency optimization problems. The network technology can be used to monitor the running state of the equipment dynamically and visually, which can help to deal with the problems on the spot in time and improve the operating efficiency and the ability to dispatch quickly. The parameter is set by the sensor on the spot, which does not affect the quality of the solution, so it can solve the problem of the warehouse scheduling in time and accurately, and the resource efficiency is low. Therefore, this paper carries out research in the following three aspects:

(1)According to the process characteristics of unmanned warehouses, the architecture of digital twin unmanned warehouse systems with multi-level features is built.

(2)The real-time mapping digital twin unmanned warehouse model is realized by using ontology modeling technology and data service systems.

(3)Combining a neural network algorithm with clustering analysis method and genetic algorithms, an optimization analysis method for the resource efficiency of digital twin unmanned warehouses is proposed.

The rest of this work is organized as follow: The first section constructs the architecture of the digital twin unmanned warehouse system; The second section proposes the digital twin modeling scheme based on the unmanned warehouse workflow; The third section studies the analysis method of resource efficiency optimization of digital twin unmanned warehouse; The fourth section verifies the effectiveness of the above framework, model and method; The fifth section summarizes the full text and gives the future expectation.

2 Architecture of digital twin unmanned warehouse system

Based on the five-dimensional conceptual model of digital twin system proposed by Tao Fei (2017) and the characteristics of an unmanned warehouse system, a digital pairing system framework is constructed, as shown in the figure 1. The system includes: a perceivable physical layer, two technical platforms (multi-network integrated network platform and data service system platform), three layers of architecture (perception layer, a data layer and a service layer), three databases (a local database, a system database and real-time database), five logical process mappings (inbound and outbound, tally, picking, order receiving, storage), and six types of real-time mapping entities (robots, AGV, goods, pallets, forklifts and stereoscopic warehouse).

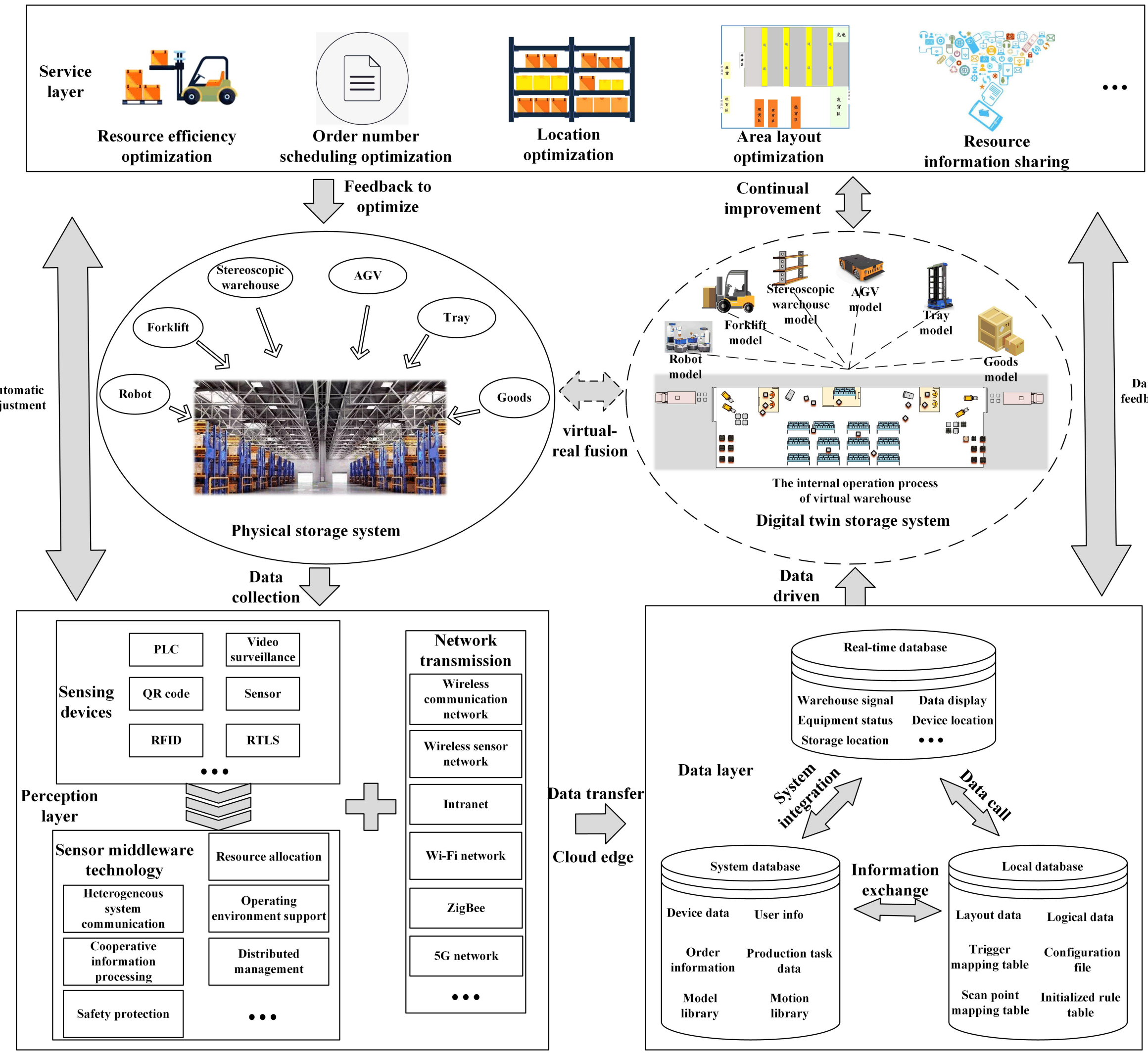

Figure 1: The frame for the digital twin unmanned warehouse system

The perception layer is used to identify objects and collect information. This layer uses sensor middleware technology to access the data which is installed on the shelves, forklifts, Automated Guided Vehicle (AGV), goods, pallets, robots, and warehouses. Then sensor middleware technology is used to process the data. Finally, the network transmission tools are applied to transmit the data to complete the collection of the bottom information.

The data layer includes: user rights management, a model interface between digital twin unmanned warehouse system and object model library, a data interface between real-time database and local database. The information contained in the real-time database, local database, system database which is shown in the frame chart: real-time database contains a warehouse signal, equipment status, a device location, a data display, a storage location; the local database contains layout data, logical data, trigger mapping table, initialized rule table, scan point mapping table and configuration file; the system database includes device data, production task data, a model library, motion library, order information and user information.

The service layer uses the drive model to run and iterate the data in the data layer to realize the functions of intelligent application, resource efficiency optimization, order scheduling optimization, storage location optimization, area optimization, resource information sharing, etc. Then the optimized information is fed back to the data center of the perception layer for virtual monitoring.

According to the frame structure of the digital twin unmanned warehouse system, the related contents in the construction of the digital twin unmanned warehouse system are further studied.

3 Model of digital twin unmanned warehouse system

The construction of digital twin unmanned warehouse models can be divided into three parts: twin modeling of entity, data service system and real-time mapping. The overall layout of the unmanned warehouse as shown in figure 2, including a three-dimensional warehouse, AGV material transportation system and other entities.

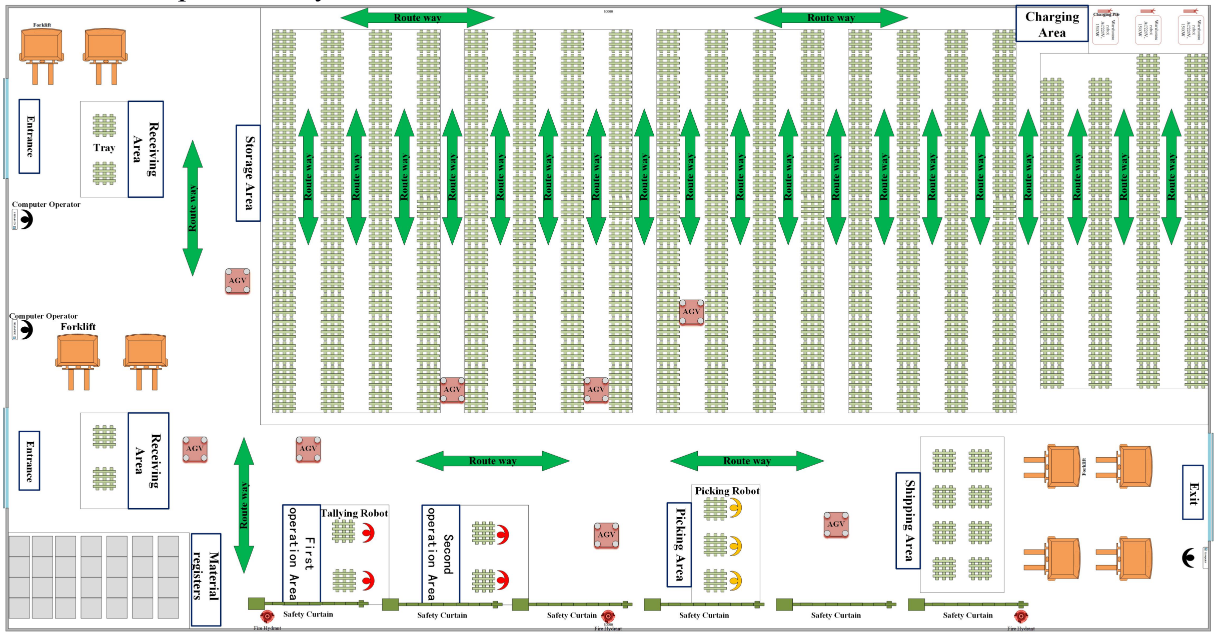

Figure 2: Unmanned warehouse layout

3.1 Entity twin modeling

The key point of ontology construction is class and attribute. Class is the definition of entity. Attribute is the description of the specific function of the class. Thus the digital twin model needs to edit the object and its attribute in advance. Then log it out and save it on the object table of the object library. Attribute, as a feature in object modeling, can be edited first. Then a multi-dimensional model of physical entity can be built using modeling software. After that the model can be imported into a simulation platform. During which the model can be lit selectively to reduce the display pressure at run time. For the moving components in the multidimensional model, they can be set as animated objects. After that, the action path of the animated components is edited. Finally, the component animation is associated with forming complete action. The attributes and interrelationships of the unmanned warehouse ontology model form a complex mesh conceptual structure as shown in figure 3.

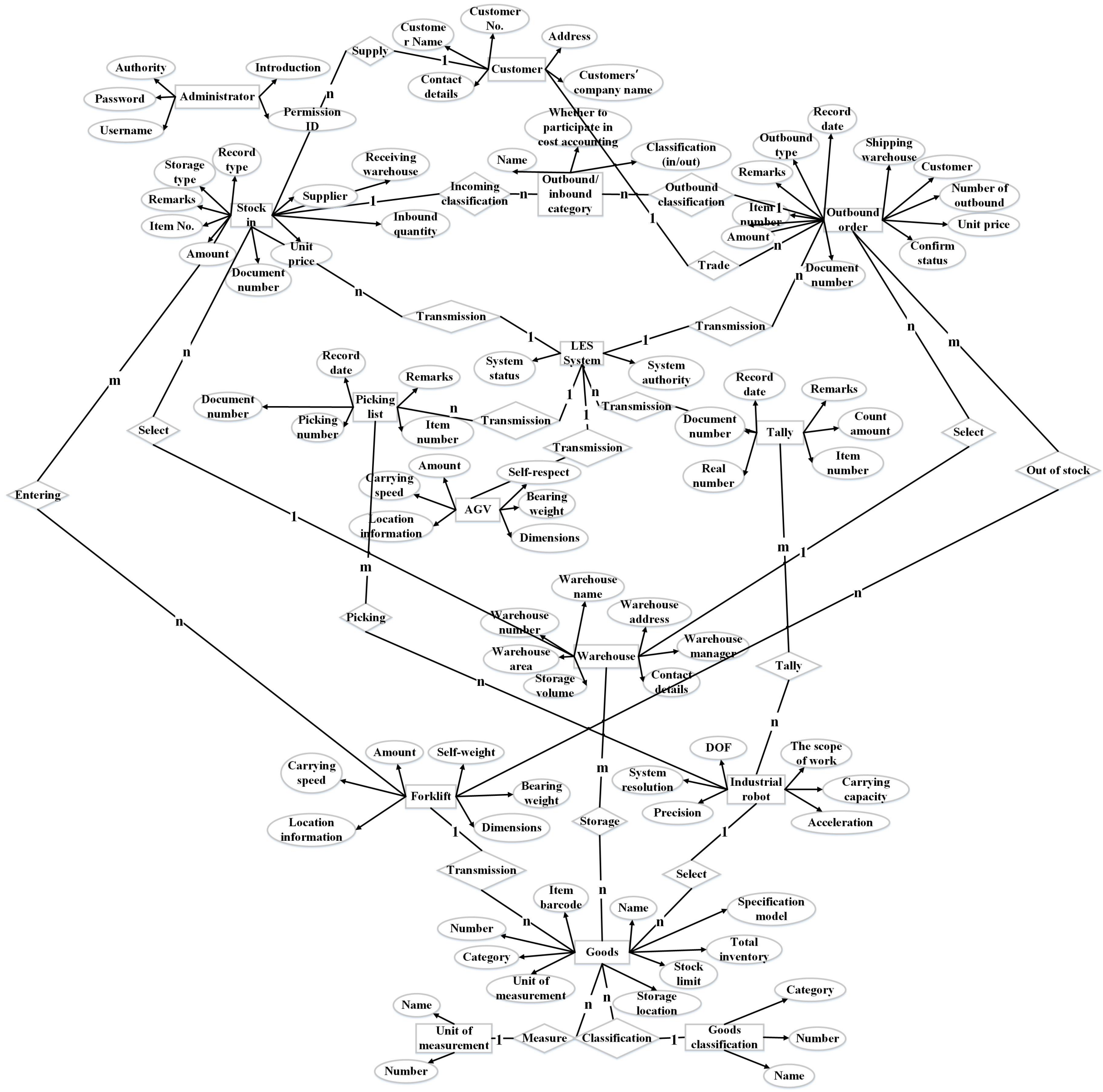

Figure 3: The mesh structure of the unmanned warehouse ontology model

The process rules and policies in the actual unmanned warehouse system are transformed into simulation logic to realize the parameterized setting of related rules and policies. The flow chart of the current unmanned warehouse is shown in figure 4.

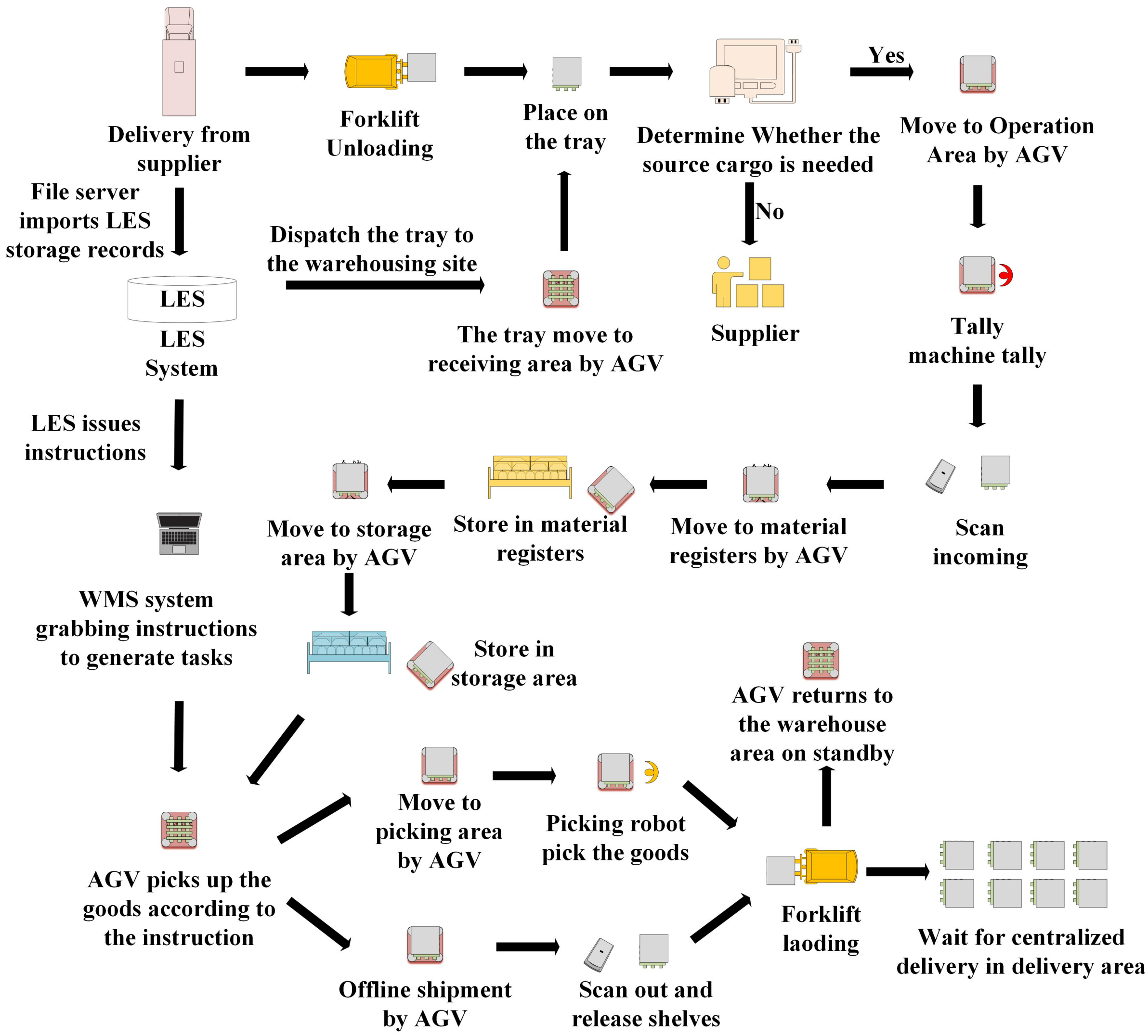

Figure 4: Flow chart of unmanned warehouse actual operation

Unmanned warehouses need to restore arriving parts and deliver them to customers. After the goods come to the supplier, the goods are unloaded by the forklift truck to the receiving area and stored on the pallets. Then the goods are transported by AGV to the tally area by the tally robot. The information is scanned to the warehouse and uploaded to the LES system. After that, the control system in the center of the unmanned warehouse will display the information about the goods' location. When the order arrives, the Les System issues instructions to the AGV vehicle. So that the AGV can go to the corresponding storage area to pick up the goods and transport them to picking area. After picking up the goods by the picking robot, the AGV is transported to the delivery area for temporary storage. Finally, when the order quantity is satisfied, the goods are transported by forklift to the shipping area for shipment.

3.2 Construction of data service system

The data service system is the connection between the real-time database, the local database and the system database. The system uses a real-time database to drive the model to run. At first, the model accesses the XML configuration file through the XML interface module to read the local database and the real-time database address information. Then the ODBC interface module is used to maintain static modeling data locally. After that, OWL-S technology is used to call the knowledge ontology of the ontology model built in owl. So that the digital twin model can be built quickly and automatically. The regular data of the real-time database can be accessed periodically according to the time stamp through the database interface selectively. Finally, the data from the local database and the system database can be parsed. And rapid restoration of an unmanned warehouse based on a digital twin model.

3.3 Construction of real-time map

The real-time mapping rules mainly include the following:

1. Based on the actual process of unmanned warehouses, the event is coded.

2. Model initialization is to create a combination of event signals related to the object. For example, when AGV moves into a fixed position, it is necessary to record the signal identification, object identification and trigger events. It uses the servlet tool to initiate matching. During servlet initialization, the container will call the init (servletconfig) method, it is passed as a servletconfig object, called the servlet configuration object.Use this object to obtain servlet initialization parameters, Servlet name, servletcontext objects and so on. There are two ways to get servletconfig interface in a servlet:

1) Use getservletconfig () method of the servlet, that is, servletconfig = getservletconfig ();

2) Overrides the init (servletconfig) method of the servlet, public void init (servletconfig) {super. init (config); must call the init ()method of the superclass.}

Where the Web server matches the rules of the URL:

1) Match the requested URL exactly to the configured URL map and call the servlet if successful, otherwise go to 2;

2) Try to match the longest prefix and then call the relevant servlet;

3) If no match can be found, use the root directory's default matching servlet or default page.

Note: When the requested URL has an extension at the end, the servlet container tries to match the servlet that handles the extension.

3. Real-time action simulation creates a trigger map in the local database, and then the device data, model data and action data in the system database are specified to realize the real-time action simulation of moving objects.

4. Real-time status display, digital twin unmanned warehouse system read data from the real-time database in a cycle according to a certain time interval to achieve workshop scene restoration and virtual transparent monitoring. On this basis, super-real-time simulation is carried out for risk assessment and optimization of unmanned warehouse scheduling. And the corresponding human-computer interface is also developed to assist decision support.

Through ontology modeling technology, the twin models have the same property and function as the physical entity in the space position, geometry size and motion characteristics. Then, the data service system is used to establish the internal and external control interfaces of the model to achieve the data interaction between the model and the three types of databases. Finally, according to the real-time mapping rule, the digital twin model can realize the effective combination of the entity elements which can complete the effective operation of the warehousing process, the tally process, the storage process, the picking process and the order receiving process, realize the whole business process of unmanned warehouse. The real-time mapping logic flow is shown in figure 5.

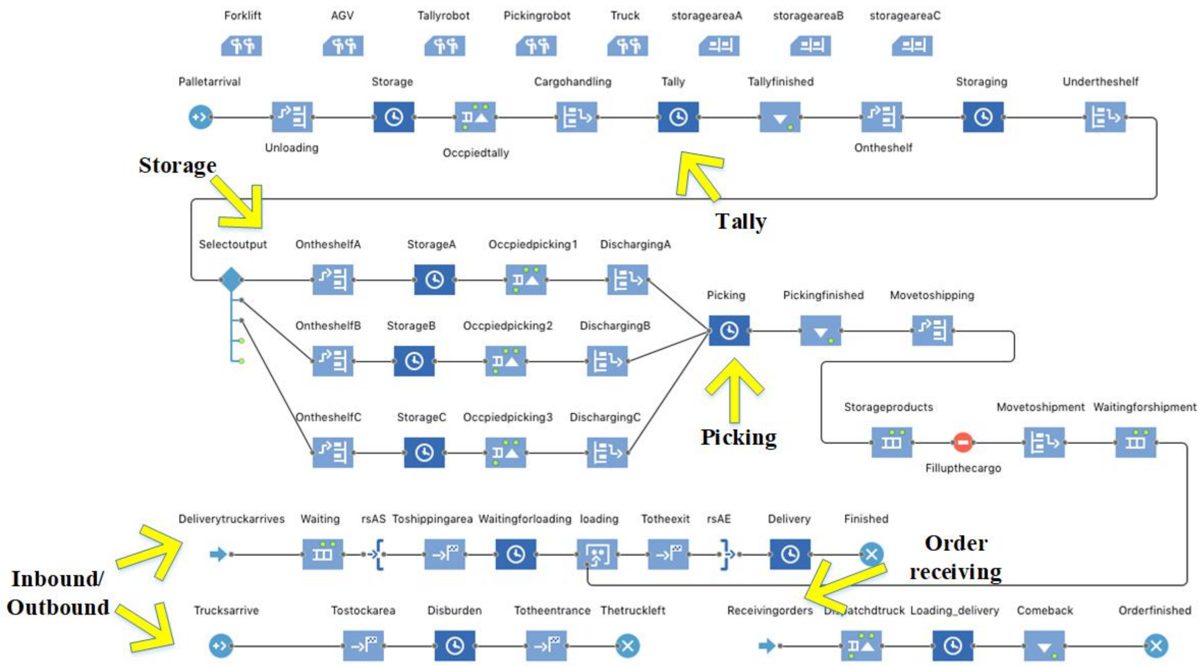

Figure 5 Digital twin unmanned warehouse real-time mapping process logic diagram

4 Optimized service of digital twin unmanned warehouse system

There are three problems in unmanned warehouses: dissatisfaction with customer order demand in time, difficulty monitoring the running status of equipment in real time and overstock increasing the cost of inventory. Traditional resource efficiency optimization methods, including simulation of the analysis and genetic algorithm optimization are based on historical data for analysis and optimization which cannot be timely feedback of real-time operation of equipment and timely processing of related issues. There exists a certain lag. The digital twin unmanned warehouse system is used to optimize the resource efficiency which is real-time and super-real-time. It can also monitor the running state of the equipment and the relevant situation that may happen in the future. So that to deal with the abnormal situation in time, it is better to raise customer satisfaction and reduce the cost of storage and inventory.

The optimization analysis flow includes: prediction analysis based on real-time data and historical data of goods and equipment running status; analysis of resource efficiency by the cluster analysis and optimization by Genetic Algorithm; the optimized resource allocation scheme is compared with the pre-optimization scheme, and the optimized data is fed back to the data service system for vector iteration and continuous optimization of the model to provide decision support for the optimization efficiency. The details are shown in figure 6.

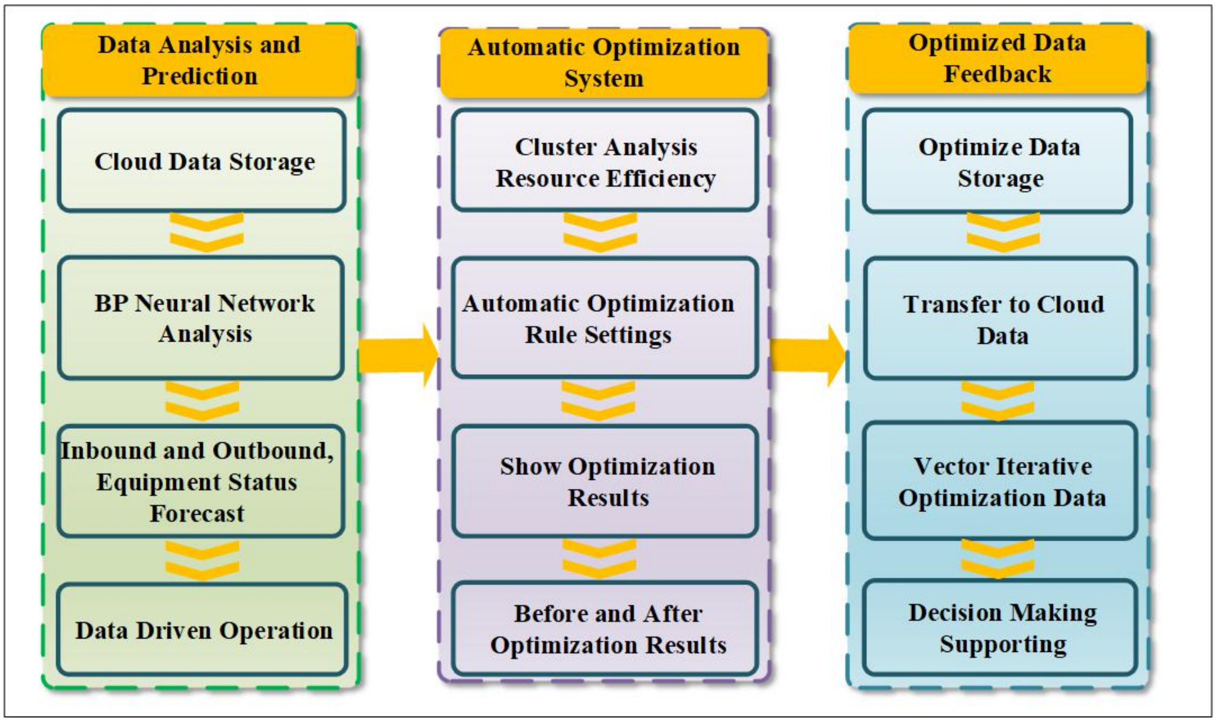

Figure 6: Resource efficiency optimization analysis process

(1) Data analysis and forecasting

The calculation is carried out by using BP neural network algorithms. The input is the relevant parameters like the historical data of the status of the goods and equipment in and out of the warehouse collected by the digital twin center, the number of hidden layers. Neural network data is divided into three parts: training data, verification data and test data. The ratio is about 7:1.5:1.5. The main aim of data training is to adjust and determine the relevant parameters of the neural network through training. The training effect of the neural network is expressed by the correlation coefficient which represents the correlation between the actual value and the predicted value. The closer to 1, the higher the fitting degree and the better the training affects prediction. The prediction data and the real-time data collected from the bottom layer are used to drive the digital twin model and feedback on the potential resource efficiency problems of unmanned warehouses.

(2) Automatic optimization of equipment resources

The process of system automatic optimization includes clustering analysis of the efficiency of the equipment and setting automatic optimization algorithms to optimize related parameters based on the analysis results.

The cluster analysis method is used to divide the resource efficiency of each kind of equipment into three categories, so as to have higher similarity within the class and lower similarity among the classes. By running the model of digital twin unmanned warehouse, the data of resource efficiency of AGV, picking robots, tally robots and forklifts are obtained. The value of resource efficiency and the direction of optimization are found by the cluster analysis. Then the genetic algorithm is used to optimize and adjust the relevant parameters to drive the model running, and realize the automatic optimization of resource efficiency.

(3) Automatic optimization of berth resources

The main objective of the optimization of shelf space is to reduce the distance of goods in the warehouse, save scheduling and transportation time. Because the structure of an unmanned warehouse is complex, it is difficult to use a specific algorithm to solve it. The system model mainly uses quantum genetic algorithms. Compared with generally used genetic algorithms, quantum genetic algorithms have better diversity and parallelism. By specifying the parameters of the shelf, inventory status and order requirements, the algorithm can be used to find the appropriate location for each batch of goods arriving. The main processes are as follows:

1) The population is initialized by quantum bit method according to the physical information of the shelf and the inventory state.

2) The fitness of the individual is calculated by taking the shortest distance of transportation as the optimization goal and considering the principle of compatibility, the constraints of centralized stacking and the size of the shelf.

3) Take the current optimal individual as the next generation's evolutionary goal. Through the quantum gate operation changes the chromosome quantum bit code, forms the next generation population.

4) Repeat until the optimization criteria are met.

(4) Optimized results feedback

The optimized resource allocation data is returned to the corresponding table of the data service system through the communication interface of the digital twin model. Then the data is transmitted back to the terminal of the service layer. Users can view the optimized model and related parameters according to the visual display interface which distributes the resources of unmanned warehouses more scientifically and reasonably.

5 Application of digital twin unmanned warehouse system

The proposed digital twin unmanned warehouse system is applied in Y company. The steps are as follows: Firstly, build the ontology model and import the data into the system database with the help of the ontology modeling software. The local database extracts the model data from PLC as the twin data of the model. Then the digital twin models are constructed by using real-time mapping technology and the running state of the unmanned warehouse is restored. Cased of this, real-time and super-real-time simulation is carried out to optimize the resource efficiency and improve the space utilization ratio of unmanned warehouses.

The data of five products in the fourth quarter of 2019 are analyzed. It was found that the number of goods in and out of the warehouse accords with Poisson Distribution. The BP neural network is used to train and forecast the order data as shown in figure 7. The correlation coefficient of the fitting degree is 0.87, which shows that the fitting degree is high and the training and forecasting effect is good. The results are uploaded to the order data table of the data service system, and the data is used to drive the digital twin model. At some time, the scene is monitoring in time and monitoring of equipment status as shown in figure 8. Including equipment operation, material storage, goods delivery, a warehouse environment, etc.

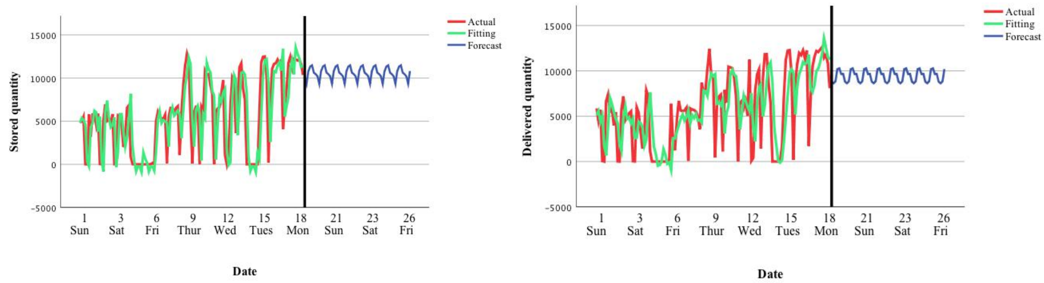

Figure 7: time series prediction of in/out storage volume

Figure 8: Large screen on site and device status data visualization

Through the data analysis of unmanned warehouse equipment resources, it can be found that the utilization ratio of automatic guided vehicles, tally robots, picking robots and other resources is unbalanced. In order to get the best allocation of resource efficiency, some rules are added to digital twin models according to the actual process and order condition. The resource quantity is adjusted dynamically by optimizing the rules.

Table 1 AGV resource utilization cluster analysis table

Auto-guided vehicles use Cluster centers			
	Club		
	1	2	3
Carriage ratio	10.83%	13.26%	21.99%
	39.57%	10.88%	27.81%
	18.18%	8.00%	40.15%
	8.42%	12.95%	36.97%
	13.01%	8.61%	8.55%

The results are as follows:

(1) From the table, it can be seen that the carrying rate of the car is unbalanced.

(2) The data is concentrated on about 10%, and the other two cluster centers fluctuate greatly.

Therefore, the automatic adjustment of resources and working hours of AGV can make it achieve higher resource efficiency, while the same adjustment of other resources and working hours can further improve overall efficiency during the operation process.

After optimization, the resource efficiency of AGV increased from 9.12% percent to 43.86% percent, and that of picking robots increased from 15.24% percent to 39.89% percent. The other resource efficiency decreased slightly, but within the acceptable range. The turnaround time of goods was shortened from 31.29 minutes to 24.90 minutes.

Furthermore, the space utilization ratio is optimized. The shelf area of the temporary storage area and the storage area are 80 and 310 respectively. The area of the temporary storage area and the storage area are 30 and 592 respectively. In order to ensure a reasonable inventory and higher resource efficiency can reduce the number of shelves in the cargo area, the resource efficiency of the storage capacity is about 60% percent when the storage capacity reaches the peak, so it is necessary to improve the space utilization efficiency of the warehouse. When the storage resource efficiency reaches 80% percent by using quantum genetic algorithms, the number of shelves needed for the temporary storage area and the storage area are 32 and 176 respectively, and the area of the corresponding temporary storage area and the storage area are reduced accordingly. The resource efficiency of storage space has improved.

From the above analysis, we can see that the resource efficiency of the unmanned warehouse and the shelf utilization has been improved. The inventory turnover efficiency has also increased. The optimized data information is fed back to the data service system for iterative optimization and to facilitate further optimization of the model. And the data will then be fed back to the server data sharing center, scientific and rational allocation of related resources decision can be made by the decision-maker according to the visual interface model and parameters.

6 Conclusion

Digital twin technology is introduced into the unmanned warehouse system, which is helpful to monitor the running status of equipment dynamically and deal with the problems on the spot in time, to improve the running efficiency and the ability of scheduling timely of equipment and promote the realization of intelligent logistics. In this paper, a model of unmanned warehouse system based on digital twin is proposed which extends the application of digital twin technology in warehouse resource scheduling. It combines the physical entity to model ontology mapping technology and ontology translation technology, based on the data analysis and optimization technology methods (BP Neural Network Algorithm, clustering analysis method, Genetic Algorithm); the real-time data-driven digital twin unmanned warehouse system can be used for real-time transparent management and simulation decision support based on the physical information of the actual warehouse. The combination rule and dynamic priority method are designed to improve the scheduling of logistics equipment and the optimization of resource efficiency and space utilization. Digital twin modeling improves the reusability of the model, realizes the combination of virtual and real, and analyses and forecasts the future situation. The theory and method of digital twin unmanned warehouse models can be used not only for the resource efficiency and cost optimization, but also for balancing a resource efficiency and a service level. Considering the implementation cost and complexity of digital twin, there is still a big gap in the high-level integrated digital twin. Based on the model in this paper, more twin data of different objects will be obtained and the data of different granularity will be further studied to better realize the work of "controlling reality by virtual".

Funding

This project was supported by the National Natural Science Foundation.China(No.71501020).

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