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Energy Efficiency Optimization Based on Digital Twin Workshops

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Abstract: *In order to realize the optimization of energy saving for the digital processing workshop, reducing the energy consumption of equipment in the workshop and improving the energy efficiency of the workshop is also imperative. Energy efficiency optimization based on digital twin workshop is proposed. According to the characteristics of the whole processing process and energy consumption of the workshop, the dynamic energy efficiency model of the digital twin workshop is established to realize the visualization platform of control substantiation and management. The NSGA-II algorithm is used to analyse the energy efficiency analysis method of machine tool scheduling and plan the digital twin energy efficiency scheduling scheme.*

Keywords: *Digital twin, Energy consumption, NSGA-II, Scheduling scheme*

1. Introduction

In the face of a new round of industrial innovation, in 2015, China proposed "Made in China 2025" and other relevant important strategies, insisted on the development path of innovation driven and quality first, and also proposed to comprehensively develop green and implement green manufacturing projects [1]. However, the traditional manufacturing industry is unable to adjust the industrial structure due to certain problems such as energy consumption and environment, so it is necessary to consider modern production technology to optimize and upgrade the industry. The United States first proposed to use digital twin technology for aerospace health maintenance. The main advantages of the UK's implementation of "Digital Twin City" are the solutions of engineering, building and low-carbon urban environment, which have a significant impact on the opportunities of technological change and emerging economy driving. In the "Fourteenth Five Year Plan", China made strategic deployment by using digital twin technology to promote high-quality socio-economic development.

The research on workshop energy efficiency and its low-carbon operation is increasingly emerging at home and abroad. Liu Fei [2] and others proposed five basic technologies for machine tool energy efficiency, including modeling of one key basic energy efficiency and consumption. Zhang [3] et al. proposed a digital twin double emission prediction for manufacturing workshops, and studied three key technologies of digital twin data processing, evaluation and service, and low carbon control methods for manufacturing workshops under low carbon. Xu W [4] et al. put forward the digital twin evaluation index, model and dynamic evaluation method by combining the model and manufacturing service technology.

To sum up, the use of digital twin simulation can analyze the optimization of production and energy efficiency of the workshop, reasonably arrange the scheduling scheme, analyze the workshop energy consumption, specify a reasonable production process route, and carry out a reasonable planning scheme of energy efficiency according to the digital twin energy efficiency optimization system.

2. Green framework of digital twin workshop

The digital twin energy efficiency workshop is a new mode of green intelligent manufacturing workshop based on the digital twin five dimensional models [5] in the full life cycle. It is a mapping virtual model of physical entities established in DTW (Digital Twin Workshop) with data as interaction. Predict and detect the production process of products in the workshop through virtual reality interaction, green feature extraction, energy consumption assessment, energy efficiency management and other effective means. Figure 1 shows the Digital Twin Energy Efficiency Framework, which is composed of

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

the physical layer, virtual entity layer, and application service layer. The service layer is layered on the basis of the application service layer, namely, the evaluation layer and the optimization layer. The physical layer is the dynamic feature of the workshop entity and corresponds to the virtual model. Data transmission is a collection of multi-level and multi-structure data output. The evaluation layer of data service is to classify, process and calculate the acquired data, including energy consumption data, real-time data, parameters, etc. The optimization layer is used to evaluate the energy consumption data and calculate the efficiency, optimize the current results, and evaluate and predict the results.

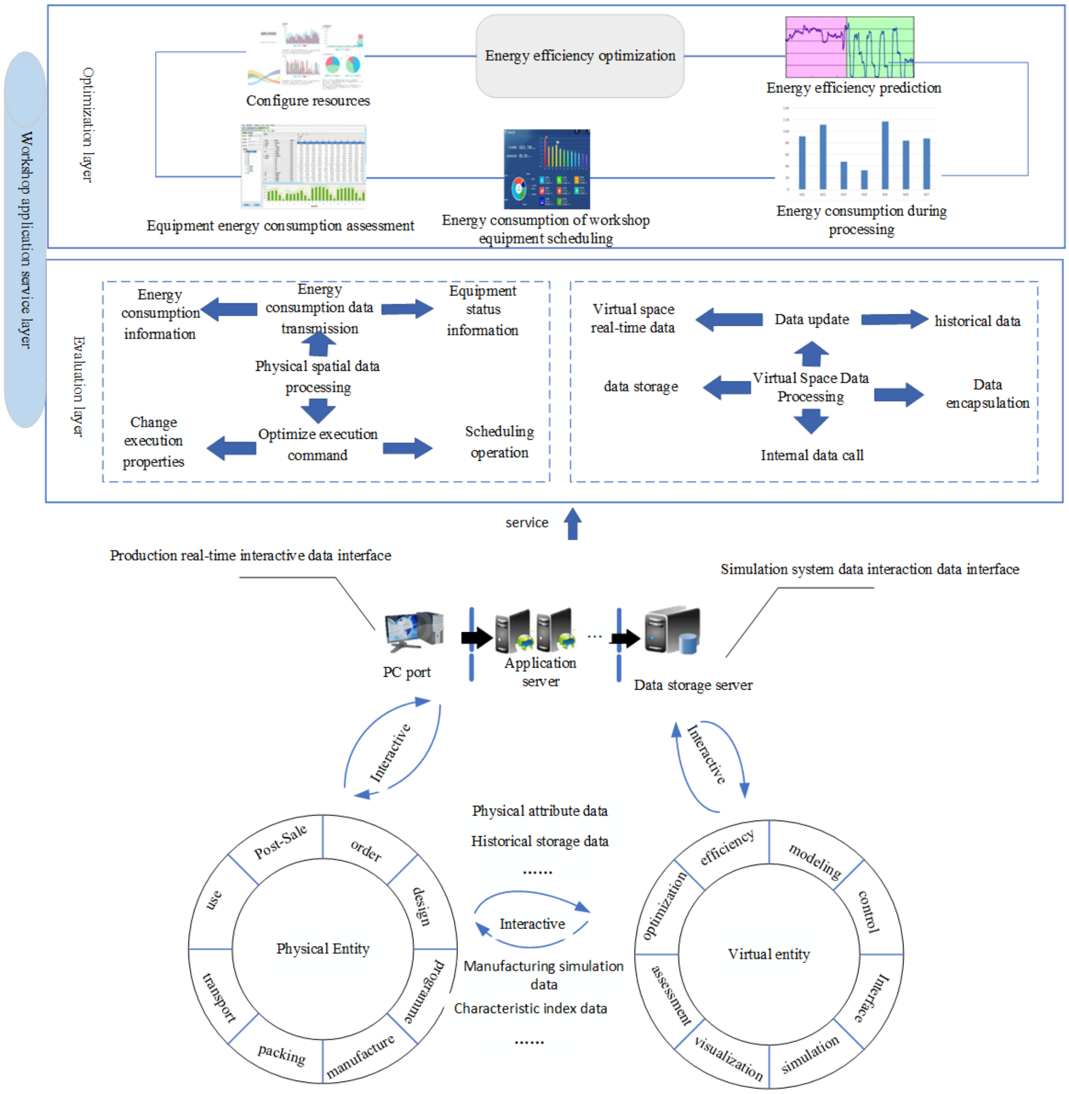

Figure 1: Energy efficiency framework of digital twin green workshop.

3. Energy consumption assessment and analysis of manufacturing workshop

The optimization object of workshop energy consumption is the manufacturing workshop. Common types of manufacturing workshops can be divided into flow shop, mixed workshop, flexible workshop and combined group workshop, as shown in Figure 2 below. Flow shop continuously processes parts with the same processing procedure on a series of machines, which are applied in manufacturing, flow assembly line and other fields. A job shop is an extension of a flow shop processing procedure. Although there are the same processing procedures, parts can first determine the processing equipment and processing procedures according to their own production routes. In the flow shop, the production mode of a flexible workshop is formed when the equipment is introduced simultaneously. In the process of workpiece processing, each process can be processed by more than two sets of equipment. One of the processing equipment can be selected for the part in the process. This production mode increases the flexibility of the processing method, and has differentiation and diversification of production. The optimization goal of the workshop is usually the shortest processing time, less cost and less energy

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

consumption. The production line realizes the energy efficiency optimization of the production line through the equipment layout of the whole production workshop, the processing sequence of the workpiece, the reasonable scheduling of the workshop, etc.

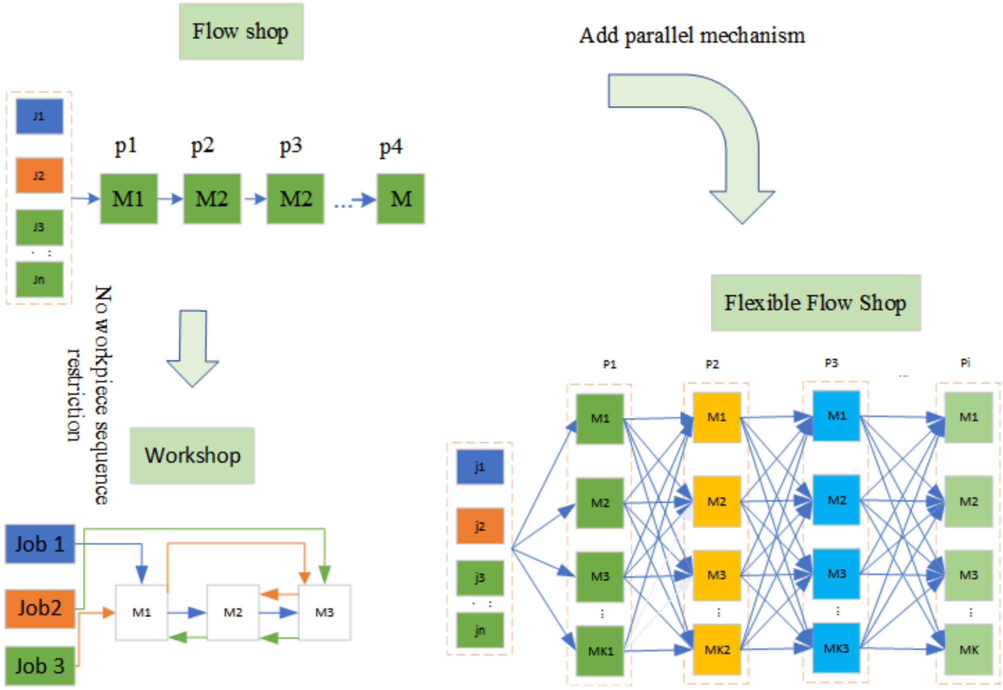

Figure 2: Three basic workshop types.

In response to the low-carbon and efficient production mode, considering the full cycle and all factor production and manufacturing relationship of product manufacturing, processing, assembly and transportation, the energy consumption assessment and analysis of intelligent manufacturing simulation production line shall be evaluated at the workshop level of process, workshop and product, and the energy efficiency analysis shall be evaluated from different production objects to improve the dynamic operation effect of the workshop. The production mode of discrete products is processing and assembling. They are composed of a bunch of components and the processing process is discrete. The manufacturing process is relatively complex and related in the service process. The processing and assembling relationship diagram are shown in Figure 3. Therefore, more skilled electromechanical equipment and intelligent instruments are needed, which can affect the evaluation of manufacturing energy efficiency. It focuses more on links, and needs to ensure modeling and simulation in different process routes and equipment.

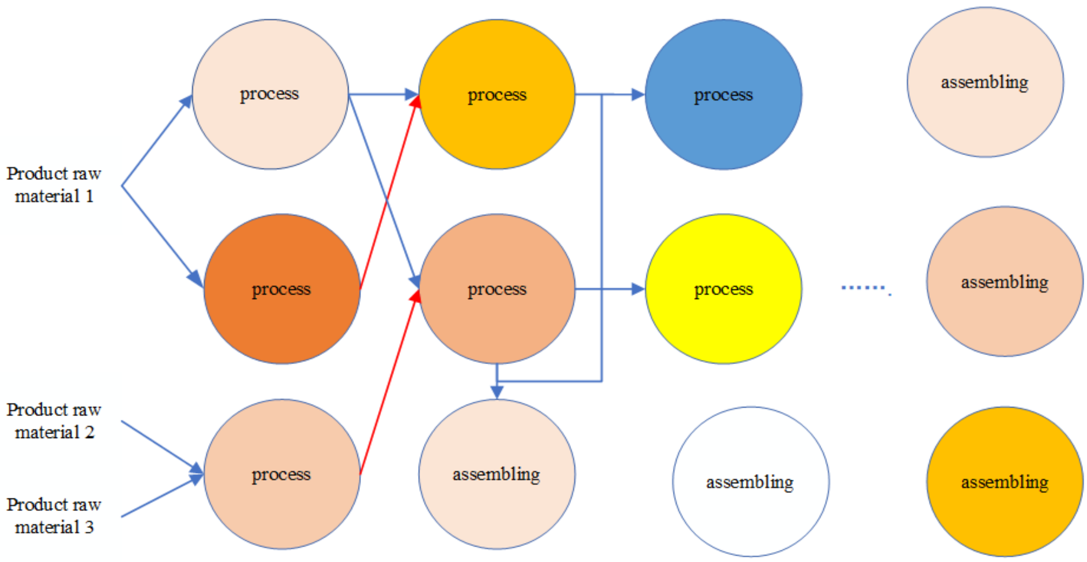

Figure 3: Processing and assembly task diagram.

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

4. Energy saving optimization of intelligent manufacturing workshop

The flexible job shop optimized for energy consumption and production indicators is more consistent with the actual production requirements and environment. On the one hand, it reduces mechanical constraints, and on the other hand, it realizes a feasible combination optimization scheme. The job shop is based scheduling method aims to reduce the job completion time in the manufacturing process and reduce the processing energy consumption. The shop floor problem can be described as: each processing workpiece contains at least one processing operation; One or more equipment can be selected for each processing operation, and the processing sequence of the workpiece is not sequential.

The processing time and load consumption will also vary depending on the selected processing machine, so the scheduling scheme should determine the processing sequence of the operation and the selection of the parallel equipment selected by the operation. It can make each index of the workshop system state achieve relative optimization. Therefore, the fundamental problem in solving the flexible workshop is to deal with the problem of equipment selection in the process and the problem of job sequencing in the process. It can be assumed that there are n (i={1,2,..., i,..., n}) workpieces and w processing operations (j={1,2,..., j,..., w}). The operation of a workpiece can be O_{ij}. For example, O_{12} indicates that the workpiece is processed in operation 2.

4.1. Construction of mathematical model

In this paper, the workshop energy efficiency scheduling model is established to minimize the maximum processing time and machine tool processing energy consumption. The formula is as follows:

$$f1 = \min(\max\{C_i \mid i = 1, 2, ..., n\}) \tag{1}$$

$$f2 = \min E_{Total} \tag{2}$$

The constraints are:

$$\sum_{k=1}^{M_j} x_{ijk} = 1 \tag{3}$$

Formula (1) and Formula (2) are objective functions, $f1$ is the minimum maximum completion time, and $f2$ is the energy consumption of the machine tool. Formula (3) is a constraint condition. The symbols in the formula are shown in Table 1.

Table 1: Symbol Definition.

Symbol	meaning
$f1$	Minimize maximum completion time
$f2$	Energy consumption of machine tool
C_i	Processing time of workpiece i
E_{Total}	Target energy consumption of equipment
M_j	M indicates the number of processing equipment that can be selected for the jth processing operation.
x_{ijk}	If it is 1, the workpiece i is processed on device k; if it is 0, the workpiece is not processed on device k

4.2. Construction of mathematical model

Srinivas and Deb put forward the non-dominated genetic algorithm (NSGA-II) [6], which is mainly based on the genetic algorithm and the concept of Pareto optimization. The biggest difference between the genetic algorithm and the genetic algorithm is that the population individuals are quickly non dominated sorted before selection to improve the probability of retaining excellent individuals. The flow chart of NSGA-II implementation is shown in Figure 4 below:

Step 1: Initialize the population, and randomly generate an initial population of N.

Step 2: Conduct non dominated sorting on the initial population, and generate the first generation's individuals after selection, crossing and inheritance.

Step 3: The parent and child generations are merged, the new population is non dominated sorted, and the crowding degree is calculated to generate a new parent.

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

Step 4: Select, cross and mutate the newborn parents to generate the next generation of sub population.

Step 5: If the set value of algebra is not satisfied, perform Gen+1 for the child, return to step 3, and merge the child with the parent to enter the next cycle. If the set value of algebra is satisfied, the cycle ends.

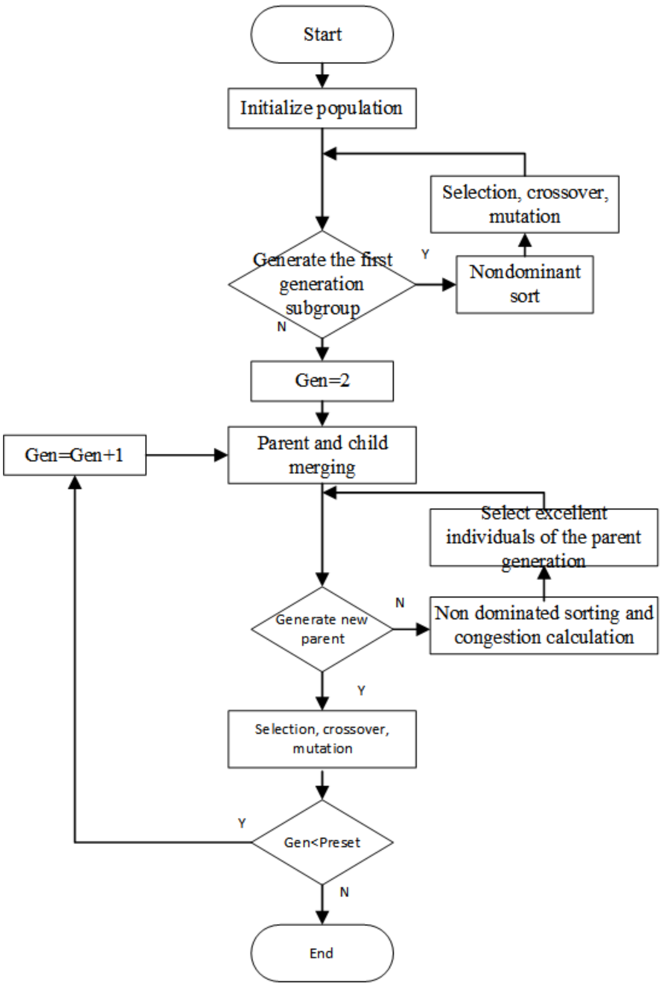

Figure 4: NSGA-II Implementation Flow Chart.

4.2.1. Encoding and decoding design

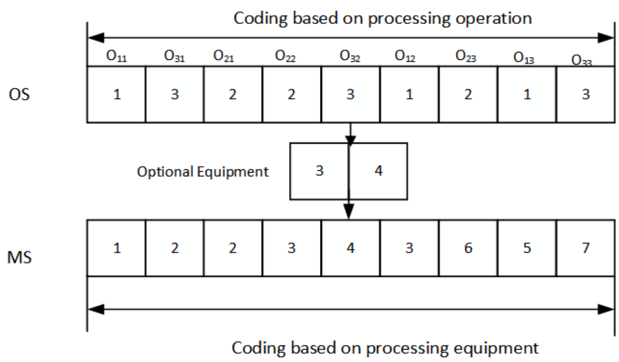

Figure 5: Coding method.

In the scheduling scheme considering the optimization of energy efficiency, the double coding method is used for coding [7]. As shown in Figure 5, the upper half is based on the coding of processing operations, and the lower half is based on the coding of processing equipment. For example, there are three to be processed, and the workpiece processing requires three processing operations. Each operation corresponds to [2,2,3] devices. The first half represents the processing procedure O_{ij} of the workpiece. For example, the third gene represents the first process of workpiece 2, and the second half is based on

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

the equipment number representing the process. For example, the fifth gene represents the processing equipment 3 and 4 that can be selected for the second process based on O_{32}. Decoding is to take out each operation in sequence according to the coding sequence of the operation, and then according to the allocation scheme of the corresponding equipment of the operation.

4.2.2. Select Action

First of all, need to do a non-dominated sort Pareto. As shown in Figure 6 below, the operation process is as follows: First, find all the non-dominated solutions of the front end, that is, they are not dominated by other solutions, and the non-dominated level can be defined as Pareto Level I; Second, we also find out that except for the non-dominated solution of level I, level II can be defined; Third, follow the steps and so on until the last stage is discharged.

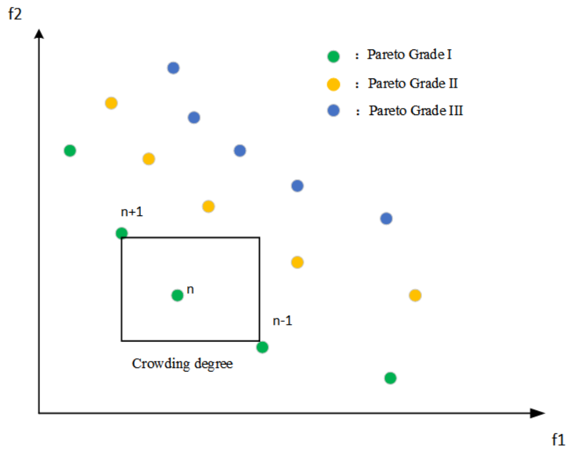

Figure 6: Pareto ranking and congestion calculation.

Secondly, the crowding degree is calculated. The dominating individuals at the same level can evenly distribute the Pareto front to ensure the diversity of non-dominating individuals at the same level. Therefore, after the non-dominating sorting, the crowding degree of the same level needs to be calculated:

$$D = \frac{f_m(n+1) - f_m(n-1)}{f_m^{\max} - f_m^{\min}} \tag{4}$$

In Formula 4, $f_m(n+1)$ represents the previous function solution of n on m, $f_m(n-1)$ represents the next function solution of n. $f_m^{\max}$ and $f_m^{\min}$ represent the maximum and minimum values of function m.

4.2.3. Crossover and variation

Cross operation is an important embodiment of genetic algorithm, which can further expand the optimization ability of the algorithm under constraint conditions. Next, select a priority based cross method (POX) [8]. Figure 7 shows the process of cross operation.

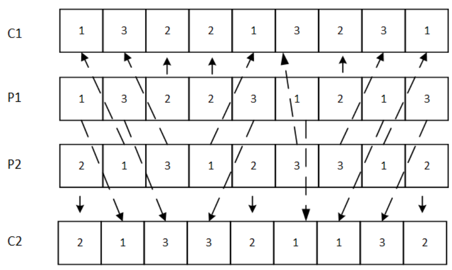

Figure 7: POX cross algorithm.

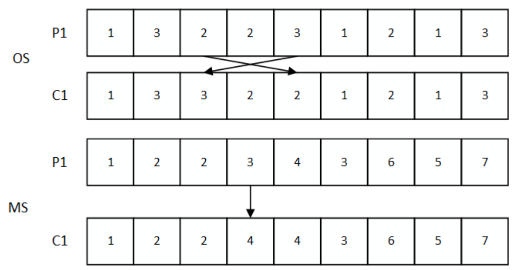

Figure 8: Mutation operation.

In the process of genetic algorithm, in order to avoid the result falling into the situation of local optimization, it is often necessary to ensure the diversity of individuals through mutation operation. The first is the mutation method of the process, which can randomly select two genes and then perform mutation operation, while other genes keep their original position and order unchanged. For the mutation operation of equipment, a gene can be randomly selected, and then one of the equipment can be randomly selected from the available equipment set for replacement, as shown in Figure 8.

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

4.2.4. Elite retention strategy

In order to prevent the disappearance of outstanding individuals in the process of evolution, elite strategy is introduced. In the process of algorithm iteration, excellent individuals shared by parents and children are retained through non dominated sorting and crowding degree calculation until the maximum iteration value of the algorithm is reached. Elite retention strategy is shown in Figure 9. P_t and Q_t are parent population and child population, P_{t+1} is iterative parent population, and Q_{t+1} is iterative child population of parent.

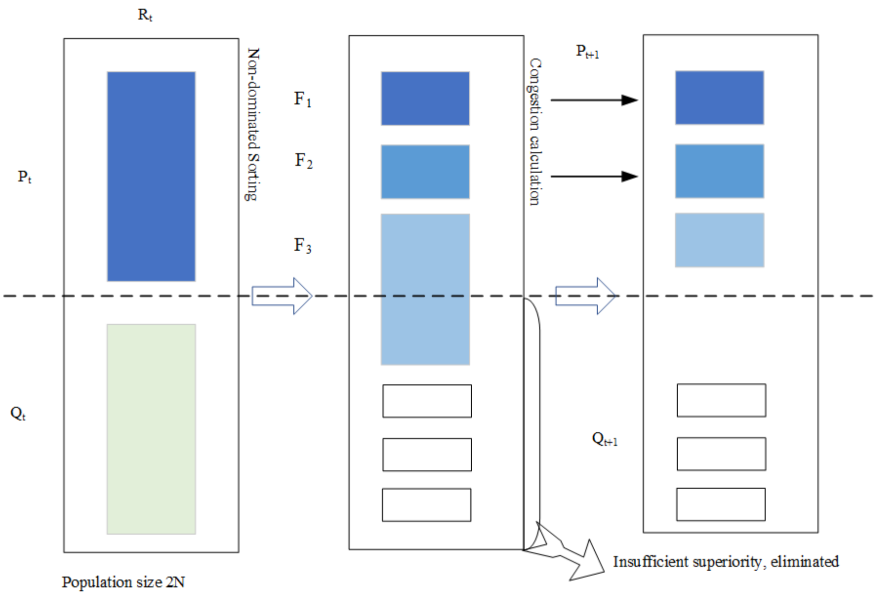

Figure 9: Elite retention strategy.

5. Verification based on digital twin manufacturing platform

5.1. Construction of virtual workshop

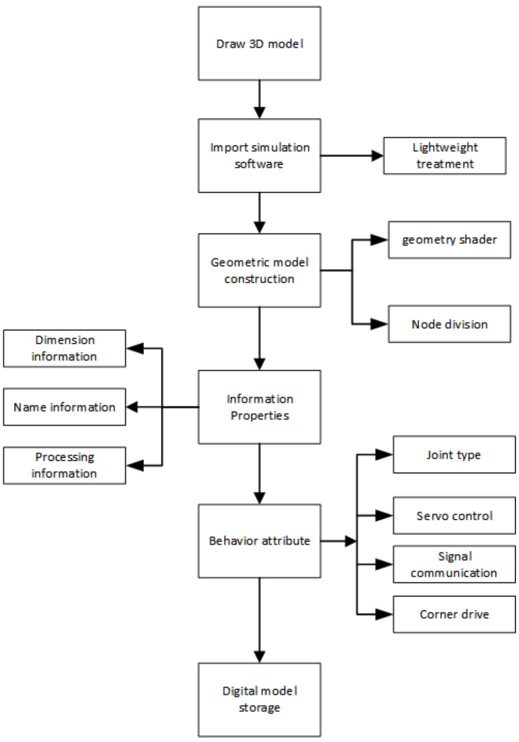

Figure 10: Workshop virtual scene construction flow chart.

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

Workshop virtual scene modeling consists of two main aspects, namely, the construction of geometric model and the model of digital twin scene. Figure 10 is the flow chart of workshop virtual scene construction. Geometric modeling is the basic component of virtual scene construction. Scene construction enriches the realism of geometric modeling, and is the real texture that can describe and analyze the scene. In the digital twin model, it is necessary to define the physical attributes of the model, including structure, joints and parameters. The motion attributes are based on the motion trajectory, orientation, motion parameters and other related definitions of the real model, and the driver is required to define the state of the model. The model needs the virtual components to mobilize the operation of the whole workshop according to the state of the entity, and the signal communication is the way of information interaction. The physical information data and model information are interconnected through the interface protocol to ensure the twin information transmission and mapping simulation.

5.2. Data acquisition and interaction based on OPC UA

The overall server model is shown in Figure 11. The OPC UA client of ordinary users communicates with the server equipment containing the embedded OPC UA server. The intermediate client of OPC UA has already acquired information and data of other devices. When responding to the request command sent by the client, it will transmit the processed data, using the C/S (client/server) bidirectional basic mode [9]. It realizes data interaction between client and server based on API [10]. In this interaction process, the information stack of client and server cooperatively completes. OPC UA has a standard and safe transmission mode. For the PLC used, it needs to perform its own security functions to achieve the conversion of OPC UA protocol and successfully interact with external devices.

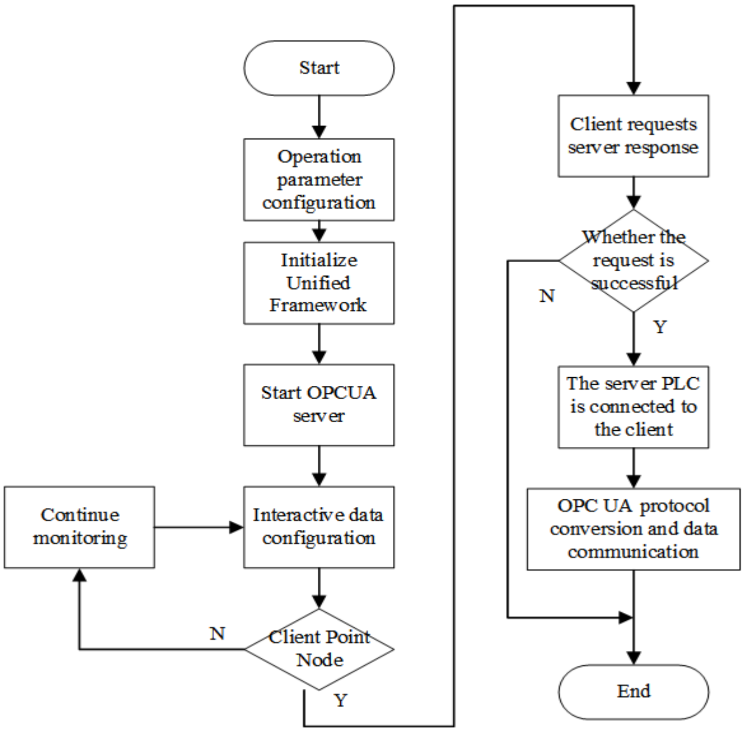

Figure 11: Data collection and interaction.

5.3. Scene layout and construction

After the model is established, the basic attributes of the model unit are given, and the layout needs to be constructed according to the actual physical entities. Through the Visual Engineering and Education platform, various operations such as model movement, splicing and interaction are spliced together, the geometric position and coordinates of the layout are adjusted, and the overall model of the production line is initially planned. Figure 12 shows the layout of the machine tool. This production line is mainly composed of seven machine tools to be processed, four manipulators and one rack manipulator. The overall model production line of the production line is formed by reasonable layout of the model blocks.

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

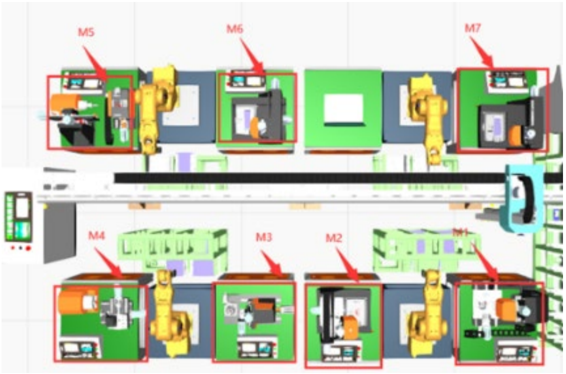

Figure 12: Layout of machine tool.

5.4. Digital twin workshop case verification

The production is simulated through the digital twin simulation model. The workshop production line produces three kinds of parts, which are processed on seven machine tools respectively. The workpiece, different workpiece processes are the same, and different processes have several optional equipment. See Table 2 and 3 for details. J1-J3 represents the workpiece, P1-P3 represents the process, T_W represents the cutting time, T_E idle time. P_W is cutting power; P_E is idle power and Pa is loss power.

Table 2: Processing time of flexible workshop.

	P1				P2				P3					
	M1		M2		M3		M4		M5		M6		M7	
	T_W	T_E	T_W	T_E	T_W	T_E	T_W	T_E	T_W	T_E	T_W	T_E	T_W	T_E
J1	46	9	47	7	31	14	28	10	40	9	43	6	43	6
J2	51	9	44	7	36	14	35	10	45	9	35	6	42	6
J3	44	9	42	7	33	14	30	10	38	9	36	6	42	6

Table 3: Processing energy consumption of flexible workshop.

	P1				P2				P3					
	M1		M2		M3		M4		M5		M6		M7	
	P_W	P_E	P_W	P_E	P_W	P_E	P_W	P_E	P_W	P_E	P_W	P_E	P_W	P_E
J1	1.52	0.91	1.65	0.87	0.39	0.12	0.19	0.54	1.95	0.80	1.15	0.52	1.65	0.53
J2	1.93	0.92	2.0	0.79	0.37	0.14	0.16	0.62	2.15	0.94	1.65	0.61	1.87	0.61
J3	1.71	0.83	1.89	0.69	0.36	0.12	0.17	0.56	2.01	0.99	1.93	0.67	2.01	0.70
Pa	0.24		0.15		0.22		0.12		0.19		0.25		0.21	

Figure 13: Gantt Chart of Twin Workshop Scheduling.

Use PyCharm2020 (the compiler is Python 3.8) to write and run the relevant scheme. Set the population size to 200, the maximum number of iterations to 175, the crossover ratio to 0.9, and the mutation rate to 0.1. By substituting the data into the algorithm, the optimal scheduling Gantt chart can

ISSN 2616-5767 Vol.5, Issue 13: 15-25, DOI: 10.25236/AJETS.2022.051303

be obtained as shown in Figure 13, minimizing the processing time of 182s. The following figure 14 shows the scatter plot distribution of Pareto optimal solution, and a group of optimal solutions are obtained. The total energy consumption of the equipment is about 571KW. S.

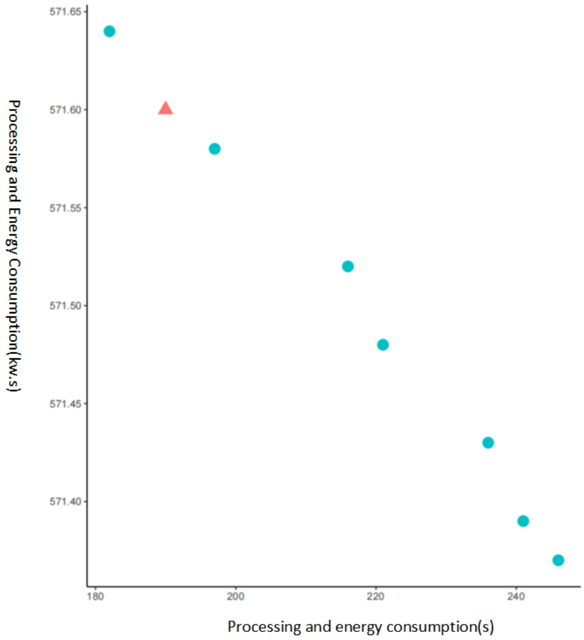

Figure 14: Scatter diagram of case optimization.

5.5. Digital twin workshop case verification

A digital twin is based energy efficiency optimization management system is designed to display the data of the running virtual workshop system in real time, display the optimization of workshop production line layout, view the application status of equipment, and plan the scheduling and energy efficiency analysis scheme of the workshop through the physical and virtual workshop energy efficiency optimization level. Figure 15 shows the energy efficiency optimization monitoring scheme, which reflects the monitoring of physical workshops on virtual workshop energy efficiency detection and time scheduling.

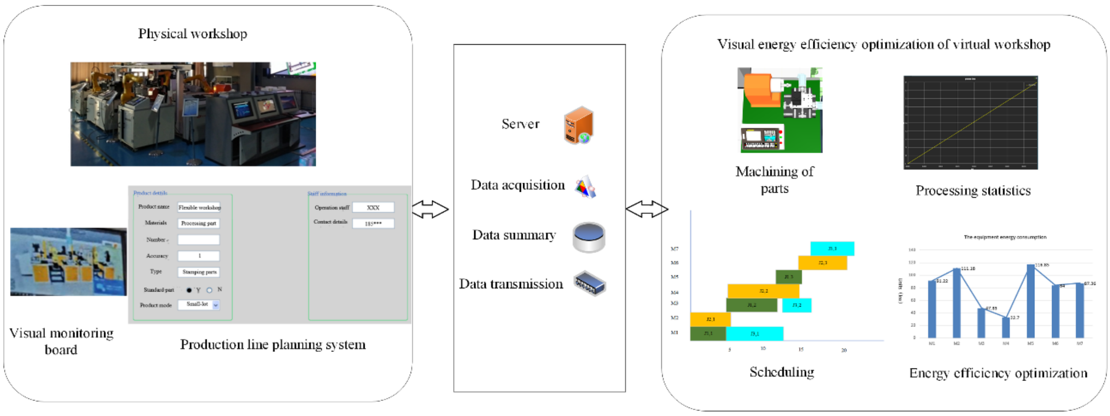

Figure 15: Energy efficiency optimization monitoring system diagram.

6. Conclusions

This paper mainly discusses the realization of workshop energy efficiency optimization analysis on the basis of digital twin platform, introduces the framework of green digital twin, mainly uses multi-objective optimization analysis scheme to analyze time scheduling and energy efficiency, uses NSGA-II algorithm to verify the example, establishes digital twin energy efficiency management and control platform, effectively analyzes workshop dynamic data and reasonably optimizes energy efficiency

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methods, and provides a feasible scheme for production optimization.

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