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A Strategic Study of Hybrid Algorithms Applied to Optimize the External Tool Repository Tool Restriction Problem in the FMS Shop Floor Planning Process

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ABSTRACT

The article firstly establishes a mathematical model of the FMS shop floor planning process problem, and combines the rescheduling strategy and rolling scheduling strategy for solving the FJSP problem. Subsequently, the simulated annealing genetic algorithm is improved by relying on genetic algorithm, simulated annealing algorithm and particle swarm optimization algorithm, and the application of hybrid optimization algorithm in problem solving is proposed. The simulated annealing algorithm is incorporated into the crossover and mutation operations of the genetic algorithm to strengthen the local search capability, and then the global annealing operation is incorporated into the new individuals obtained. The overall design of the mixed reality-based FMS virtual simulation system was tested with a view to optimizing the external tool library tool limitation problem in the FMS shop floor planning process. The results of the simulation experiments show that although the algorithm of this paper, SaDE and CoDE algorithms can reach the optimal solution, the convergence speed of the algorithm proposed in this paper is significantly better than the other two algorithms. Based on the experimental results, the article finally constructs a mixed reality-based FMS virtual simulation system to solve the external tool library tool limitation problem in the FMS shop floor planning process.

Keywords: genetic algorithm, simulated annealing algorithm, scheduling strategy, virtual simulation system, FMS shop floor planning

1. Introduction

Flexible manufacturing system (FMS) is an automated manufacturing system composed of CNC machining equipment, material storage and transportation devices and computer control systems. It includes multiple flexible manufacturing units, which can be quickly adjusted according to changes in manufacturing tasks or production, and is suitable for multi-species medium and small batch

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production [1-4]. Its emergence marks the machinery manufacturing industry has entered a new stage of development, overcoming the original mechanical production line is only suitable for mass production of rigid characteristics, can adapt to small and medium-sized batches, multi-species flexible production methods, and will be manually operated to a minimum, with a high degree of automation characteristics [5-8]. With the social recognition of multi-species, small and medium batch products, the demand for short production cycle, low manufacturing cost increases, coupled with microelectronics technology, computer technology, communication technology, machinery and control equipment technology is increasingly mature, flexible manufacturing technology has been widely used [9-12].

In the modern manufacturing industry, the efficient operation of the workshop is crucial to the production efficiency and product quality of the enterprise. However, in the actual production process, the workshop often faces a variety of problems such as poor equipment management, irrational production processes, personnel management problems, and so on [13-16]. For the FMS workshop planning process, the external tool library tool limitation problem is the most important problem it faces, in order to improve the workshop's production efficiency, product quality and working environment, the use of intelligent algorithms to optimize this limitation problem is of great significance [17-20].

The article firstly puts forward the corresponding assumptions and constraints according to the characteristics of the FJSP problem, designs the evaluation indexes, establishes the mathematical model, and proposes to decompose the complex FJSP problem into consecutive multiple static scheduling intervals in order to reduce the computation time of solving the FJSP problem and ensure the stability of the job shop. A combination of rescheduling strategy and rolling scheduling strategy is proposed for solving the FJSP problem. Subsequently, particle swarm optimization algorithm and simulated annealing algorithm are incorporated on the basis of genetic algorithm to deal with the initial population, crossover and mutation operations of genetic algorithm. Two advanced and improved differential evolution algorithms, SaDE and CoDE, are selected to simulate the scheduling problem to verify the advantages of the proposed algorithm, decode the optimal solution to determine the processing sequence of workpiece processes, select the optimal processing process for the shop floor production scheduling problem based on the minimization of the maximum completion time, and draw Gantt charts based on the processing parameters of the workpieces for the convenience of the staff to carry out the shop floor production scheduling. The Gantt chart is drawn according to the processing parameters of the workpiece to facilitate the staff to carry out the workshop production scheduling, and the energy consumption of the method proposed in this paper is analyzed. Finally, a mixed reality-based FMS virtual simulation system is designed, and its related key technologies and development steps are investigated to solve the limitation of external tool libraries in the FMS shop floor planning process.

2. Mathematical modeling of the FJSP problem and dynamic scheduling strategy

2.1. FJSP problem and modeling study

2.1.1. FJSP problem description. The FJSP problem can be described as follows: there are n workpieces in the job shop, which are machined on m machines, each of which is to be machined according to its process, and each of which has one or more machining machines to choose from [21]. The core of the FJSP problem is how to arrange the machining sequence of each workpiece and each process of that workpiece on the corresponding machine, so as to improve the performance of a certain evaluation of flexible job shop performance of a metric.

2.1.2. Mathematical modeling of the FJSP problem. FJSP problem is an extension of the traditional job shop scheduling problem, compared with the traditional job shop scheduling problem, now the

FJSP problem in each part of each process has one or more alternative machines. In the process of production and processing will be affected by a variety of interfering factors, at this time how to arrange each workpiece and each process of the workpiece in the corresponding machine processing order, so that a certain evaluation index of the flexible job shop to reach the optimum, it is very important.

In order to accurately describe the mathematical model of the dynamic scheduling problem in a flexible job shop, the paper makes the following assumptions:

1) The computation time of rescheduling is negligible and the machining process is executed immediately when the rescheduling is completed.

2) There are no dynamic events during the rescheduling time although they occur randomly.

3) The initial states of the equipment are all idle and zero-moment states, and they are all good states that can be selected for use.

4) The preparation time of all processes is included in the processing time of the process, and the processing time of the process is related to the equipment being processed, independent of the processing sequence.

5) All processes, once started on the equipment, cannot be stopped until the processing is completed, unless the equipment fails [22].

Based on the above assumptions, in order to more easily describe the mathematical model of the FJSP problem, some variables that will be used subsequently are defined below:

n: Total number of workpieces to be processed in the job shop.

m: Total number of machines on the job shop production line.

Ω: The machine set consisting of all machines on the job shop production line.

i, e : Serial number of each machine on the job shop production line, $i, e = 1, 2, 3, \cdots, m$.

j, k : Serial number of each workpiece on the job shop production line, $j, k = 1, 2, 3, \cdots, n$.

h_j : The total number of processes for the jth workpiece to be machined in the job shop.

l: The process serial number of the workpiece to be machined in the job shop, $1 = 1, 2, 3, \cdots, h_j$.

Ω_{jh}: The set of machines in the job shop that can process the hth process of the jth workpiece.

m_{jh} : The number of machines in the job shop that can process the hrd process of the jnd workpiece in the concentration of machines.

O_{jh} : The hth process of the jth workpiece to be processed in the job shop.

M_{ijh}: The hth process of the jth workpiece to be processed on machine i in the job shop.

p_{ijh} : Processing time required to process the hth process of the jth workpiece in the workpiece set on machine i in the job shop.

s_{jh}: Time to start the hth process of the jth workpiece in the workpiece set in the job shop.

c_{jh}: Time in the job shop to complete the hth process of the jth workpiece in the set of workpieces.

s_{jh}: The time of the hrd process of the jnd workpiece in the work shop that starts machining the workpiece set.

c_{jh}: The time to complete the hth process in the job shop for the jth piece in the set of pieces.

L : A positive number.

d_j : Delivery time for the jth workpiece in the workpiece set.

C_j: Completion time of the jth workpiece.

C_{max}: Maximum completion time.

T_0 : $T_0 = \sum_{j=1}^{n} h_j$, the total number of processes for all workpieces.

x_{ijh} : If process O_{jh} selects machine i for processing, $x_{ijh} = 1$. Conversely, $x_{ijh} = 0$.

y_{ijhkl}: If O_{ijh} is processed before O_{ikl}, then $y_{ijhkl} = 1$. and vice versa $y_{ijhkl} = 0$.

The constraints are:

1) The individual processes of each workpiece are determined and the order in which they are machined cannot be changed.

$$s_{jh}+x_{ijh}\times p_{ijh}\leq c_{jh} \tag{1}$$

In the formula $i=1,2,3,\cdots,m$. $j=1,2,3,\cdots,n$. $h=1,2,3,\cdots,h_j$.

$$c_{jh}\leq s_{j(h+1)} \tag{2}$$

The formula $j=1,2,3,\cdots,n$. $h=1,2,3,\cdots,h_j-1$.

2) The completion time of each workpiece cannot exceed the total completion time.

$$c_{jh_j}\leq C_{\max} j=1,2,3,\cdots,n \tag{3}$$

3) Only one process can be processed on the same machine at the same time.

$$s_{jh}+p_{ijh}\leq s_{kl}+L\left(1-y_{ijhkl}\right) \tag{4}$$

In the formula $i=1,2,3,\cdots,m$. $j=1,2,3,\cdots,n$. $k=1,2,3,\cdots,n$. $h=1,2,3,\cdots,h_j$. $l=1,2,3,\cdots,h_k$.

$$c_{jh}\leq s_{j(h+1)}+L\left(1-y_{iklj(h+1)}\right) \tag{5}$$

In the formula $i=1,2,3,\cdots,m$. $j=1,2,3,\cdots,n$. $k=1,2,3,\cdots,n$. $h=1,2,3,\cdots,h_j-1$. $l=1,2,3,\cdots,h_k$.

4) At the same moment, the same workpiece can only be processed on one machine for the same course.

$$\sum_{\mathrm{i}=0}^{m_{jh}} x_{ijh}=1 \tag{6}$$

The formula $h=1,2,3,\cdots,h_j$. $j=1,2,3,\cdots,n$.

The minimum indicator of the maximum completion time of the job shop is the time to finish the last process of all the dispatched workpieces, which is also the largest one in this dispatch, and it is one of the most widely used indicators in the evaluation indexes. The purpose of the minimum indicator of the maximum machine load in the job shop is to improve the utilization rate of each machine, so that the production load of each machine should be minimized and balanced as much as possible. The purpose of the minimum total machine load indicator is to minimize the total load of the entire production system in the job shop. The objective function of these three is:

Maximum Completion Time Minimum Objective Function:

$$f_1=\min\left(\max\left(C_j\right)\right)\left(1\leq j\leq n\right) \tag{7}$$

Maximum load machine min:

$$f_2=\min\left(\max\left(\sum_{j=1}^{n}\sum_{h=1}^{h_j}p_{ijh}x_{ijh}\right)\right)1\leq i\leq m \tag{8}$$

Total machine load is minimized:

$$f_3=\min\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{h=1}^{h_j}p_{ijh}x_{ijh}\right) \tag{9}$$

2.2. Dynamic Scheduling Strategy for Flexible Job Shop

2.2.1. Rescheduling strategy. The scheduling problem of job shop can be generally categorized into two types: static scheduling and dynamic scheduling, while dynamic scheduling can be categorized into three types according to the specific environment and requirements: fully reactive rescheduling, pre-reactive rescheduling and robust rescheduling. The structure of flexible job shop rescheduling strategy is shown in Figure 1. Since fully reactive rescheduling has the characteristics of real-time scheduling and is very suitable for application in environments with frequent dynamic events and high uncertainty, this paper adopts fully reactive rescheduling to solve the FJSP problem.

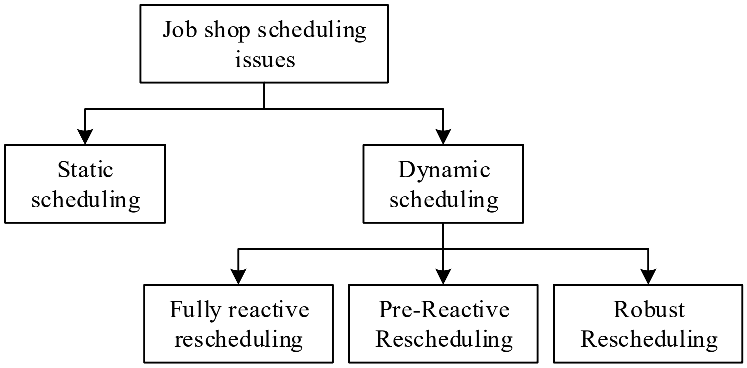

Fig. 1. Structure diagram of flexible job shop rescheduling strategy

2.2.2. Rolling scheduling strategy. When the job shop starts production, all the machines are idle and a certain number of workpieces are scheduled and a scheduling program is generated to get the job shop up and running. As many unexpected events may occur in the job shop, it is necessary to reschedule the job shop. At the beginning of the rescheduling process, the completed workpieces are removed, a certain number of new workpieces are added, and the rescheduling process is performed. This rescheduling process is repeated until all workpieces have been processed, which is the rolling window technique. The rolling scheduling strategy consists of two main elements: the rolling rescheduling mechanism and the workpiece window. Rolling rescheduling includes: cycle rescheduling, event-driven rescheduling, and hybrid rescheduling. The structure of the rolling scheduling strategy is shown in Figure 2.

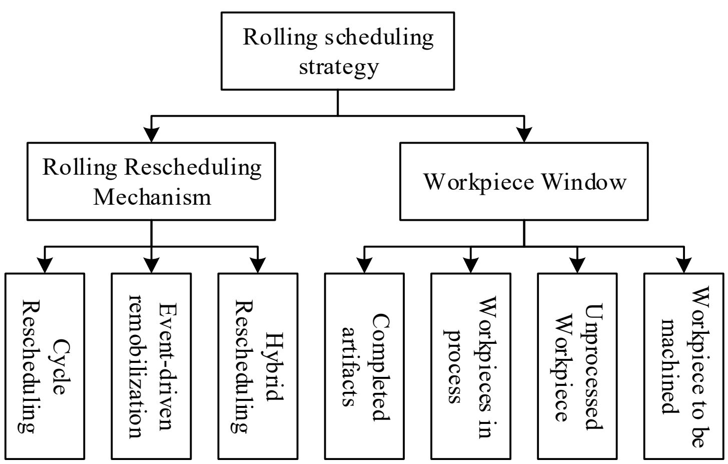

Fig. 2. Structure diagram of rolling scheduling policy

2.3. Design of modified simulated annealing genetic algorithm

2.3.1. Various Algorithms in Modified Simulated Annealing Genetic Algorithms:
1) Particle Swarm Optimization Algorithm. Particle swarm optimization algorithm, also known as particle swarm optimization algorithm, is a stochastic search algorithm gradually developed by scientists through the observation of the foraging behavior of birds. The basic idea of the particle swarm algorithm for optimization calculation is to convert the solution of the problem into tiny particles with a certain initial speed and initial position in three-dimensional space, and make these

tiny particles in the solution space to constantly search for the optimal particles, and in the process of searching for the particle's speed and position will be adjusted continuously.

The equation of motion of the particle in the solution space is:

$$v' = wv + c_1 r_1 \left(b_b - p_p\right) + c_2 r_2 \left(g_b - p_p\right) \tag{10}$$

$$p_p' = p_p + v \tag{11}$$

Where: w is the inertia weight. v is the particle velocity, v' is the velocity at the next position of the particle. c_1, c_2 are constants. r_1, r_2 are random numbers. b_b is the current best position of the individual. p_p is the current position of the individual. g_b is the current position of the particle population. p_p' is the next position of the individual at position p_p [23].

2) Simulated annealing algorithm. Simulated annealing algorithm has been more widely used in shop scheduling and combinatorial optimization problems for its simplicity and flexibility. The mathematical formula of simulated annealing algorithm is:

$$P_{xy} = \begin{cases} e^{\frac{E_y - E_x}{T}} & E_y - E_x \geq 0 \\ 1 & E_y - E_x \leq 0 \end{cases} \tag{12}$$

3) Genetic Algorithm. The use of genetic algorithms to solve combinatorial optimization problems is similar to the optimization problem of finding the maximum value (or minimum value) of a function with a mathematical planning model:

$$\begin{gathered} \max f(X) \\ X \in R \\ R \in U \end{gathered} \tag{13}$$

Where: $\max f(X)$ is the objective function. X is the decision variable. $X \in R$ and $R \in U$ are the constraints. U is the basic space. R is the subset of U.

2.3.2. Design of modified simulated annealing genetic algorithm. Simulated annealing algorithm almost does not have the ability of global spatial search, but its local spatial search ability is stronger, while the genetic algorithm is poor in the local optimization ability, so the combination of simulated annealing algorithm and genetic algorithm can take the strengths and complement the weaknesses. Then the particle swarm optimization algorithm is integrated into the population initialization of the genetic algorithm, which can optimize the population individuals in one step first, making the optimization efficiency of the algorithm higher and the optimization effect better [24]. The flow chart of the modified simulated annealing genetic algorithm is shown in Figure 3. The specific steps are as follows:

1) Setting the fixed parameters related to the algorithm, individual crossover probability P_c, individual variation probability P_m, initial temperature of the simulated annealing algorithm T_0, population size M, maximum number of iterations N, and so on.

2) Obtain the initial population by particle swarm algorithm.

3) Evaluate the adaptability of individuals in the population, and then select the excellent individuals to generate the population, which is carried out by a combination of roulette and maximum retention methods in selecting the excellent individuals.

4) Perform individual crossover operation. Take the crossover probability as an index to carry out individual crossover, compare the adaptation value of the generated offspring individuals with that of the parent individuals, and if the adaptation value of the offspring individuals is greater than that of the parent individuals, then accept the offspring individuals as the current individuals. If the fitness value of the offspring individual is less than or equal to that of the parent individual, it will be judged

according to the acceptance probability p, and if $p > random$, the offspring individual will be accepted as the current individual, otherwise the parent individual will be kept as the current individual.

5) Perform individual mutation operation. The acceptance principle is similar to individual crossover, and the mutation probability P_m is used as the judgment index.

6) Global annealing operation. The global annealing concept means that the individual fitness value in the global range is appropriately stretched operation, to avoid individual particularly excellent individuals to fill the whole population, which affects the search efficiency. When the temperature is high, individuals with similar performance have less difference in fitness value, and when the temperature is low, the fitness value of individuals is expanded, which is convenient to show the advantage of excellent individuals.

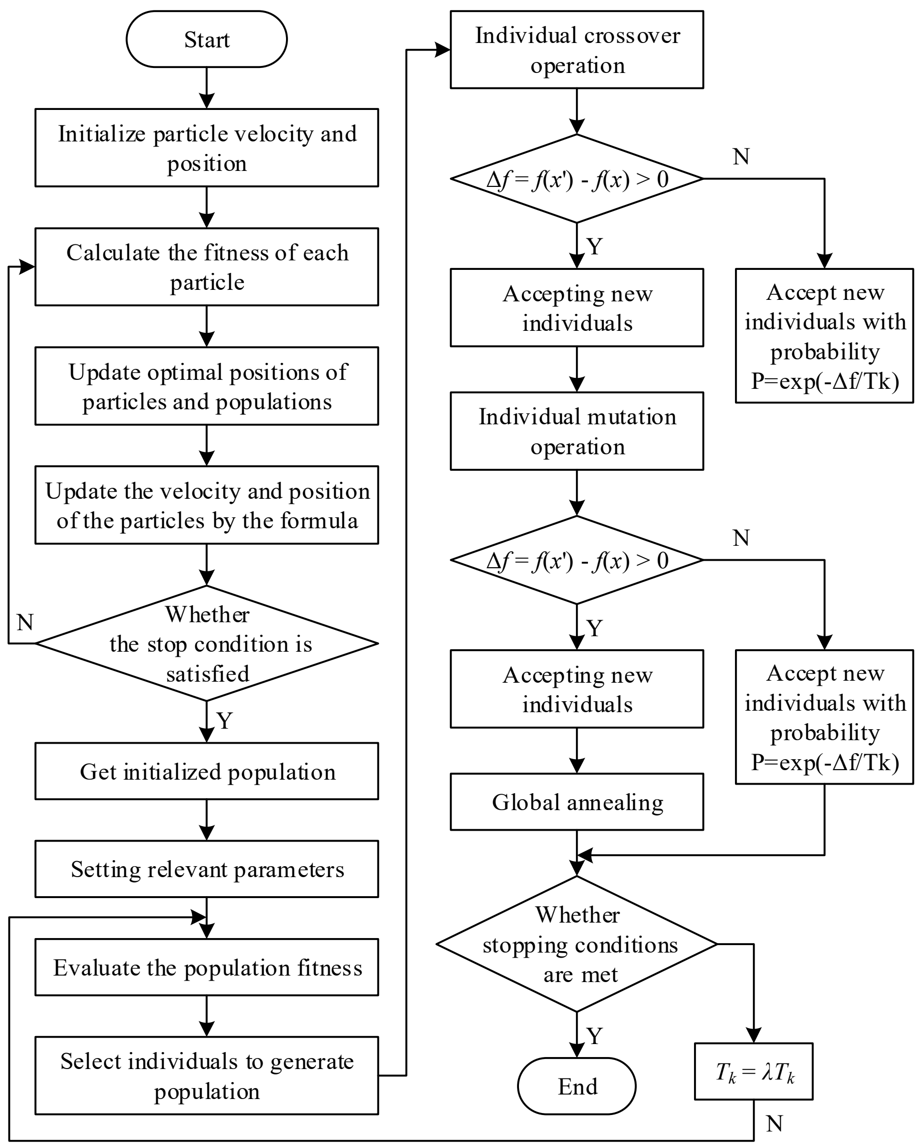

Fig. 3. The basic process of the modified simulated annealing genetic algorithm

Its algorithm is:

$$f_n' = \frac{e^{f_n/T}}{\sum_{i=1}^{M} e^{f_n/T}} \tag{14}$$

$$T = \left(0.99^{g-1}\right)T_0 \tag{15}$$

Where: f_n is the fitness value of the nnd individual, f_n' is the new fitness value after the nth individual iteration. T is the current temperature. M is the population size. g is the number of iterations. T_0 is the initial temperature in the simulated annealing algorithm.

7) Determine whether the stopping condition is satisfied. If the stopping condition is satisfied, then output the optimal solution, if the condition is not satisfied, then update the value of temperature T_k and jump to step 3.

2.4. Scheduling solution based on modified simulated annealing genetic algorithm

2.4.1. Constraints. In the application of FMS for the production machining of machine tool box type parts, the maximum completion time minimization is taken as the optimization objective and its mathematical model is given as:

$$f(x) = \min_{1\le k\le m}\left\{\max_{1\le i\le n}\{C_i\}\right\} \tag{16}$$

Where: k is the machine serial number. m for the number of machines. i for the workpiece serial number. n is the number of workpieces. C_i is the workpiece i completion time.

2.4.2. Chromosome coding. Chromosome coding is the beginning and the key of genetic algorithm, excellent coding can improve the efficiency of the algorithm and avoid falling into local optimal solutions.

2.4.3. Adaptation. Adaptability is an index to evaluate the ability of an individual to adapt to the environment, the larger the value of adaptability, the stronger the ability of the individual to adapt to the environment, and vice versa, the weaker the ability of the individual to adapt to the environment. Therefore, when generating offspring, we should try to make the individual with a large value of adaptability as the parent, and inherit the good genes from the parent to the offspring. Namely:

$$F_i = \frac{1}{f(x)} \tag{17}$$

Where: F_i is the fitness value. $f(x)$ is the part completion time.

2.4.4. Crossover and mutation operations:

1) Crossover. Allelic random crossover method is used in the machine coding layer and combined with simulated annealing algorithm to make trade-off judgments on new individuals. After the crossover operation is completed, the fitness values of the new individuals C_1 and C_2 are calculated, and if the fitness value is greater than that of the old individual (P_1, P_2), the new individual is retained; if the fitness value is less than that of the old individual, the new individual is retained or discarded with probability $P = \exp(-\Delta f / T_k)$.

2) Mutation. The method of randomly assigning optional machines in the machine coding layer using variant bits. In the machine coding layer, n mutation bits are randomly selected (generally the number of mutation bits is not higher than 1/4 of the total number of bits), and the replaceable machine serial number is randomly assigned in the position. After the mutation operation is completed, the fitness value of the new individual C_1 needs to be calculated, and if the fitness value is greater than that of the old individual (P_1), then the new individual is retained, and if the fitness value is less

than that of the old individual, then the probability $P = \exp(-\Delta f / T_k)$ is used to determine whether the new individual is retained or discarded.

3. Experimental tests

3.1. Algorithm performance comparison experiment

First, the FT6-6 shop production scheduling problem is simulated based on Visual Studio C++ 2012 and MATLAB combination programming. The size of the problem is 6 machines, 6 kinds of workpieces, each kind of workpiece contains 6 processes, then the dimension of its operation is 36, the optimal solution is 55, the process hours of the workpieces are the matrix T, and the machining equipment of the workpieces' processes are the matrix M. In order to validate the advantages of this paper's algorithm, two advanced and improved differential evolution algorithms, SaDE and CoDE, are selected for comparison. In order to make a fair comparison, the parameter settings of SaDE and CoDE algorithms are the same as those of their original literature, and each algorithm is simulated independently for 10 times, and the termination condition is 20000 function evaluations. With the number of function evaluations as the horizontal axis and the maximum completion time (objective function value) as the vertical axis, the average convergence curve of each algorithm is plotted for 10 simulations, and the convergence diagram of the simulation of the FT6-6 problem is shown in Figure 4. From the figure, it can be seen that the three algorithms of this paper's algorithm, SaDE and Co DE can reach the optimal value 54, but the convergence speed of this paper's algorithm is better than that of SaDE and CoDE.

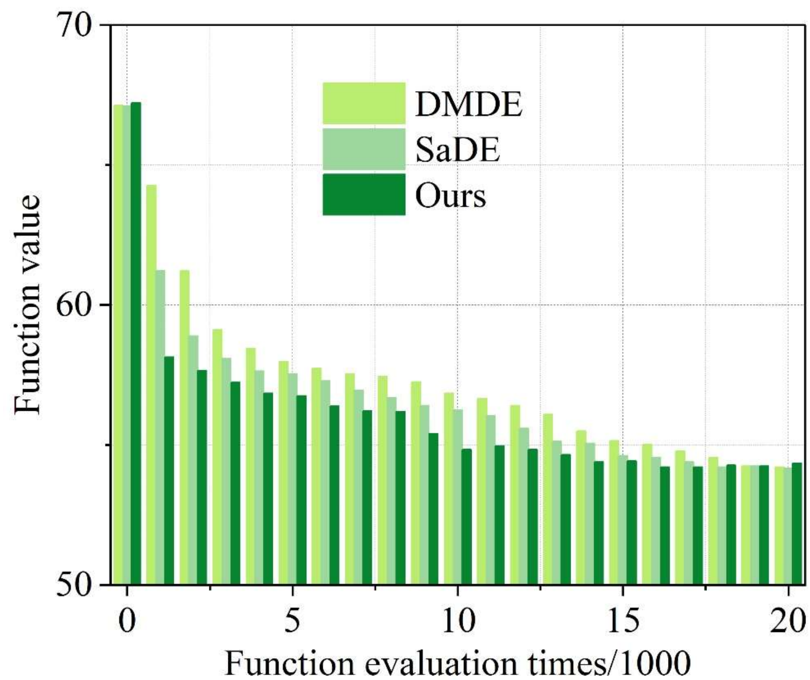

Fig. 4. Ft6-6 problem simulation convergence diagram

The optimal solution is decoded and the program is based on the machining parameters of the optimal solution process generated by the constraints.The optimal scheduling scheme for the FT6-6 problem is shown in Table 1. Through the optimal scheduling scheme in the table, it can be seen that the algorithm can be generated according to the code of the solution through the program to calculate the workpiece process corresponding to the machining machine number, the start of the process processing time and the end of the process time. The optimal scheduling program table query shows that the maximum completion time of the workpiece process of the machine number 1 and 2 are 51 units of time, and the maximum completion time of the machine number 6 is 55 units of time. Therefore, through the analysis, it can be seen that the final maximum completion time of the program is 58 units of time, i.e., the final completion time of all the workpieces is 55 units of time.

Table 1. The optimal scheduling plan for FT6-6

Serial Number	Machine Number	Process Number	Begin	Finish	Serial Number	Machine Number	Process Number	Begin	Finish
1	3	22	0	10	19	0	36	23	35
2	1	62	8	9	20	2	66	29	39
3	4	30	1	4	21	4	46	30	31
4	3	10	4	6	22	6	55	27	30
5	3	23	8	13	23	1	25	41	51
6	3	50	13	21	24	3	33	28	31
7	1	12	8	9	25	5	14	30	43
8	4	30	4	7	26	7	57	36	43
9	2	41	8	17	27	2	52	50	51
10	3	12	18	22	28	5	14	41	46
11	2	53	25	25	29	4	44	29	36
12	6	34	11	17	30	6	34	34	48
13	2	41	16	21	31	4	64	44	51
14	4	23	14	23	32	7	45	47	51
15	4	61	10	13	33	2	67	52	51
16	4	43	21	26	34	5	16	46	58
17	5	61	17	27	35	3	26	53	54
18	7	24	28	36	36	6	54	55	55

The Gantt chart of the optimal solution is shown in Figure 5.

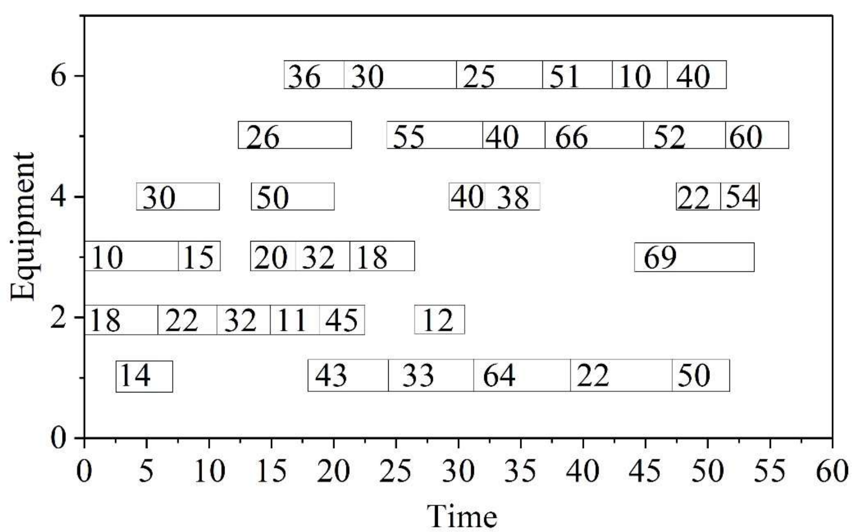

Fig. 5. The optimal gantt diagram

In order to verify the algorithm's ability to solve complex scheduling problems, the FT10-10 workshop production scheduling test problem is used to further verify the algorithm. The size of the problem is 10 machines, 10 types of workpieces, each type of workpieces contains 10 processes, the dimension of the operation is 100, the optimal solution is 1017, the process hours of the workpieces are matrix T, and the machining equipment of the workpieces' processes are matrix M. The proposed algorithm is used to solve the test problem, and the effectiveness of the algorithm is finally further verified. The optimal solution is decoded and the program is based on the machining parameters of the optimally solved process generated by the constraints.The optimal scheduling scheme for the FT10-10 problem is shown in Table 2. The optimal scheduling scheme in the table shows that the maximum completion time of the workpiece process of the equipment with machine number 1 is 615 units of time, and the analysis shows that the maximum completion time obtained by the program is 738 units of time, i.e., the final completion time of all the workpieces is 738 units of time.

Table 2. Optimal scheduling

Serial Number	Machine Number	Process Number	Begin	Finish	Serial Number	Machine Number	Process Number	Begin	Finish
1	6	77	2	35	26	7	81	468	492
2	2	50	33	46	27	2	51	421	443
3	1	98	1	77	28	2	10	445	523
4	2	95	2	82	29	9	87	490	513
5	1	83	74	155	30	9	79	495	526
6	3	34	90	168	31	6	68	425	517
7	3	60	48	132	32	3	10	528	542
8	1	64	170	171	33	1	34	414	502
9	2	81	173	217	34	6	55	493	559
10	2	16	159	207	35	4	13	535	570
11	3	92	213	281	36	11	91	528	539
12	4	41	167	259	37	8	44	493	575
13	1	74	279	328	38	10	91	536	591
14	-1	48	205	213	39	10	22	591	604
15	8	82	216	290	40	1	34	576	615
16	2	102	207	226	41	9	86	582	629
17	6	82	286	324	42	3	24	612	677
18	3	100	262	317	43	11	75	530	622
19	3	93	289	355	44	9	64	613	663
20	4	23	326	412	45	7	76	619	651
21	6	68	286	339	46	5	13	571	622
22	0	41	263	328	47	2	52	684	704
23	7	93	361	411	48	10	68	662	738
24	9	108	316	334	49	8	98	536	578
25	1	73	332	369	50	0	30	675	705

The Gantt chart corresponding to the optimal solution is shown in Figure 6.

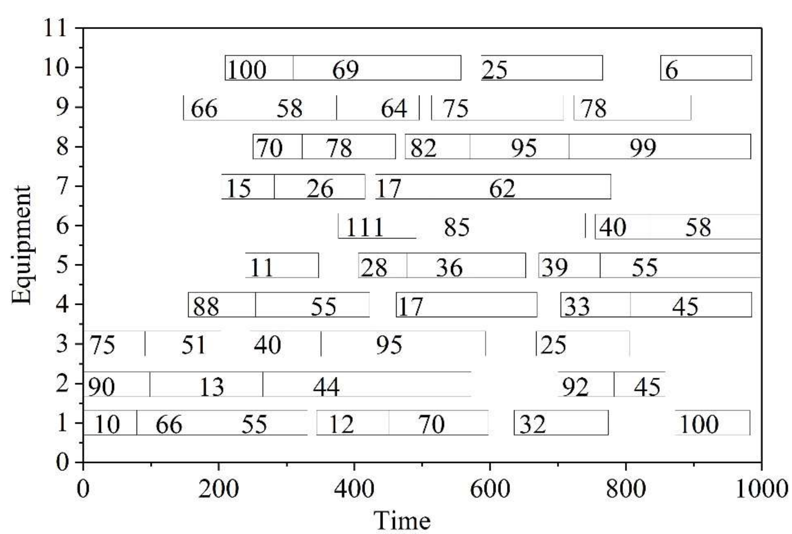

Fig. 6. The optimal solution is the gantt diagram

3.2. Analysis of energy consumption

Energy consumption can be used to reflect the workload of the equipment, and energy consumption analysis helps to identify the bottleneck process of the production line. Therefore, this section adopts the minimum optimized energy consumption as an example to further analyze the energy consumption of each station and the energy consumption of each manipulator in the FMS model. The comparison results of the processing, adjustment and idling energy consumption of each station are shown in Table 3, from which it can be seen that the processing energy consumption of each station occupies a large proportion of the energy consumption, and the adjustment energy consumption and idling energy consumption are very small. For example, the adjusted energy consumption of station 1 in the initial solution is 0.

Table 3. Energy consumption comparison of each station machine table

		Position 1	Position 2	Position 3	Position 4	Position 5
	Initial solution					
Energy consumption/ kwh	Process	6.8131	8.1368	6.9254	17.7913	5.1283
	Adjust	0	0.0028	0.01496	0.0286	0
	Idling	0.4264	0.9849	1.0641	2.6028	0.6637
	Optimization solution					
	Process	4.4455	9.0407	5.5411	16.9116	4.0215
	Adjust	0	0.017	0.0173	0.0302	0
	Idling	0.2324	1.0145	1.1227	2.2996	1.00102

The comparison of the total energy consumption results of each station is shown in Figure 7. From the figure, it can be seen that station 4 has higher energy consumption compared with other stations, and it is known that the process of station 4 is milling the top surface, which has certain precision requirements and large machining allowance, and it is the station with the largest load in the production line. At present, the effect of scheduling and layout optimization is limited, and further improvements in technology and equipment are needed to effectively reduce the energy consumption of this station.

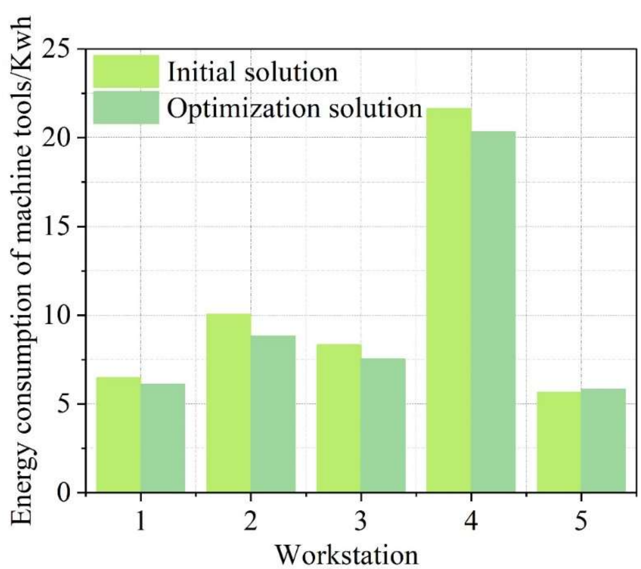

Fig. 7. The total energy consumption results were compared

The load and no-load energy consumption of each manipulator is shown in Table 4, from which it can be seen that the no-load energy consumption of manipulator H0 is relatively high and occupies a large proportion in the total energy consumption of the manipulator.

Table 4. The load and empty energy of each machine

		H0	H1	H2	H3	H4	H5
Energy consumption/ kwh	Initial solution						
	load	0.8311	0.8974	0.898	0.9745	0.9397	0.944
	No load	4.2575	0.1997	0.1837	0.2223	0.1453	0.1523
	Optimization solution						
	load	0.8125	0.9521	0.8294	1.0803	1.029	0.86261
	No load	3.8261	0.1823	0.1626	0.2545	0.2412	0.1386

The comparison of the results of the energy consumption of each manipulator is shown in Figure 8. From the comparison results of the figure, it can be seen that after optimization, the energy consumption of manipulator H0 appears to be reduced, and the energy consumption of manipulators H4 and H5 appears to be increased, and it can be considered that after optimization, the total energy consumption of the manipulators at each station has gained a certain balance. However, the optimization effect on the balance of energy consumption of the manipulator through the scheduling and layout is limited, the manipulator H0 needs to move back and forth between multiple frames in the loading process, so it consumes a lot of no-load time, which is directly related to the unreasonable loading method, and it needs to be optimized through the loading mechanism in order to further reduce the energy consumption of the manipulator.

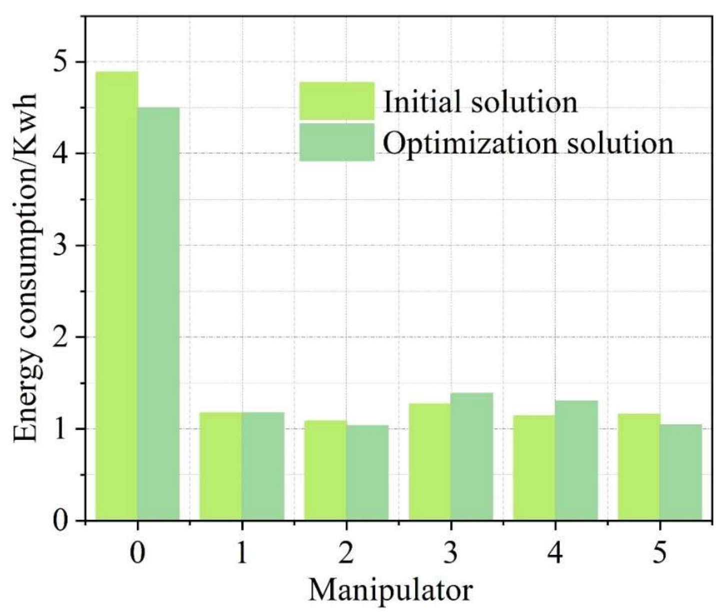

Fig. 8. Comparison of energy consumption results of each machine

4. Overall design of FMS virtual simulation system based on mixed reality

In this section, a virtual simulation implementation based on mixed reality is investigated for the design of the FMS virtual simulation system and its application to the FMS shop floor planning process, which solves the problem of external tool library tool limitation in the shop floor planning process, and achieves the purpose of improving the efficiency.

4.1. Overall system program design

Based on the functional requirements, the overall framework of the simulation system is designed, and the overall framework of the virtual simulation system is shown in Figure 9. The simulation system adopts the framework form of "dual-mode, multi-function". The system is divided into offline mode and collaborative mode, the discrete mode mainly contains roaming function, overview function, interactive function and other functional modules, the collaborative mode mainly includes collaborative interaction, manufacturing simulation, perspective display, program evaluation and other functional modules. Different function modules realize different virtual simulation effects. The offline mode runs in the standalone HoloLens headset device without network support. Collaborative mode supports running in HoloLens devices, PCs, cell phones and other mobile devices, each device needs to be connected to the same LAN, and each device communicates with each other based on the LAN. The system should develop different applications for different platforms such as Android and Windows 10.

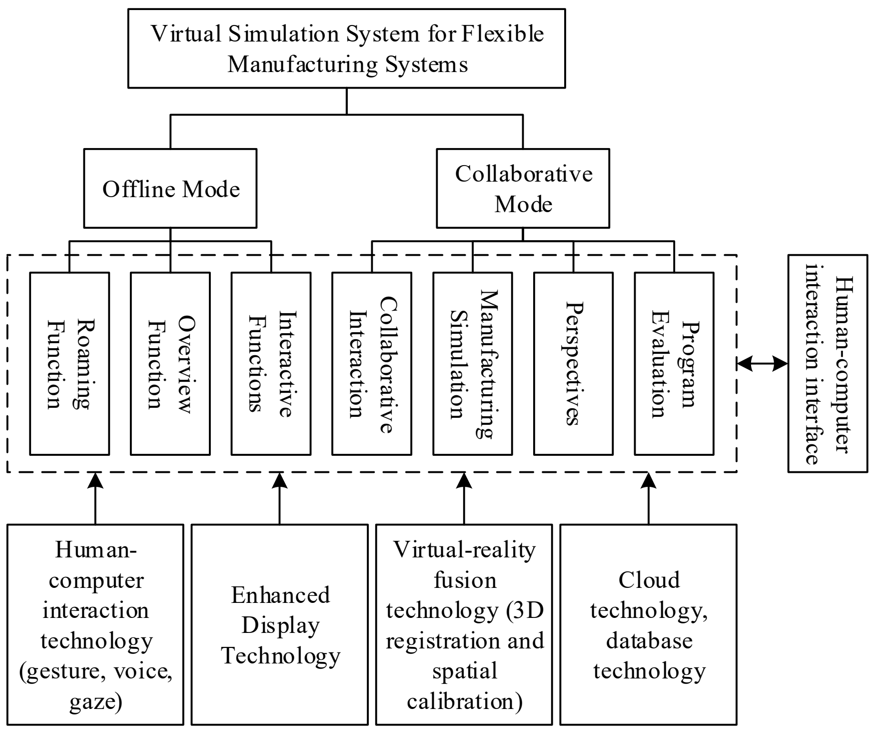

Fig. 9. The overall framework of the virtual simulation system

4.2. Development steps

The development process is broadly divided into three segments: modeling, rendering, and virtual interaction development. Each link is carried out in different software, and the file format compatibility problem should be fully considered.

According to the equipment configuration, material transportation system configuration, equipment layout and other information obtained in the design stage and the relevant equipment size data, the 3D model of FMS is constructed in Solid Edge, a 3D CAD/CAM software, 1:1, and the STP file, a common format of the model, is exported. In 3ds Max software import STP file, simplify the model, texture, material settings and other rendering, export FBX file containing the model, material, camera and other information. In the virtual reality engine software Unity 3d import FBX files, loaded into the scene to build the FMS virtual scene, based on the application of the MRTK open source toolkit, use C# language to write scripts, develop the corresponding function modules of the virtual scene and the human-computer interface (UI), and complete the HoloLens client UWP application software, PC client application software, Android client application software development. The scripting process and HoloLens application deployment process use Visual Studio 2019.

5. Conclusion

The article firstly establishes the mathematical model and dynamic scheduling strategy of the FJSP problem, proposes the hybrid optimization algorithm which improves on the simulated annealing algorithm, and comprehensively applies the hybrid algorithm to solve the strategy research of the problem of tool limitation of external tool libraries. The experimental results are as follows:

Simulation experiments with the workshop production scheduling problem, this paper's algorithm, SaDE and Co DE three algorithms can achieve the optimal value of 54, but in the convergence speed, this paper's algorithm convergence speed is better than the other two algorithms. The optimal scheduling scheme for the FT10-10 problem has a maximum completion time of 738 unit time. The comprehensive results indicate that the algorithms in this paper are effective and feasible and can be utilized in practical production.

By analyzing the energy consumption of each station in the FMS model, it can be obtained that the energy consumption of each station is very small in the adjusted energy consumption of machining energy and idling energy consumption, in which the adjusted energy consumption of station 1 in the initial solution is 0.

Finally, mixed reality technology is introduced to construct a mixed reality-based FMS virtual simulation system, with a view to solving the problem of external tool library tool limitation in the process of flexible shop floor planning.

References

[1] Yadav, A., & Jayswal, S. C. (2018). Modelling of flexible manufacturing system: a review. International Journal of Production Research, 56(7), 2464-2487.

[2] Florescu, A., & Barabas, S. A. (2020). Modeling and simulation of a flexible manufacturing system—A basic component of industry 4.0. Applied sciences, 10(22), 8300

[3] Mahmood, K., Karaulova, T., Otto, T., & Shevtshenko, E. (2017). Performance analysis of a flexible manufacturing system (FMS). Procedia Cirp, 63, 424-429.

[4] Erdil, A. (2021). Manufacturing-Production Systems and Their Importance: Evaluation of Flexible Manufacturing Systems (FMS). Avrupa Bilim ve Teknoloji Dergisi, (29), 331-342.

[5] Daniyan, I., Mpofu, K., Ramatsetse, B., Zeferino, E., Monzambe, G., & Sekano, E. (2021). Design and simulation of a flexible manufacturing system for manufacturing operations of railcar subassemblies. Procedia Manufacturing, 54, 112-117.

[6] Ojstersek, R., Acko, B., & Buchmeister, B. (2020). Simulation study of a flexible manufacturing system regarding sustainability. International journal of simulation modelling, 19(1), 65-76.

[7] Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies. Internet of Things and Cyber-Physical Systems, 2, 49-62.

[8] Fan, Y., Yang, J., Chen, J., Hu, P., Wang, X., Xu, J., & Zhou, B. (2021). A digital-twin visualized architecture for Flexible Manufacturing System. Journal of Manufacturing Systems, 60, 176-201.

[9] El-Khalil, R., & Darwish, Z. (2019). Flexible manufacturing systems performance in US automotive manufacturing plants: a case study. Production planning & control, 30(1), 48-59

[10] Gania, I. P., Stachowiak, A., & Oleśków-Szłapka, J. (2017). Flexible manufacturing systems: Industry 4.0

solution. idea, 10(1), 7-11.

[11] Kaushal, A., Vardhan, A., & Rajput, R. S. (2016). Flexible manufacturing system a modern approach to manufacturing technology. International Refereed Journal of Engineering and Science, 5(4), 16-23.

[12] Huang, Y., Fan, X., Chen, S. C., & Zhao, N. (2019). Emerging technologies of flexible pressure sensors: materials, modeling, devices, and manufacturing. Advanced functional materials, 29(12), 1808509.

[13] Adzande, A. O. (2021). Methods of improving maintenance of workshop and equipment for effective service delivery in fce (t) asaba. Journal of practicing, 5(1), 117.

[14] Ma, J., Chen, H., Zhang, Y., Guo, H., Ren, Y., Mo, R., & Liu, L. (2020). A digital twin-driven production management system for production workshop. The International Journal of Advanced Manufacturing Technology, 110, 1385-1397.

[15] Zhang, Z., & You, F. X. (2018, May). Informatization Workshop Personnel Management System Based on MES. In 4th Annual International Conference on Management, Economics and Social Development (ICMESD 2018) (pp. 670-675). Atlantis Press.

[16] Andryashina, N. S., Romanovskaya, E. V., Kuznetsov, V. P., Kuznetsova, S. N., & Kozlova, E. P. (2020). Development of the Production System of the Enterprise on the Example of Workshop of the PJSC "GAZ". Growth Poles of the Global Economy: Emergence, Changes and Future Perspectives, 747-758.

[17] Durga Prasad, G., Ravi Teja, K. M. V., Nageswara Rao, M., Phanindra Kshatra, D., & Rakesh, K. (2022). Experimental investigation on FMS environment with operational completion time. In Technology Innovation in Mechanical Engineering: Select Proceedings of TIME 2021 (pp. 951-960). Singapore: Springer Nature Singapore.

[18] Nageswara Rao, M., Prakash Babu, K., Dama, K. K., Malyala, S. K., & Rajak, U. (2022). Implementation of Jatinder ND Gupta algorithm for FMS scheduling problems. In Technology Innovation in Mechanical Engineering: Select Proceedings of TIME 2021 (pp. 837-845). Singapore: Springer Nature Singapore.

[19] Chidiebube, I. N., Chukwuemeka, I., Perpetual, E. C., Chijioke, K., & Mba, W. (2024). Analysis of workshop safety and productivity improvement in an engineering workshop. Engineering Science and Technology Journal, 5(6), 1930-1934.

[20] Nejad, M. Z., Mojarad, M., & Arfaeinia, H. (2020). Solving the Workshop Production Planning Problem Using the Meta-Heuristic Algorithm. Int. J. Sci. Res. in Network Security and Communication Vol, 8(6).

[21] Liao Wen-jie & Fujimura Shigeru. (2023). The Optimization of Multi-objective FJSP Based on the Hybrid Algorithm. Journal of Physics: Conference Series(1).

[22] Zarrouk Rim,Daoud Wided Ben,Mahfoudhi Sami & Jemai Abderrazak. (2022). Embedded PSO for Solving FJSP on Embedded Environment (Industry 4.0 Era). Applied Sciences(6),2829-2829.

[23] Hegang Ji,Jian Zhang,Shi Hua,Renwei Liu & Sanxia Shi. (2025). Study on stress prediction model of EH36 steel in polar environments: Optimization of basis functions using adaptive genetic algorithm and simulated annealing. Applied Ocean Research104402-104402.

[24] Birhan Isik,Mehmet Sah Gultekin,Ismail Fidan & Martin Byung Guk Jun. (2024). Optimum Cutting Parameters for Carbon-Fiber-Reinforced Polymer Composites: A Synergistic Approach with Simulated Annealing and Genetic Algorithms in Drilling Processes. Processes(7),1477-1477.