Research on balance optimization of medical rubber protective cap production line based on improved GA

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Abstract: In view of the low production line balance rate and the low production efficiency caused by the large load gap of each station in the production process of small and medium-sized medical device companies, this paper takes Company H as the research object, first uses traditional industrial engineering techniques to improve it, establishes the bottleneck process through the Flexsim model, and then builds a dual population genetic algorithm with the maximum production balance rate The algorithm is optimized with Matlab. The results show that when the number of workstations m=5, the balance rate of the production line is the largest and the production smoothness index is the smallest. The balance rate of the production line is increased from the initial 55.13% to 91.24%, reducing the number of workstations and reducing the cost. This method improves the production efficiency of H Company and increases the proportion of workshop workstation load. It is an effective improvement scheme.

Key words: line balance; Flexsim simulation; Station optimization; Double population genetic algorithm; Matlab

1. Introduction

With the development of society, the demand for the medical aesthetics industry has been rising year by year, and the medical device industry has been developed accordingly. Today, the concentration of the medical device industry is increasing, forming a competitive situation in which the strongest is getting stronger [2]. However, many small and medium-sized medical device manufacturing companies still have problems in production, such as poor 5S management, uneven work tasks, and a high inventory of work in progress. In the face of gradually increasing demand, improving efficiency and eliminating waste have become top priority in the production process.

Early production line balance improvement mainly used traditional IE methods to find bottleneck processes [7] analyzed the bottleneck processes, and optimized the bottleneck processes through 5S management, ECRS principles, other IE methods to achieve the optimization of the entire production line. Xiaojijun et al. analyzed the traditional assembly line balance problems and bottleneck processes and established a balance hybrid model for small batch production lines [11]. Wang Shijie conducted an operational study on the production line to improve the production balance rate by adjusting the production beat through the method of standard time measurement [10]. Peijie Zhao and Haojian Shen improve the production line based

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on the lean production model to improve the balance rate of the production line by 7.5% for the problem of long manufacturing cycle time and low efficiency [13]. Jie Yu improved employee efficiency and incentives by standardizing workshop 6S management and implementing visualization management to improve the production balance rate [12].

With the advancement of computer technology, more and more heuristic algorithms and simulation software are gradually used in the improvement methods of production lines. Tisa, Li-Hui proposed that the balancing problem of an assembly line is a multi-objective optimization problem [9]. Hujunyi et al. added a heuristic task set filtering mechanism to the ant colony algorithm and proved through a case study that the algorithm has significant effects on the optimization of production lines [3]. Huang Pengpeng and Deng Zengyu improved the production line for problems such as unbalanced operational load and simulated the optimization results by Witness, which showed that the production line balance rate increased from the initial 58% to 81% [4]. Dong Jin established a 0-1 integer planning model based on traditional IE and solved it with LINGO software, and then simulated the improved results by Flexsim. The results showed that the production balance rate of the production line was greatly improved and the number of idle stations above 50% was reduced from 9 to 0[1]. Jiang Daiyu and Zhou Yuanling used simulation modeling with Wintess software to identify the problems in the production process and optimized the line by genetic algorithm to increase the production line output by 54% [5]. Jie-Yun Situ built an improved genetic algorithm with the minimum beat and load equalization at each station as the objective function to solve the second type of production line balancing problem, and the results showed that the algorithm has a good effect on solving the second type of production line balancing problem [8].

In this paper, the production line for pre-can seal syringes is selected as the research object, and the production problems of low production efficiency, uneven production load distribution, and low production balance rate faced by the small and medium-sized manufacturing enterprises are addressed, and the bottleneck processes are identified through simulation by Flexsim software. A dual objective model with maximum production balance rate P and minimum production smoothing index SI as the objective function is established for the target enterprise. In response to the problem of poor global search capability of the traditional genetic algorithm [6], this paper builds a two-population genetic algorithm model to optimize the entire production line stations and uses Matlab software to solve the model to complete the assignment of global jobs, optimize the bottleneck process for the enterprise, reduce the work-in-process waiting time and improve production efficiency.

2. Example analysis and production simulation

Company H was established in 2017, is a medical device manufacturing limited company with medical equipment, plastic products and other packaging products as the main products, after the foreign investment in 2021 to a Sino-foreign joint venture, the number of customers increased, the demand increased, but due to the workshop perennial management chaos, unskilled staff operation, old equipment and other problems lead to the company facing low production efficiency, uneven production ,and other problems. Therefore, the company urgently needs to transform and upgrade to the direction of high efficiency and low waste.

2.1. Data measurement

The production plant of brombutyl rubber caps for pre-can seal syringes in Company H is mainly divided into five major areas, namely, the film storage area, vulcanization area, edge removal area, cleaning area, and inner packaging area, and the material handling in each area is done by employees. In this paper, each production process is firstly divided into operational elements by IE method, and operational measurements are made by the stopwatch timing method. To avoid the influence of various factors on the productivity of employees, this paper takes multiple measurements for different employees to find the average value, and adopts the triple standard deviation method to eliminate the outliers.

The production line of bromobutyl rubber caps for pre-cannulated syringes of company H is selected as the object of study. The production process of this product consists of 7 processes, namely, pre-curing processing, curing, post-curing processing, light inspection, edge removal, cleaning, and inner wrapping, which are subdivided into 27 operation units according to the operation content, and the total operation time of production is 565.7s (excluding inter-process transportation time and waiting time for the time being). The production process and the time spent in each process are shown in Table 1, which shows the number of workstations in the production line and the work units contained in each workstation, with the duration of each work unit on the far right. Figure 1 shows the sequence of operations, and the total process time is developed through the sequence diagram.

Tab.1 Operation Time of Each Process

Workstations	Process name	Assignment unit	Assignment name	Time(s)
1	Pre-vulcanization processing	1	Remove the barrier film	10.7
		2	Separation of films	7.5
		3	Weighing film	23.4
		4	Cut and fill weight	10
		5	Put in the area to be vulcanized	4
2	Vulcanization	6	Silicone oil spraying	10.2
		7	Spray mold release agent	10.8
		8	Put in the film	7.8
		9	Vulcanization of the mold	38
3	Uncoating after vulcanization	10	Air gun film removal	61.9
		11	Cutting film	68.4
4	Light Inspection	12	Take film	12.6
		13	Light detection	54.5
		14	Cut out the bad	66.3
		15	Put in the finish area	13.2
5	Except for the sides	16	Immersion film	23.2
		17	Film into the edge-removal machine	19.2
		18	Compacting plate compaction	11.2
		19	Press to remove the edge	12.8

6	Cleaning	20	Put in the rubber plug	3.6
		21	Set the cleaning machine	38
		22	Start cleaning	4.2
		23	Open the valve	3.2
		24	Open the discharge port	2.7
		25	Snap Chute	1.2
		26	Remove the rubber plug	1.7
7	Inner Package	27	Bagging and sealing	45.4

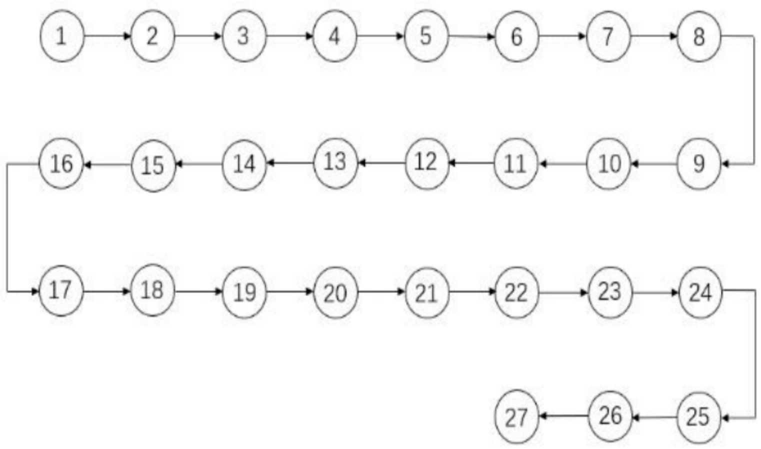

Fig. 1 Process Sequence Diagram

2.2. Modeling

By observing factors such as production methods and employment status in the workshop of Company H, the corresponding simulation model was built using Flexsim software to address the problem of its low productivity, combined with the actual process and the actual layout of the workshop.

Add the corresponding entities in the Flexsim model, this model mainly uses the generator, processor staging area, and absorber 4 kinds of resource entities. The processor represents the processing process of each workstation, and different processors in this model represent different workstation processing processes, and the processing time of the processor is the processing time of the workstation. The total amount of production and the load of each workstation during the simulation time can be read. Finally, each entity is connected according to the production process.

Run the simulation model, set the run time to 2592000s (30 days), automatically end the run after the simulation, run the simulation, and the simulation results are shown in Figure 2. During the production process, the operation load share of each workstation is shown in Figure 3.

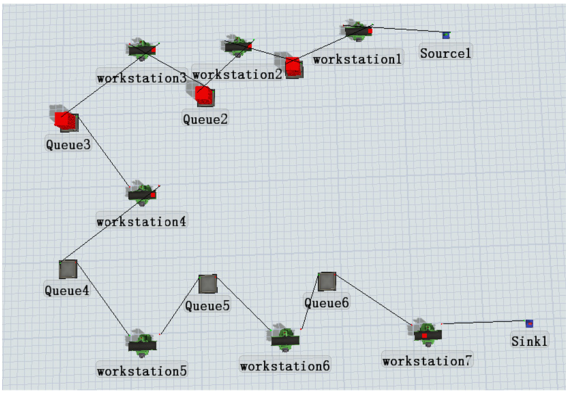

Fig. 2 Simulation Model of Production Line

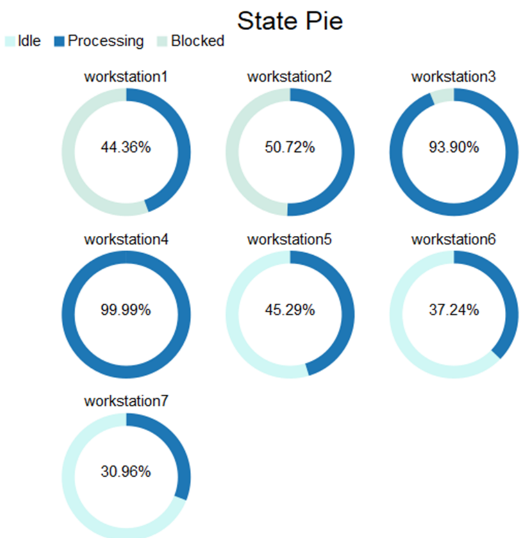

Fig. 3 Proportion of Workstation Load

The bottleneck process of the production line is the light inspection process, and the bottleneck process beat time before improvement is 576.6s. In this paper, the production line is analyzed from two aspects: production line balance rate and production smoothing index. The larger the production line balance rate, the more balanced the workload distribution of each workstation, and the smaller the production smoothing index, the smoother the production line, the formulae for the production balance rate P and production smoothing index SI are given below.

The expression for the production line equilibrium rate P is

$$P = \frac{\sum_{i=1}^{m} st_i}{m \times CT} \times 100\% \tag{1}$$

In equation (1), the$st_i$is the operating time of each workstation process.m is the total number of workstations.CT is the production beat.

The production smoothing index SI whose expression is

$$SI = \sqrt{\sum_{i=1}^{m}(ct - T(si))^2 / m} \tag{2}$$

According to the formula, the line balance rate P of the line before improvement can be found to be 55.13%, and the line smoothing index SI before improvement is 76.

3. Traditional IE to improve the production line

The traditional IE approach to production line optimization is to reduce waste, optimize processes, and reduce the workload of employees by establishing bottleneck processes and making improvements to them to improve productivity and reduce costs. By running the production line simulation model of Company H, the bottleneck process of the production line has been identified, but the optimization of the bottleneck process will generate new bottleneck processes, so this paper adopts the principle of optimizing the bottleneck process mainly and optimizing multiple processes together to improve the production efficiency of the production line.

3.1. Bottleneck process analysis and improvement

The bottleneck process is subject to a variety of factors and is analyzed in terms of employees, equipment, materials, methods, and the environment. The bottleneck process is optimized by adjusting the work environment for employees, improving their operational proficiency, reducing motion waste, and simplifying the production process, and is ready for optimization of other processes.

First of all, for the bottleneck process light inspection staff action analysis, found that employees have more right-handed work, left-hand idle for a long-time one-handed operation state, and longer operation time, indicating that staff action waste is more serious, will lead to long time operation situation staff right-hand fatigue, the low efficiency of the state, so need to improve the order of operation and action specification, the use of tools to replace the staff hand. Therefore, it is necessary to improve the work order and action specification, and use tools to replace employees' hands, so that the workload of both hands can be reduced and evenly distributed, thus the smoothness of the production line operation can be improved, and the efficiency of the production line can be effectively improved. Figure 4 shows the analysis of the two-hand work of the light inspection process before the improvement, because of the high-quality requirements of medical packaging, therefore, through repeated observation and consultation with relevant professionals, this paper adopts the repetitive inspection three times as the operation standard of the staff light inspection process.

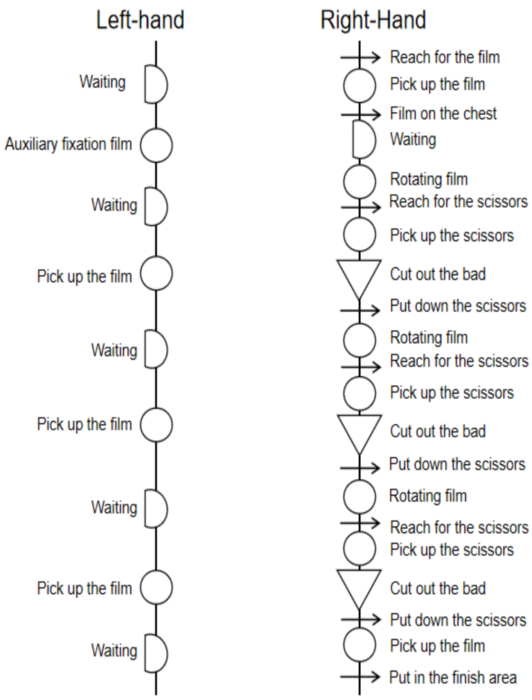

Fig.4 Analysis Chart of "Light Inspection" with Two-Hands before Improvement

Based on the traditional industrial engineering principles of action economy and combined with the ECRS principles for analysis, the following improvements are proposed for light detection employee operations.

(1) Reduce the number of times you take scissors, use a safer and lighter pen to mark, and then use scissors to cut off the defective products at once, thus improving the safety and smoothness of the operation.

(2) Reasonable arrangement of material placement, the left hand will focus on the transfer or auxiliary operation of the action, the right-hand dedicated to the technical operation of the action, to reduce the idle time of the left-hand, reduce the right-hand work, so that the work of both hands more balanced distribution.

(3) Improve the working light conditions, as the light inspection process requires employees to use their eyes for a long time, easily causing eye fatigue, which leads to low productivity, and may also cause employees to lose their eyesight and other diseases for a long time. Therefore, the strong light irradiation concentrated in one point will be changed to soft light surrounded by the surrounding type to reduce the eye fatigue of employees.

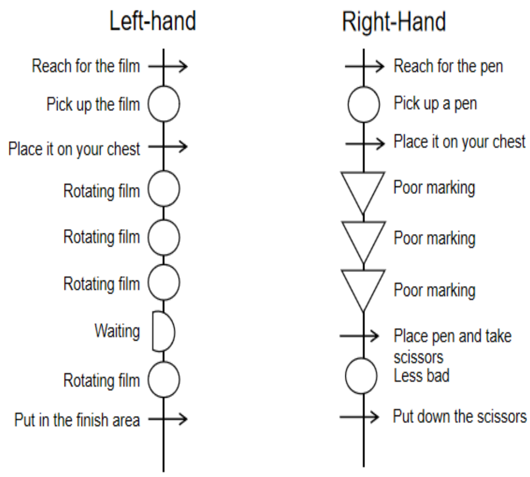

Fig.5 Analysis Chart of "Light Inspection" Two-handed Operation after Improvement

After the implementation of the improvement program, we obtained a schematic diagram of the two-handed action analysis of the light inspection process after improvement, as shown in Figure 5. The improvement of the light inspection process has balanced the workload of the left and right-hands of the employees, significantly reduced the waiting time, and to a certain extent alleviated the fatigue of the employees due to long time one-handed operations, and reduced the eye fatigue caused by the employees' long-time use of light, and improved the operation efficiency. The operating time of the light inspection process was reduced from 146.6 seconds to 114.8 seconds.

3.2. Other process improvements

Other processes, such as the vulcanization process, which also takes up a lot of work time, are optimized by applying the ECRS principle to remove some unnecessary processes, simplify the work content, and analyze the employees' actions according to the action economy principle, and after improvement by traditional IE methods, the work time of each process is shown in Table 2.

Table 2 Operation time of each process after improvement of traditional IE

Work sequence	Process name	Assignment Unit	Assignment Name	Time(s)
1	Pre-vulcanization processing	1	Remove the barrier film	10.7
		2	Separation of films	7.5
		3	Weighing film	28.4
		4	Put in the area to be vulcanized	4
2	Vulcanization	5	Silicone oil spraying	10.2
		6	Spray mold release agent	9.8
		7	Put in the film	7.8
		8	Vulcanization of the mold	38

3	Uncoating after vulcanization	9	Air gun film removal	41.9
		10	Cutting film	56.3
4	Light Inspection	11	Take film	10.8
		12	Light detection	64.5
		13	Cut out the bad	26.3
		14	Put in the finish area	13.2
5	Except for the sides	15	Immersion film	23.2
		16	Film into the edge-removal machine	16.2
		17	Compacting plate	10.7
		18	Press to remove the edge	12.8
6	Cleaning	19	Put in the rubber plug	3.6
		20	Set the cleaning machine	38
		21	Start cleaning	4.2
		22	Open the valve	3.2
		23	Open the discharge port	2.7
		24	Snap Chute	1.2
		25	Remove the rubber plug	1.7
7	Inner Package	26	Bagging and sealing	45.4

After the improvement of traditional IE practices, the comparison between Table 2 and Table 1 shows that the operation time of several processes has been shortened, the total product production time has been shortened from 565.7s to 497.3s, the production line balance rate has been increased to 61.88%, and the production line smoothing index has been reduced to 50.

4. Model building and solving based on improved genetic algorithm

After improving the production line with traditional IE techniques, the balance rate of the production line has improved, but it is still below 80% and there are still problems such as unbalanced distribution of workload. To address these problems, a genetic algorithm can be used to rearrange the processes and to satisfy constraints such as the number of workstations, the production schedule, and the priority of each process. In this paper, a two-population genetic algorithm is developed to optimize the workstation allocation of the production line to balance the load distribution among workstations to reduce production cost and improve production efficiency. Compared with the traditional genetic algorithm, the two-population genetic algorithm adds subpopulation 2 to the traditional genetic algorithm, and subpopulations 1 and 2 are exchanged between certain nodes to expand the search range, which improves the disadvantages of the traditional genetic algorithm of premature convergence and falling into local optimum. During the execution of the algorithm, subpopulation 1 is given a larger crossover operator and variation operator to ensure a larger search range, and subpopulation 2 is given a smaller crossover and variation operator to search for individuals that can satisfy the conditions to the greatest extent.

4.1. Establishing a mathematical model for optimal ranking

In this paper, the objective of optimizing the production line is achieved by increasing the production balance rate and reducing the production line smoothing index. In this paper, the minimum value of solving the production smoothing index is transformed into the maximum value of its inverse by taking the inverse of the production smoothing index, so that the dual objective function can be converted into a single objective function, according to which the objective function of this paper is established as follows.

$$F = f(x) = \alpha P + \beta \times \frac{1}{SI + 0.01} \tag{3}$$

formula, P is the line balance rate and SI is the line smoothing index.α andβ are the respective weights of the production line balance rate and the production line smoothing index. In this paper, the production balance rate and production line smoothing index are regarded as equally important, so in this paper, the same weight is given to production line balance rate and production line smoothing index. InSI 0.01 is added after it to preventSI the case that the function has no solution when it is 0.

This paper makes the following assumptions about the model.

(1) There is a certain constraint between each process, and the constraint is only the constraint of the sequence before and after the process, and there is no other constraint.

(2) All job units must be assigned to complete, and a job unit can only be assigned to one workstation in one assignment.

(3) All workstations are operating below the production beat, i.e.

$$T(si) \leq CT \qquad i = 1,2,\cdots,m \tag{4}$$

(4) The production line maintains normal operation without considering the case of failure shutdown, etc. And the employees at each workstation remain stable, and there is no cross-workstation operation, etc.

4.2. Solving according to genetic algorithm

Since the production line still has a large load gap between workstations and an unbalanced production line after the improvement by traditional IE techniques. Therefore, this paper establishes a two-population genetic algorithm to solve the problem. Compared with the traditional genetic algorithm, the two-population genetic algorithm adds a sub-population, and the two sub-populations set different variation operators to find the individuals that can best satisfy the conditions in the region basis on ensuring a large enough search range. The schematic diagram of the two-population genetic algorithm is shown in Figure 6. During the operation of the algorithm, when the population stabilizes or reaches the maximum number of iterations, the algorithm stops running and outputs the results.

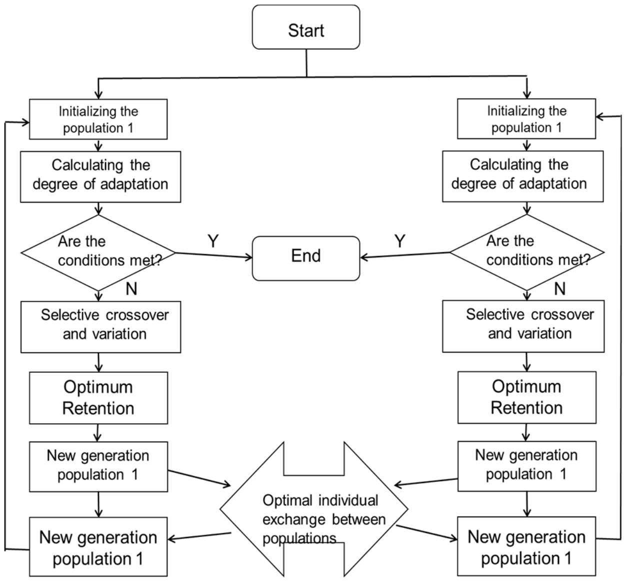

Fig. 6 Schematic Diagram of Double Population Genetic Algorithm

1) Coding

The article model uses a random function to encode the initial population while maintaining the process sequence and generating the initial population randomly.

(2) Adaptability function

The objective function of the model is defined as the fitness function, i.e.

$$\mathrm{Fit} = \mathrm{Fit}_1 + \mathrm{Fit}_2 \tag{5}$$

$$\mathrm{Fit}_1 = \mathrm{P} = \frac{\sum_{i=1}^{m} st_i}{m \times CT} \times 100\% \tag{6}$$

$$\mathrm{Fit}_2 = \frac{1}{SI+\Delta} = \frac{1}{\sqrt{\sum_{i=1}^{m}(ct - T(si))^2 / m} + \Delta} \tag{7}$$

3）Select

Primary population selection was performed using a roulette wheel, where all primary populations were normalized and the probability of each being selected as a parent population was assigned according to fitness.

4) Crossover

The intersection operator is designed using the two-partition point hybridization method, which swaps the left and right sides of the parent after randomly choosing the location of the partition point, e.g.

<table>
<tr><td>[15 |423 |6]</td><td rowspan="3">Crossbreeding</td><td>[32 |423 |4]</td></tr>
<tr><td>[32 |651 |4]</td><td>[15 |651 |6]</td></tr>
<tr><td>Paternal chromosomes</td><td>Offspring chromosomes</td></tr>
</table>

5) Variation

In the two-population genetic algorithm, to ensure that the global search can be performed, a larger variance operator is set for subpopulation 1 and a smaller variance operator is set for subpopulation 2. If the difference between the maximum fitness and the average fitness between subpopulation 1 and subpopulation 2 is large, it indicates that the difference in the composition of the 2 subpopulations is large, and a smaller variance operator can be used to obtain a larger search range, and if the difference between the maximum fitness and the average fitness between subpopulation 1 and subpopulation 2 is small, it indicates that the difference in the composition of the 2 subpopulations is small, and a larger variance operator can be used to obtain a larger search range. If the difference between the maximum fitness and average fitness between subpopulation 1 and subpopulation 2 is smaller, it means that the difference between the composition of the two subpopulations is smaller, and a larger variation operator can be used to obtain a larger search range.

6) Individual exchange between populations

After going through the previous series of steps, the best individuals of the respective populations are retained and exchanged, and the remaining individuals are exchanged randomly.

7) Parameter setting

Given that the number of two initial populations n1 and n2 are equal, the crossover probability pc1 and variation probability pm1 probability values of population 1 should be larger to prevent premature convergence of the function; the global optimal solution of the microsphere, the crossover probability pc2 and pm2 values of population 2 should be smaller, so the parameters of the algorithm are set as follows.

n1=n2=100, pc1=0.8, pc2=0.2, pm1=0.2, pm2=0.05, the number of iterations is 100, and the number of exchanges is set to NumExc=5 when the two groups are exchanged.

4.3. Analysis of results

Using Matlab software to solve the previous dual population genetic algorithm, according to the previous parameter setting, the number of workstations m is taken as 5, 6, 7, 8, and 9 from the actual production situation and workshop area and other factors, and solved, and the running results are shown in Table 3. As can be seen from the table, when the workstation m is taken as 5, the objective function achieves the maximum value of 0.47806, at this time the production line balance rate P=91.242%, and the production line smoothing index is 22.8772. The following figure shows the result when the production line workstation m=5, Figure 7 shows the workstation topology diagram when m=5, Figure 8 shows the job assignment diagram when m=5 and Figure 9 shows the algorithm convergence diagram when m=5. Subsequently, when the number of workstations is taken as 6, 7, 8, and 9, the objective function value cannot exceed the objective function value at m=5.

Tab.3 Comparison of Effects of m=5,6,7,8,9

Number of workstations m	n1	n2	pc1	pc2	pm1	pm2	NumExc	Number of iterations	Production balance rate	Production Smoothing Index
5	100	100	0.8	0.2	0.2	0.05	5	100	91.242%	22.8772
6									78.049%	29.8745
7									80.895%	23.8479
8									73.353%	28.8179
9									87.058	12.8088

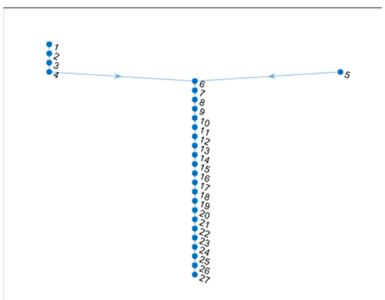

Fig. 7 Topology of m=5

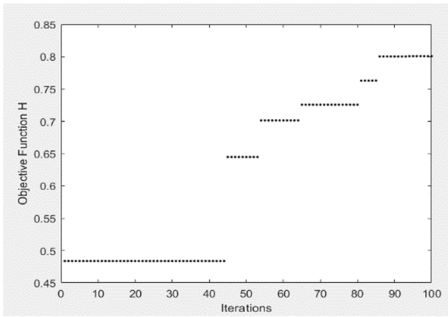

Fig. 8 Assignment Diagram of m=5 Operation

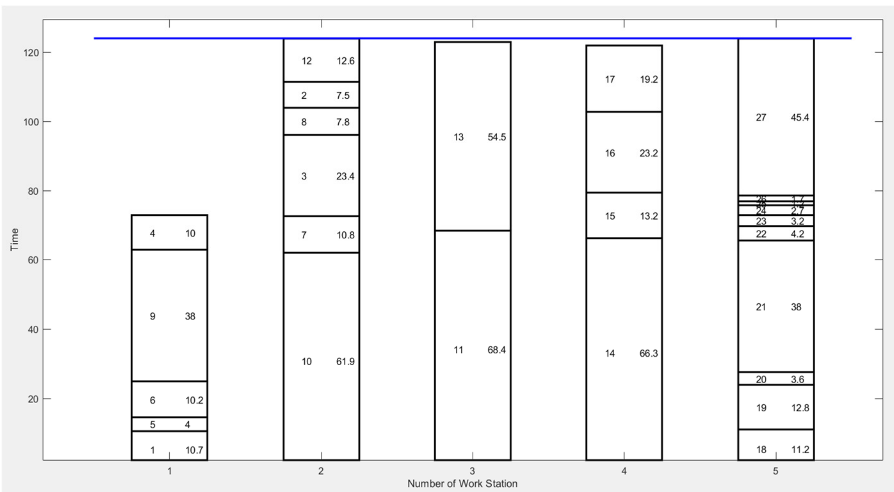

Fig. 9 Convergence diagram of m=5 algorithm

5. Optimization effect evaluation

The article compares the three optimization results of the pre-filled rubber cap production line of Company H before optimization, initial optimization using traditional IE techniques, and further optimization by building a two-population genetic algorithm, and the comparison results are shown in Table 4.

Tab.4 Comparison of the Production Line before and after Improvement

Production Line	Production balance rate	Production Smoothing Index
Initial production line	55.13%	76
Traditional IE improvement	61.88%	50
Two-population genetic algorithm improvement	91.24%	23

By comparison, it can be seen that the production balance rate of this production line is 55.13% and the production smoothing index is about 76 in the initial situation before optimization; after the initial improvement by the traditional IE method, the balance rate of this production line is 61.88% and the production smoothing index is about 50 after optimization; finally, the global workstation optimization of this production line is carried out by building a two-population genetic algorithm model, and the balance rate of this production line is improved to 91.24% and the production smoothing index is about 23 after optimization. It can be seen that after the optimization of the production line by the two-population genetic algorithm, the balance rate of the production line has been significantly improved and the production smoothing index has been decreased. The optimized production line is modeled using Flexsim.

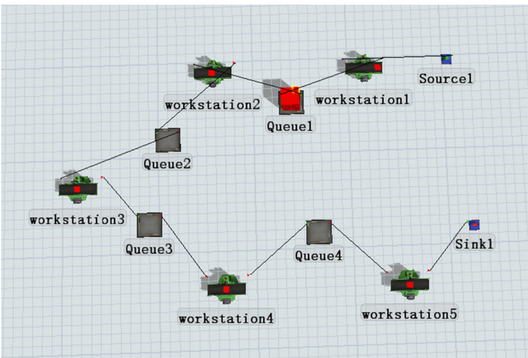

Fig.10 Improved Production Line Simulation Model

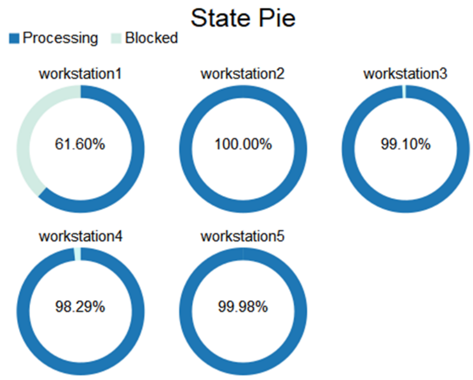

Fig. 11 Proportion of a load of each station after improvement

The optimized production line is simulated and run by Flexsim software, and it can be found that the workstation load ratio of the workstations in the production line is more evenly distributed, except for workstation 1, the workstation load ratio of all other workstations reaches more than 98%, the work-in-process inventory is reduced, and the production efficiency is improved.

6. Conclusion

In this paper, the Flexsim simulation modeling is performed based on the actual layout of the real workshop with the pre-filled rubber cap production line of Company H as the research object. At the same time, the bottleneck process of the production line is determined by combining with the actual production situation. Firstly, it was optimized by traditional IE techniques. Secondly, a two-population genetic algorithm is built with the objective function of line balance rate and line smoothing index. Matlab software is used to find the optimal solution for the production time and production load distribution at each workstation. In this way, the objective of improving the productivity and balancing the production line can be achieved.

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