RESEARCH OF MULTI-PROCESS ON ASSEMBLY LINE BALANCE OF CABLE PRODUCTS

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In order to improve the efficiency of the assembly line of S-company's cable products, the relationship model between process and structure based on the polychromatic set theory is established in the paper, the relationship between each process is analyzed, the method of process route generation is designed, and the algorithm of assembly line balance for the layout of U-shaped pipeline is designed too. Examples show that the method studied in this paper can effectively solve the problem of unbalanced bottleneck process.

Keywords: Polychromatic Set; U-shaped Production Line; Assembly Line Balancing

1. Introduction

With the increasing competition in manufacturing industry, many manufacturing enterprises are facing the pressure of increasingly heavy production costs. The cable products are widely used in industrial products, and the output is very large. For example, the vehicle products, heavy machinery and equipment are widely used, and the production demand is very large [1-4]. However, the assembly process of cable products has obvious characteristics, such as the use of auxiliary equipment, the layout of production line and the control of production process are more complex. At the same time, the cable products are slender, flexible in the middle, large in size, very easy to bend and deform, it is difficult to achieve complete mechanical automation [5, 6]. At present, in addition to individual processes completed by machinery and equipment, most of the processes in the assembly process are still completed by manual operation.

Aiming at the problem of excessive waste of time in production process of cable products and unbalanced assembly line, the relationship model between structure and process is designed in the paper, a method of process path planning is established, and an algorithm of assembly line balance is established.

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2. Assembly process analysis of cable products

In this paper, the most commonly used cable structure of S-company is studied. The general structure of cable products is generally composed of casing pipe, casing cap, steel rope, joints of steel rope, protective rubber pad and fixing block, as shown in Fig. 1. The casing pipe is hollow and the steel rope can move back and forth inside. The tension acts on the joints at both ends of the steel rope. The fixing block is installed in the middle of the casing pipe and needs to be connected with other parts. The protective rubber pad is used to protect the casing pipe. The number of protective rubber pads and fixing blocks of different series of cable products will be different, while the structure of other parts is similar.

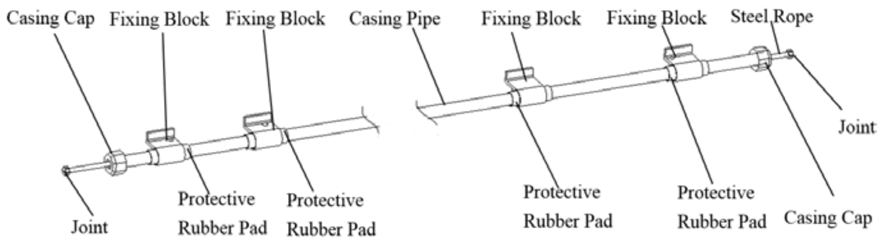


Fig. 1. Structural diagram of cable products

There are many assembly processes of cable products, and the time of each process is quite different. Some processes are completed by special fixture or automatic equipment, such as the process of "putting steel ropes through the casing pipes", it is completed by automatic equipments.Including the following basic processes: (1) Cutting casing pipes; (2) Chamfering casing pipes; (3) Sticking rubber pads 1, 2, …, n; (4) Riveting fixing blocks1, 2, …, n; (5) Riveting left casing caps; (6) Riveting right casing caps; (7) Riveting left joints; (8) Oiling steel ropes; (9) Putting steel ropes through; (10) Riveting right joints; (11) Pre-drawing joints; (12) Shearing residual ropes; (13) Marking products; (14) Inspection products; (15) Cleaning products; (16) Packing products.

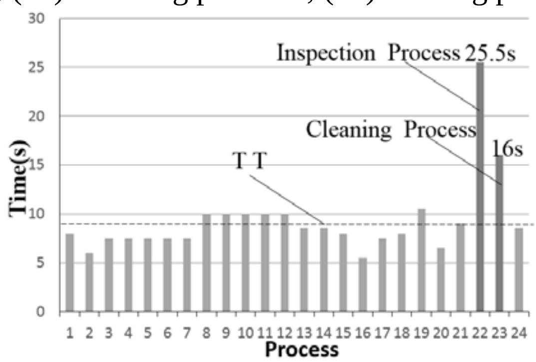


Fig. 2. The hill plot

According to the statistics of similar working procedure time in S-company and the calculation of theoretical working procedure time, the time of each working procedure is obtained and the process Hill plot as shown in Fig. 2 is made. From the hill plot, we can see that the bottleneck process is in the inspection process which takes 25.5 s, followed by the cleaning process. Some enterprises set up two or more workstations for bottleneck process, but can not ensure that the relationship between each process time is multiplied. Therefore, it is impossible to achieve a good balance of assembly line according to “one person and one station”.

3. Assembly process planning model of cable products

3.1 Establishment of assembly process model

Each assembly process of cable products is represented by set P, and each element is the element of polychromatic set [7], which can be expressed as $P=(p_1,\cdots,p_i,\cdots,p_n)$, $p_i \in P$, p_i denotes the assembly process of the cable product. Its meaning refers to the contour matrix as shown in Table 1 [8, 9].

The structure is represented by a uniform color $B(P)=(B_1,\cdots,B_j\cdots B_m)$, B_j represents the components of the cable product, As is shown in Table 1.

$B_j(P)$ represents the sum of the p_i processes required by the B_j components. For example, $B_4(P)=(p_{15}, p_{16}, p_{17}, p_{18}, p_{19}, p_{20})$, which means that if a product has a structure B4, the processes of $p_{15}, p_{16}, p_{17}, p_{18}, p_{19}, p_{20}$ need to be assembled. It can be expressed by Boolean matrix: $B_4(P)=(\overbrace{0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0}^{24})$.

The individual coloring of all elements in a polychromatic set is represented by a boolean matrix and it can be written in the form shown in Formula (1) [7-9].

$$\left\|c_{i(j)}\right\|_{P,B(P)}=[P\times B(P)]=\begin{array}{c} \begin{array}{ccccc} B_1 & \cdots & B_j & \cdots & B_m \end{array} \\ \begin{bmatrix} p_{1(1)} & \cdots & p_{1(j)} & \cdots & p_{1(m)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{i(1)} & \cdots & p_{i(j)} & \cdots & p_{i(m)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{n(1)} & \cdots & p_{n(j)} & \cdots & p_{n(m)} \end{bmatrix} \end{array} \begin{array}{c} p_1 \\ \cdots \\ p_i \\ \cdots \\ p_n \end{array} \tag{1}$$

Among them, i=1, 2, 3, ..., n, j=1, 2, 3, …, m. It needs to be satisfied at the same time: $[P\times B(P)]\subseteq P\times B(P)$.

When $c_{i(j)}$= 1, the cells in row i and column j in Table 1 are represented as “●”, which means that if the product has Bj structure, the assembly process of Pi should be completed. The structure of cable products is similar. When the number of protective rubber pads and fixing blocks increases, the assembly process can be increased appropriately. The status of five protective rubber pads and five fixing blocks is discussed in Table 1.

Table 1

Contour Matrix $[P \times B(P)]$

Contour Matrix		Casing pipe	Left casing cap	Right casing cap	Steel rope	Left joint	Right joint	rubber pad 1	Fixing block 1	rubber pad 2	Fixing block 2	rubber pad 3	Fixing block 3	rubber pad 4	Fixing block 4	rubber pad 5	Fixing block 5
		B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}
Cutting casing pipes	P_1	●															
Chamfering casing pipes	P_2	●															
Sticking rubber pads 1	P_3							●									
Sticking rubber pads 2	P_4									●							
Sticking rubber pads 3	P_5											●					
Sticking rubber pads 4	P_6													●			
Sticking rubber pads 5	P_7															●	
Riveting fixing blocks1	P_8								●								
Riveting fixing blocks2	P_9										●						
Riveting fixing blocks3	P_{10}												●				
Riveting fixing blocks4	P_{11}														●		
Riveting fixing blocks5	P_{12}																●
Riveting left casing caps	P_{13}		●														
Riveting right casing caps	P_{14}			●													
Riveting left joints	P_{15}				●	●											
Oiling steel ropes	P_{16}				●		●										
Putting ropes through	P_{17}				●												
Riveting right joints	P_{18}				●												
Pre-drawing joints	P_{19}				●	●	●										
Shearing residual ropes	P_{20}				●												
Marking products	P_{21}	●															
Inspection products	P_{22}	●															
Cleaning products	P_{23}	●															
Packing products	P_{24}	●															

3.2 The finding of the assembly process path

By the structure analysis of products, The most adjustable process in the process route is the assembly sequence of casing caps, protective rubber pads and fixing blocks. as shown in Fig. 3.

Fig. 3. Diagram of the relationships between riveting fixing blocks and sticking rubber pads

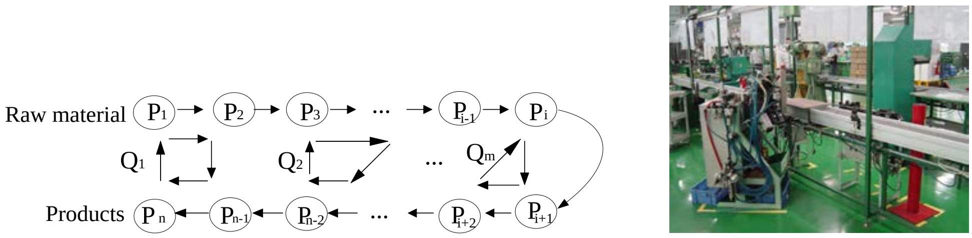
According to the graphic requirements of cable, the structure of the product is obtained. And according to the composition of product assembly and the relationship between each process, the operator of assembly process can be obtained. By the disjunction operation, the process set B(P) of each structural part is obtained , as is shown in Formula (2) [10-12].

$$B(P) = B_1(P) \vee B_2(P) \vee B_3(P) \vee \ldots \vee B_i(P) \vee \ldots \vee B_n(P) = \bigvee_{i=1}^{n} B_i(P) \quad (2)$$

According to the result of disjunction operation and the relation graph of process, the set of the assembly process route can be obtained, and then a more reasonable process route is generated according to the actual situation.

3.3 Algorithms for assembly process allocation

In order to solve the problem of unbalanced process in assembly process, the U-shaped pipeline is used to design the process, as shown in Fig. 4(a), and an actual pipeline is shown in Fig. 4(b). The mode of "One person, Multi-process" can adjust the combination of process time between adjacent processes to achieve the goal of adjusting the balance of production lines [13, 14]. The following basic assumptions are made: (1) One worker operates no more than t workstations, because too much work can easily cause confusion in operation. (2) The routes taken by two persons should not be crossed to avoid interference in the movement of workers. (3) There are n processes in the assembly line, TPi is the sum of the time of the i process, including operation time, moving time, material transfer time and preparation time. (4) There are m workers in an assembly line, Qj is the j operator and TQj is the sum of the working procedure time of the Qj. (5) The average time of all processes operated by each worker is TG.



(a) (b)

Fig. 4. Pipeline layout diagram

Based on the results of Qi-1 calculation, t stations are taken at the entrance:

$P_{x_1+x_2+\cdots+x_{i-1}+1}$, $P_{x_1+x_2+\cdots+x_{i-1}+2}$, $\cdots$, $P_{x_1+x_2+\cdots+x_{i-1}+t}$

The t stations are taken at the exit: $P_{y_{i-1}-t}$, $P_{y_{i-1}-t+1}$, $\cdots$, $P_{y_{i-1}-1}$

A set S(TQi) can be expressed as:

$$S(TQ_i) = (TP_{x_1+x_2+\cdots+x_{i-1}+1}, TP_{x_1+x_2+\cdots+x_{i-1}+2}, \cdots, TP_{x_1+x_2+\cdots+x_{i-1}+t}, P_{y_{i-1}-t}, P_{y_{i-1}-t+1}, \cdots, P_{y_{i-1}-1})$$

In S(TQi), the arrangement is selected so that the sum time of TQi is close to the value of TG, so that $|\delta_i|$ is the minimum value,as shown in Formula (3).

$$\delta_i = \min\left(\sum_{x_1+x_2+\cdots+x_{i-1}+1}^{x_1+x_2+\cdots+x_{i-1}+x_i} TP_k + \sum_{y_{i-1}-y_i}^{y_{i-1}-1} TP_k - T_G\right) \tag{3}$$

The xi workstations are taken for Qi at the entrance:

$$P_{x_1+x_2+\cdots+x_{i-1}+1}, P_{x_1+x_2+\cdots+x_{i-1}+2}, \cdots, P_{x_1+x_2+\cdots+x_{i-1}+x_i}.$$

And The n-y1-y2-…-yi workstations are taken for Qi at the exit:

$$P_{y_{i-1}-y_i}, P_{y_{i-1}-y_i+1}, \cdots, P_{y_{i-1}-1}.$$

In the same way, until all Pi are allocated, the working hours of all workers can be obtained, as shown in Fig. 5, so that the balance of a process route can be calculated.

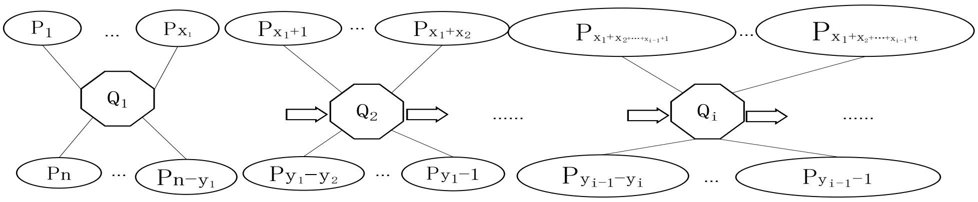


Fig. 5. Schematic diagram of personnel and process assignment

3.4 Calculation of assembly line balance

After determining the relationship between personnels and workstations, the balance of assembly line should be evaluated. The evaluation indexes of production line mainly include production line balance rate (LB) and smoothness index (SI). The balance rate (LB) of production line can reflect whether the distribution of working hours among operators is balanced, and the greater the balance rate, the better. The balance of cable assembly line can be calculated according to Formula (4) [14, 15].

$$LB = \frac{\sum_{i=1}^{m} Tp_i}{TP \bullet N} \tag{4}$$

Among them, N is the number of workstations, TP is the bottleneck time, and Tpi is the operating time of the i station. The expressions can be calculated: TPi= (TQ1,TQ2,…,TQm), and TP=max(TQ1, TQ2, …, TQm), and N=m. and then Formula (5) can be obtained.

$$LB = \frac{\sum_{i=1}^{m} TQ_i}{\max(TQ_1, TQ_2, \cdots, TQ_m) \bullet m} \tag{5}$$

Formula (6) can be used to evaluate the results of LB, which can be divided into three grades: Excellent, General and Bad [13-15].

$$\begin{cases} LB \geqslant 90\% & ,\text{Excellent} \\ 80\% \leqslant LB < 90\% & ,\text{General} \\ LB < 80\% & ,\text{Bad} \end{cases} \tag{6}$$

The same method can be used to analyze the smoothness index SI. SI can be used to evaluate the distribution of work time in production line. The SI value reflects the fluctuation range of work time. The larger the SI, the greater the fluctuation, the worse the balance.

According to the same method, the number of workers can be changed, or the number of workstations per person can be changed, or the process route can be changed, and the balance status of assembly line under various conditions can be calculated, and the optimal technological scheme can be selected finally. On the basis of this scheme, more detailed optimization is carried out, such as moving distance, operation action and so on, so as to obtain more optimized assembly line effect. The assembly line can also be optimized from the aspects of ergonomics to reduce the labor intensity of workers.

4. Case study

As shown in Fig. 6, it is necessary to complete the assembly process design of cable products and complete the balance of assembly lines. The structure of the product is similar to that shown in Fig. 1. The difference is that the middle of the product consists of three fixing blocks and three rubber pads.

Fig. 6. Examples of assembly products

4.1 Process route acquisition

By analyzing the product structure shown in Fig. 6, a polychromatic set of structures can be obtained.

$$B(P) = (B_1, B_2, B_3, B_4, B_5, B_6, B_7, B_8, B_9, B_{10}, B_{11}, B_{12})$$

According to the relationship of the contour matrix shown in Table 1, Process operator p_i can be obtained by searching $B(P)$.

It is expressed by Boolean matrix. Then the disjunction operation is performed, and the result is obtained.

$$B(P) = \begin{cases} B_1(P) = \overbrace{(1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1)}^{24} \\ \text{¡Â} \\ B_2(P) = \overbrace{(0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0)}^{24} \\ \text{¡Â} \\ B_3(P) = \overbrace{(0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0)}^{24} \\ \text{¡Â} \\ B_4(P) = \overbrace{(0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0)}^{24} \\ \text{¡Â} \\ \vdots \qquad\qquad \vdots \\ \text{¡Â} \\ B_{12}(P) = \overbrace{(0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0)}^{24} \end{cases}$$

The calculated results are as follows:

$$B\ (P) = \overbrace{(1,1,1,1,1,0,0,1,1,1,0,0,1,1,1,1,1,1,1,1,1,1,1,1)}^{24}$$

According to Fig. 1 and Fig. 6, three types of process routes can be obtained: Route 1: Riveting casing caps-Sticking rubber pads-Riveting fixing blocks. Route 2: Sticking rubber pads-Riveting casing caps-Riveting fixing blocks. Route 3: Sticking rubber pads- Riveting fixing blocks-Riveting casing caps.

4.2 Assembly line planning

Through on-site measurement of similar process and theoretical rhythm analysis of production process in S Company, the time of each process is obtained as follows:

P1(8s);P2(13s);P3(7.5s);P4(7.5s);P5(7.5s);P8(10s);P9(10s);P10(10s);P13(8.5s);P14(8.5s);P15(8s);P16(5.5s);P17(7.5s);P18(8s);P19(10.5s);P20(6.5s);P21(9s);P22(25.5s);P23(16s);P24(8.5s).

Assumption: A worker operates no more than five jobs and the number of workers is five.The total number of working hours is calculated:

$$\sum_{k=1}^{24} TP_k = TP1 + TP2 + TP3 + \ldots + TP24 = 195.5\text{s}$$

The average working time per person is: TG=39.1s

Distribution Calculation of Process Q_1:

Five stations at the entrance: P_1, P_2, P_3, P_4, P_5. Five stations at the exit: P_{24}, P_{23}, P_{22}, P_{21}, P_{20}, Combining into a set: Q_1 (P_1, P_2, P_3, P_4, P_5, P_{20}, P_{21}, P_{22}, P_{23}, P_{24}). The combination closest to T_G is: $TP_1+TP_2+TP_3+TP_{24}=37$s.

Distribution Calculation of Process Q2:

Five stations at the entrance: P_4, P_5, P_8, P_9, P_{10}.Five stations at the exit: P_{19}, P_{20}, P_{21}, P_{22}, P_{23}.Combining into a set : Q_2(P_4, P_5, P_8, P_9, P_{10} ,P_{19}, P_{20}, P_{21}, P_{22}, P_{23}). The combination closest to TG is: TP4+TP5+TP8+TP23=41s.

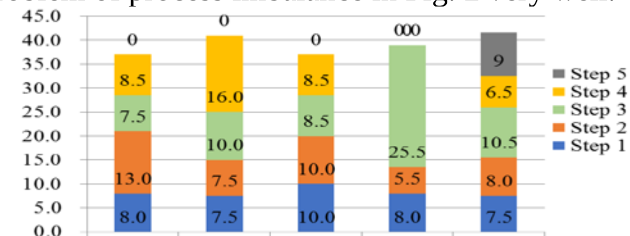
Similarly, Q3, Q4 and Q5 are obtained in turn, and the set closest to the value of TG is obtained as follows: Q_3(P_9, P_{10}, P_{13}, P_{14}), $TP_9+TP_5+TP_8+TP_{23}=37$s, Q_4(P_{15}, P_{16}, P_{22}), $TP_{15}+TP_{16}+TP_{22}=39$s,$Q_5$($P_{17}$, P_{18}, P_{19}, P_{20}, P_{21}), $TP_{17}+TP_{18}+TP_{19}+TP_{20}+TP_{21}=41.5$s.

4.3 Verification of balance rate

The operation time of Q1, Q2, Q3, Q4, Q5 is arranged and calculated by Formula (5). The Balance rate is obtained.

$$LB = \frac{\sum_{i=1}^{m} TQ_i}{\mathrm{Max}(TQ_1, TQ_2, \cdots, TQ_m) \bullet m} = \frac{195.5}{41.5 \times 5} = 94.2\%$$

According to Formula (6), it can be judged that the balance of this scheme is “Excellent” [13, 15]. The process plot of each person is shown in Fig. 7, which has solved the problem of process imbalance in Fig. 2 very well.



	Q1	Q2	Q3	Q4	Q5
Step 5	0	0	0	0	9
Step 4	8.5	16.0	8.5	0.0	6.5
Step 3	7.5	10.0	8.5	25.5	10.5
Step 2	13.0	7.5	10.0	5.5	8.0
Step 1	8.0	7.5	10.0	8.0	7.5

Fig. 7. The hill plot

If the balance rate of the assembly line does not meet the requirements, then change the process route again, or change the number of workers, Or change the number of workstations each person is responsible for, and calculate again. The example shows that the algorithm based on polychromatic set theory and assembly line balancing is feasible. It is easy to realize the programming by computer and has strong practicability.

5. Conclusions

In order to improve the efficiency of S-company’s cable product assembly line, the characteristics of cable products and the relationship between assembly processes are analyzed in the paper, the theory of polychromatic sets which is easy to implement computer programming is applied for modeling. Based on the polychromatic set theory, the relationship model between product structure and process was established. The U-shaped production line is used to design the process route, and the algorithm of assembly line balance for cable products is designed with the mode of “One person, Multi-process”. The example calculation proves that the algorithm based on polychromatic set theory is feasible, and it is very suitable for the design of assembly process of S-company’s cable products.

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