Scheduling optimization of aging employees considering physical load

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Abstract: Considering the influence of age on the task completion time of the workforce, the scheduling problem of the workforce under physical load was extended, and a mathematical optimization model was proposed, preventing the workforce from continuously engaging in high workload work in the same body part and minimizing the standard deviation of task completion time. The influence of age on the workforce's reaction and endurance ability was discussed and formulated reasonably. The high and low workload of the workstation was evaluated by Rapid entire body assessment. A particle swarm optimization algorithm was designed by permutation coding based on set rules, and the rationality of the model and the effectiveness of the algorithm were proved by an example. The results show that the model can not only eliminate the risk of continuous high workload but also improve the performance of the assembly line.

1. Introduction

Work-related musculoskeletal disorders (WMSDs) refer to musculoskeletal injuries caused by physical work or other work. Among them, WMSDs caused by physical work will cause high medical costs to enterprises, loss of productivity, and higher employee mobility [1-2]. With the progress and development of society, more and more manufacturing enterprises begin to pay attention to the health of employees and the sustainable development of production. In the people-oriented production system, job rotation is an appropriate organizational strategy to prevent WMSDs and improve productivity. Nearly 42.7% of enterprises in the United States adopt this method. Although the level of manufacturing automation in China has been greatly developed, there is still a great demand for manual workers in production. Therefore, developing a low-cost and adaptive scheduling strategy for manual workers is not only of theoretical significance but also of significant practical value.

Carnahan [3] firstly, based on NIOSH lifting equation, a simple mathematical model based on ergonomics was constructed for the lifting environment, and the genetic algorithm was used to model and solve the back injury problem of employees. Tharmophornphilas [4] made a quantitative study on the frequency of shift scheduling. Through two examples of the minimum injury risk of manual lifting operation and the minimum noise risk of the sawmill, it was concluded that the effect of shift rotation was the best under the condition of changing shifts every two hours. Nader [5] proposed a mathematical
model to minimize the total delay of the production cycle caused by employees' negative work and skill change according to the influence of job rotation interval on employees' job enthusiasm and skill change.

In this paper, the assembly line with highly repetitive manual tasks and multiple high workload workstations is taken as the research object, focusing on the impact of aging employees on task completion time and production line performance, and a human factor-based job rotation scheduling model is constructed to minimize the standard deviation of task completion time of each workstation. A set rule particle swarm optimization algorithm based on the REBA evaluation method is designed, and an automobile assembly line is taken as an example to verify the rationality of the model and the effectiveness of the algorithm.

2. Problem description

In this paper, the ergonomics-based employee scheduling problem can be described as follows.

2.1. The ergonomics-based employee scheduling problem

The workload of several workstations on the assembly line is evaluated by REBA, and the workload index of each workstation on each part of the body is obtained and graded. Then, the ergonomics-based scheduling model is constructed, and the work rotation schedule of employees for several working periods every day is obtained. From the perspective of ergonomics, the model needs to ensure that the daily workload of employees is within a reasonable range, avoid scheduling as far as possible, so that employees use the same posture and muscles at work, ensure that all parts of the body are not continuously in a high load state, and make the previous parts get to rest in the work rotation, so as to meet the ergonomics requirements that can avoid the long-term high load risk of employees Learning objectives. From the perspective of production, due to the heterogeneity of employees, the characteristics of skill level, reaction ability, and endurance are not the same. When employees complete different tasks in different jobs, the overall performance of the assembly line will be affected. Considering the production requirements of the enterprise, it is necessary to minimize the sum of the standard deviations of the task completion time of each workstation on the assembly line after scheduling.

The research questions are based on the following assumptions:

(1) The maximum working time of each working day of employees and workstations is 8 hours; (2) a working day is divided into multiple working periods with equal length of time, and the change of the employee's workstation only occurs at the end of each working period; (3) each employee participates in one work at most in each working period; (4) the employee can perform all the work stations; (5) for any work period What employee, the accumulated workload will not continue to the next working day.

2.2. The effect of age on task completion time

In the assembly line, the change of employee age structure will have an impact on the performance of the assembly line. The higher the average age of employees, the higher the risk of not meeting the production requirements. First of all, in the assembly line scheduling, the skill level of employees statically affects the completion time by changing the time required to complete a task. When it comes to age-related attributes, the response factor will statically affect the job completion time of employees according to their age group, while the endurance factor will dynamically affect the job completion time of employees in each working period. Therefore, the task completion time of employee I can be expressed by equation (1) when employee i transfers to workstation j in the working period of k rounds:

$$t_{ijk} = x_{ijk} \cdot t_j \cdot \lambda_i \cdot \alpha_i \cdot \theta_{ijk}$$

Among them, $x_{ijk}$ refers to the working status of the j workstation of employee i in the k working period, the working status is 1, otherwise it is 0. $t_j$ is the task completion time of workstation j in the ideal state. $\lambda_i$ is the skill level of employee i. $\alpha_i$ is the endurance factor of employee i. $\theta_{ijk}$ is the endurance factor of employee i in the k working period.
Aging will undoubtedly affect personal physical function. Several reviews on the relationship between age structure and work efficiency show that with the growth of age, employees' dexterity, intuition, and motor ability will decline [6]. This process starts from 20 years old to 60 years old and decreases by 10% every 10 years. On the job, it can be reflected in the increase of response factors $\alpha$ to complete a task. In the face of the task, the elderly employees need longer time to process information and start to perform the task correctly. Based on the reaction factor $\alpha_0$ of an employee with the best reaction speed (the employee belongs to the smallest age group), the reaction factor $\Delta \alpha$ of the employee increases with each grade of the age group $Ag_i$. Therefore, the response factor of employee $i$ can be expressed linearly by equation (2):

$$\alpha_i = \alpha_0 + \Delta \alpha \times Ag_i$$

(2)

Similarly, with the increase of age, people's endurance level also shows a decline of 10% every 10 years from 20 to 60. In the work with repetitive manual tasks, due to the accumulation of fatigue, we can reasonably assume that older employees need more time to complete a task at the end of the shift, that is, the accumulation of work period $k$ gradually affects the employee's endurance factor until it reaches the maximum endurance factor set by the age group. At the same time, if the same part of the body is successively engaged in high load work during the workstation rotation, it is more likely that the part cannot get enough rest time and need more time to complete this type of work. Therefore, the endurance factor of employee $i$ in working period $K$ can be expressed by formula (3):

$$\theta_k = \theta_0 + (\Delta \theta_k \times Ag_i \times k) \times \left[1 + \left(V_{iA}(k-1,k) + V_{iB}(k-1,k)\right)/10\right]$$

(3)

Among them, $\theta_0$ indicates the endurance factor (employees belong to the smallest age group) when employees have the best ability level, $\Delta \theta_k$ is an increased coefficient of endurance factor related to age group and working period. $V_{iA}(k-1,k)$ and $V_{iB}(k-1,k)$ are situations about whether it causes high workload to the same part of the body before and after work rotation for an employee $i$, calculated by equations (4) and (5):

$$V_{iA}(k-1,k) = \sum_{j=1}^{J}\left[(x_{ij(k-1)} \times BPS_{jA}) + (x_{ij(k-1)} \times BPS_{jA})\right]$$

(4)

$$V_{iB}(k-1,k) = \sum_{j=1}^{J}\left[(x_{ij(k-1)} \times BPS_{jB}) + (x_{ij(k-1)} \times BPS_{jB})\right]$$

(5)

$BPS_{jA}$ and $BPS_{jB}$ are the working load of workstation $j$, which can be obtained from equation (6) and equation (7).

2.3. Workload assessment of body parts A and B

In job rotation, the cumulative high workload caused by continuous use of the same part of the body is a major ergonomic risk factor of the assembly line. The task characteristics of the workstation and the body parts involved should be considered to reduce the occurrence of this kind of situation. REBA is a posture analysis system that can assess the risk of various types of musculoskeletal injuries. It divides the body into two groups A and B. The workload index of workstation $j$ for body part A $PS_{jA}$ is composed of the scores of the neck, trunk, and leg, while the workload index $PS_{jB}$ for body part B is composed of the scores of the upper arm, forearm, and wrist. The overall workload index $REBA_{j}$ of workstation $j$ is calculated by the composite score of the two. According to the media $PS_{mA}$ and $PS_{mB}$ of part A and part B
of workstation, the workload index of the assembly line can be divided into the high and low workload of group A \( BPS_A \) and high and low workload of group B \( BPS_B \) according to equations (6) and (7):

\[
BPS_A^j = \begin{cases} 
1, & \text{if } PS_A^j > PS_m^j \\
0, & \text{else}
\end{cases} \tag{6}
\]

\[
BPS_B^j = \begin{cases} 
1, & \text{if } PS_B^j > PS_m^j \\
0, & \text{else}
\end{cases} \tag{7}
\]

3. Construction of scheduling model

Based on the explanation of problems in sections 2.1, 2.2, and 2.3, the following decision variables are introduced. \( x_{ijk} = 1 \) mean employee \( i \) in position \( j \), working period \( k \) is in working state, otherwise, it is 0. In order to meet the production requirements of the enterprise, the objective function is set here as equation (8):

\[
\text{Minimize } F = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \left( \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{j=1}^{J} t_{ijk} - \bar{t}_{ijk} \right) \right)^2 \tag{8}
\]

The constraints are as follows:

\[
\sum_{j=1}^{J} x_{ijk} \leq 1, \forall i, \forall k \tag{9}
\]

\[
\sum_{i=1}^{I} x_{ijk} = 1, \forall j, \forall k \tag{10}
\]

\[
\sum_{k=1}^{K} x_{ijk} \leq 1, \forall i, \forall j \tag{11}
\]

\[
V_A^j (k-1, k) \leq 1, \forall i, \forall k = 2...K \tag{12}
\]

\[
V_B^j (k-1, k) \leq 1, \forall i, \forall k = 2...K \tag{13}
\]

\[
x_{ijk} = \{0, 1\}, \forall i, \forall j, \forall k \tag{14}
\]

Equation (8) is the objective function, that is, the sum of the standard deviations of the task completion time of all work periods is minimized; equation (9) indicates that an employee can only be assigned to one work station in each work period; equation (10) indicates that an employee can only be assigned to one work station in each work period; equation (11) indicates that an employee cannot be assigned to the same work station multiple times in a workday; equation (12) and (13) prevent employees from being assigned to a continuous workstation with the high workload at the same body part. Equation (14) is the feasible region of decision variables.

4. Construction algorithm

PSO is a population intelligence algorithm proposed by Kennedy and Eberhart[7] to simulate bird prey behaviour. It has simple solution and few parameters. In solving combinatorial optimization problems, it shows strong global optimization ability and fast convergence speed. Therefore, particle swarm optimization is used to solve the model.
4.1. The idea of particle swarm optimization
PSO simulates the predator process of birds. Although individuals have no rules in flight, the flight of the whole group can keep consistent and gradually approach food. Each particle in PSO algorithm represents a solution, and the particle reaches the optimal solution by speed update and position update. In the process of updating, the particles update with their own historical and global optimal positions, which combines local optimization and global optimization. The update process can be expressed in expressions (15) and (16):

\[
V_{sd}^{g+1} = \omega V_{sd}^g + c_1 r_1 (P_{sd}^g - X_{sd}^g) + c_2 r_2 (P_{gd}^g - X_{gd}^g)
\]  
(15)

\[
X_{sd}^{g+1} = X_{sd}^g + V_{sd}^{g+1}
\]  
(16)

\(V_{sd}^g\) and \(X_{sd}^g\) are the velocity and position of \(g\) generation particles; \(\omega\) is the inertia weight; \(c_1, c_2\) are the learning factor; \(r_1, r_2\) are random number from 0 to 1; \(P_{sd}^g, P_{gd}^g\) are the position of individual extreme value and population extreme value.

4.2. Decoding and coding based on set rules
The scheduling based on ergonomics is a combination optimization problem which is matched by \(I\) employees, \(J\) workstations and \(K\) working periods, which is very complex. Since the new constraints (12) and (13) are introduced, the scheduling method obtained by the random generated particles directly decodes is basically infeasible. Therefore, in order to ensure that the feasible scheduling scheme can be obtained after decoding and improve the decoding efficiency, this paper proposes a set rule-based arrangement coding method for constraints (12) and (13), as shown in Table 1.

| Set   | Set definition                        | Optional collection for the next workstation |
|-------|---------------------------------------|---------------------------------------------|
| O     | A. B part are not high workload       | O, A, B, AB                                 |
| A     | Only part A has high workload         | O, B                                        |
| B     | Only part B has high workload         | O, A                                        |
| AB    | A, B part are high workload           | O                                           |

All workstations are divided into four different sets according to the \(BPS_s^A\) and \(BPS_s^B\) value of the workstation in the way in Table 1. In the process of scheduling, there are constraints on the assignment of work stations in two working periods, that is, the A and B parts of any employee's adjacent two shifts cannot be in the high workload state continuously. Therefore, based on the set rules, the decoding process of this paper is shown as follows:

Step 1: the particles search in dimension space, sort the position values of the first row, and fill in the number of 1 to \(j\) workstations (personnel arrangement of the first workstation) according to the sorting size, and then go to step 2.

Step 2: the position value of lines 2 to \(K\) indicates the priority weight of each personnel shift. Select the person with the largest priority weight in line \(k\), and select one randomly if there are more qualified personnel. Judge the set properties of the previous workstation of the personnel, and select the first \(k-1\) workstation from the optional collection of the latter workstation, and put it into the workstation.
Step 3: judge whether the workstation in line k has been assigned, if not, delete the assigned workstation and go to step 2. Otherwise, refresh the unassigned workstation number set and K = K + 1 and go to step 4.

Step 4: judge whether all the dimension space is decoded, if not, go to step 2.

4.3. Algorithm flow
The specific solution process of the algorithm is as follows:
   - Step 1: initialize the particle population.
   - Step 2: decode the particles according to the steps in 4.1.
   - Step 3: calculate the fitness value of each particle, here is the objective function of this paper.
   - Step 4: update the individual and population optimal particles according to the maximum fitness.
   - Step 5: update the particle velocity and position according to equations (15) and (16).
   - Step 6: when the maximum number of iterations is reached, the algorithm ends and outputs the current optimal particle. Otherwise, return to step 2.

Results of job rotation considering workload
In this section, the pruning assembly line of the automobile production line is taken as an example to verify the rationality of the model and the effectiveness of the algorithm. There are 8 workstations in the trimming assembly line, as shown in table 2. Ideally, the task completion time cycle of each workstation is about 60s. In order to reduce the WMSDs risk of employees in working days, this paper studies the scheduling model for days, and sets the working station K of one day as 4. Table 2 shows the detailed contents of the workload scores of each part of the body of the workstation and the collection of the workstation. It can be seen from Table 2 that most of the workstations have higher $PS_j^A$ than $PS_j^B$, because the staff mainly deal with wires, inner and outer fabrics, and decorations in the posture of waist flexion or squatting, so the workload of lower back and legs is greater.

| Parameters | Station | Median |
|------------|---------|--------|
| $t_j$      | 1 2 3 4 5 6 7 8 |
| $PS_j^A$   | 65 62 59 60 67 57 60 56 |
| $PS_j^B$   | 2.0 1.5 2.1 2.3 2.4 2.5 3.0 1.9 |
| $REBA_j$   | 4.5 3.8 4.0 2.5 4.4 2.9 4.9 2.4 |
| Set        | A O A B AB B AB O |

In order to evaluate the influence of the heterogeneity of employees in different age groups on the assembly line balance rate, the employees are divided into four age groups according to their ages, under 30 years old, 30-40 years old, 40-50 years old and over 50 years old. $\alpha_0$ and $\theta_0$ are set to 1, and according to $Ag_i = 4$ and the age difference within the age group, the $\Delta \alpha$ is set to 0.1, $\Delta \theta_k$ is set to 0.025. This paper does not consider the influence of different skill levels of employees on schedule, so the skill levels of employees $\lambda_i$ are set to 1. Considering 8 employees, 2 for each age group, Table 3 shows the detailed parameters of eight employees.

| Employees | 1 2 3 4 5 6 7 8 |
|-----------|---------------|
| $Ag_i$    | 1 1 2 2 3 3 4 4 |
| $<30$     | <30 30-40 30-40 40-50 40-50 >50 >50 |
The PSO algorithm is programmed in MATLAB (r2017a) with 2.6GHz dominant frequency, 4GB memory, and Intel (R) Core (TM) i5-3230m CPU. The parameters of the algorithm are set as follows: the population size NP is 200, the maximum number of iterations G is 300, the inertia weight ω is 0.4, the learning factor is 2, 4, the particle is a vector of dimension, and each coordinate is a random number between 0 and 1. The particle swarm optimization algorithm is used to calculate the models of equations (8) to (14). After running for 57.9s, the objective function value is 50.9889. Figure 1 shows the shift scheduling of employees in one working day under Ergonomic job rotation (EJR) mode.

Table 1: Parameters of the PSO algorithm

| αi | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.3 | 1.4 | 1.4 |
|---|---|---|---|---|---|---|---|---|
| θ_{i01} | 1.025 | 1.025 | 1.05 | 1.05 | 1.075 | 1.075 | 1.1 | 1.1 |

Figure 1 job rotation scheduling based on human factors

5. Discussion

In order to verify that the model proposed in this paper can reduce the workload of employees and improve the performance of the assembly line through more scientific scheduling, the results of three scheduling methods, no job rotation (NJR), random job rotation (RJR) and ergonomic job rotation (EJR), are compared and analysed. In NJR scheduling mode, employees work in a workstation for one day without job rotation. In RJR, employees are randomly transferred to other workstations during break time.

According to table 4, under the shift arrangement of NJR, there will be 6 times of continuous high workload operation in body part A, body part B, body part A, and B on the assembly line respectively. According to table 1 and table 2, employees 1 and 3 will bear WMSDs risk from body part A (trunk, neck, leg) for a long time under this shift arrangement. Similarly, WMSDs risk of Part B (upper arm, forearm, and wrist) is borne by employees 4 and 6, while employees 5 and 7 are both A and B parts. In the NJR shift arrangement, the risk of workload borne by employees is different, and the work with high load is long undertaken by individual employees, which means that these employees cannot get good rest and overload work. When this situation occurs in employees of high age level such as employee 7, it may cause employees to be injured, and they need more time to recover health, which results in the loss of personnel in an assembly line.
Compared with NJR scheduling, RJR can reduce the number of three continuous and high workload jobs by rotating employees. The optimization of the target value was also obtained, which decreased from 55.2592 to 53.2028, so the balance of the assembly line was also improved.

Further, the implementation of EJR scheduling can eliminate three continuous high workload operations. According to figure 1, the daily workload of high-risk work is assigned to multiple employees, such as the employees assigned to the workstation 7 on one working day are 3, 8, 4, and 7 in turn. Meanwhile, because of the absence of continuous high workload, such as in the first workstation, employee 3 is assigned to workstation 2 belonging to collection O after the work of Workstation 7 is finished. After a low workload operation of one workstation, the third workstation is allocated to workstation 5 belonging to the collection AB, which greatly reduces the probability that the employee needs to bear WMSDs risk. Meanwhile, the goal of the EJR shift arrangement is worth further optimization, which is reduced from 55.2592 to 50.9889.

Table 4 Comparison of three scheduling results

| Scheduling method | Times of continuous high workload | goal     |
|-------------------|----------------------------------|----------|
|                   | Part A  | Part B  | Part A and B |      |
| NJR               | 6      | 6      | 6            | 55.2592 |
| RJR               | 4      | 3      | 4            | 53.2028 |
| EJR               | 0      | 0      | 0            | 50.9889 |

By comparing the results of the three scheduling schemes, although the EJR scheduling method cannot eliminate the WMSDs risk factors of the assembly line, it can reduce the exposure time of each employee and ensure that employees will not be continuously assigned to the workstation with the high workload of the same part of the body. For assembly lines with employees of different ages, the EJR scheduling method can not only reduce the harm of extreme work to aging employees but also allocate high workload to different employees with the progress of scheduling, so the endurance factor of employees will not be further improved due to continuous high workload work, so employees can complete the work of workstation at a faster speed Task so that the performance of the assembly line has been improved.

6. Conclusion
Considering the influence of the change of the age structure of the employees on the performance of the assembly line, an ergonomic scheduling model is proposed to eliminate the continuous high workload of the employees and minimize the standard deviation of the task completion time of the employees. Firstly, employees are divided into four age groups according to their age, and the actual task completion time is calculated according to the influence of age on employees’ reaction and endurance ability. The rationality of the model is verified by the example of automobile assembly line. The group intelligent algorithm will be developed to improve the quality of the solution.

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References
[1] APTEL M, CAIL F, Gerling A, et al. Proposal of parameters to implement a workstation rotation system to protect against MSDs[J]. International Journal of Industrial Ergonomics, 2008, 38(11-12):900-909.
[2] KANG Fumei, ZHANG Fang, SHAN Yong Le, et al. Research status and progress of work-related musculoskeletal diseases [J]. Chinese Journal of Industrial Medicine, 2019, 32 (06): 495-497

[3] CARNAHAN B J, REDFERN M S, NORMAN B. A genetic algorithm for designing job rotation schedules considering ergonomic constraints[C]. Congress on Evolutionary Computation. IEEE, 1999.

[4] THARMMAPHORNPHILAS W, NORMAN B A. A quantitative method for determining proper job rotation intervals[J]. Annals of Operations Research, 2004, 128:251-266.

[5] AZIZI N, ZOLFAGHARI S, LIANG M. Modeling job rotation in manufacturing systems: The study of employee's boredom and skill variations[J]. International Journal of Production Economics, 2010, 123(1):69-85.

[6] ABUBAKAR M I, WANG Q. KEY human factors and their effects on human centered assembly performance[J]. International Journal of Industrial Ergonomics, 2018, 69:48-57.

[7] LIU Xiaohua, LIN Jie, DENG Ke. Reentrant production scheduling optimization based on genetic particle swarm optimization [J]. Journal of Tongji University (Natural Science), 2011, 39 (05): 726-730 + 772