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Study on the charging combination optimization for forging production based on discrete shuffled frog leaping algorithm

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1. Introduction

Forging industry is a high energy consumption industry and also arises serious pollution problems. However, the forging industry is one of the basic industries for people's livelihood. There is broad consensus in the forging industry to ensure the rapid development and implementation of cleaner production, energy saving, emission reduction and noise elimination [1].

The charging combination optimization belongs to a large scale combination optimization problems. It can be described as multiple knapsack problem. It's difficult to build the model and the solving procedure is complex. So the conventional methods often fail to get the optimal solution. In literature [2], the combination multi-knapsack model based on multi-furnace types, uncertain installed furnace number was proposed for the steel coil. In view of annealing production of steel coil, the mathematical model to minimize the total time of heating is established for stacking combination optimization [3].

SFLA(Shuffled Frog Leaping algorithm) was firstly proposed in 2003 by the Eusuff and Lansey to solve combinatorial optimization problems. As a bionics intelligent optimization algorithm, SFLA is integrated with the advantages of MA (memetic algorithm) based on memes (meme) evolution and PSO (particle swarm optimization) based on group behavior. Therefore, SFLA is characterized by simple concept, less parameter adjustment, fast calculation, strong global search optimization capability, and easiness to implement. At present, SFLA was mainly used to solve the multi-objective optimization problems, such as job shop schedule, pier maintenance, water distribution and other actual engineering problems.

Many scholars studied the application of shuffled frog leaping algorithm for solving combination optimization problem or multi-knapsack problem. Wang [4] makes use of the global optimal solution as the guidance of each sub population overall forward evolution based on the shuffled frog leaping algorithm for solving combination optimization problems. Cai and Li proposed an improved shuffled frog leaping algorithm, defining the similarity and distance of frog. Accordingly, a frog shift strategy was constructed [5]. Pan designed a discrete shuffled frog leaping algorithm to solve batch production line scheduling problem [6]. A multi-agent shuffled frog leaping algorithm, combined with the evolution mechanism of shuffled frog leaping algorithm, was researched to continuously apperceive the local environment [7].

Aiming at the problem of best load with furnace weight constraints, a discrete shuffled frog leaping algorithm for forging furnace was proposed by our previous research [8]. But the charging combination optimization is not solved. In this presentation, the problem regarding to the combination optimization of forging work-pieces with different holding temperature and holding time was studied. A model for optimizing the charging combination with the goal of energy saving was established. Then a discrete shuffled frog leaping algorithm based on the same furnace heating rules is designed for solution.

2. Problem description

Forging heating and temperature holding have important effect on the forging internal micro-structure homogenization. The homogenization will not be distinct if temperature holding time is too short, and the too long holding time will cause overheating or burning. For work-pieces in the same furnace, it is stipulated technically that the lowest holding temperature of work-piece in the furnace is holding temperature of the furnace batch, and the longest time of temperature holding is holding temperature time of the whole furnace batch. The shorter holding time is, the less heating furnace energies are consumed. When a batch of work-pieces with different holding time are partially combined, different batching plan will cause different holding time of furnace batches. The distribution of forgings is not only related to the holding time, but also its holding temperature as well as the furnace batch weight. The optimization goal of forging for energy-saving furnace combination is not only the holding time, but also includes furnace batch number, average loading capacity and average holding temperature.

3. Modeling

3.1. Basic assumption

1. Each work-piece only belongs to one furnace batch.

2. A batch of work-pieces are put into the furnace and heated in the same time.

3. Maximum load weight does not exceed the load capacity of heating furnace.

4. The heating furnace can reach the temperature that meet all requirements of the work-piece holding temperature.

3.2. Modeling

Providing there are N work-pieces that their weight, holding temperature and holding time are given. Those work-pieces have to be divided into B batches and each batch corresponds to a heating job. The maximum capacity of furnace is S and the heating furnace can reach the temperature that meet all requirements of the work-piece holding temperature. The ultimate holding time must also meet all work-piece furnace holding time requirements. The optimization goal is to minimize the quantity of charging batches with maximum average charging amount (i.e. minimum average charging difference), minimum average holding temperature and minimum average holding time.

3.2.1. Constrains

Definition 1: Temperature compatibility: The temperature range of work-piece *i* and *j* are $\left[T_{i\,min}, T_{i\,max}\right]$ and $\left[T_{j\,min}, T_{j\,max}\right]$, if:

$$\left[T_{i\,min},\, T_{i\,max}\right] \cap \left[T_{j\,min},\, T_{j\,max}\right] \neq \varphi, \tag{1}$$

where the work-piece *i* and *j* have temperature compatibility.

Definition 2: Time compatibility: The time range of holding temperature of work-piece *i* and *j* are $\left[C_{i\,min}, C_{i\,max}\right]$ and $\left[C_{j\,min}, C_{j\,max}\right]$, if:

$$\left[C_{i\,min},\, C_{i\,max}\right] \cap \left[C_{j\,min},\, C_{j\,max}\right] \neq \varphi, \tag{2}$$

where the work-piece *i* and *j* have time compatibility.

Definition 3: Same furnace heating rule: If the work-piece *i* and *j* can simultaneously satisfy the temperature compatibility and time compatibility, it is claimed the two meet the same furnace heating rules, i.e. the work-piece *i* and *j* can be placed in the same furnace batch.

3.2.2. Optimization model

Definition 4: Average furnace holding temperature: The average value of holding temperature of all furnace batch in one batching, i.e.:

$$T = \frac{1}{k}\sum_{b=1}^{k} T_b\,, \tag{3}$$

where T is the average temperature in the furnace charging, k is the furnace batch number, and T_b is the holding temperature of furnace batch (Section b) ($b = 1, 2, \cdots, k$).

Definition 5: Average furnace holding time: The average value of holding time of all furnace batch in one batching plan, i.e.:

$$C = \frac{1}{k}\sum_{b=1}^{k} C_b\,, \tag{4}$$

where C is the the average holding time, k is the furnace batch number, and C_b is the holding time of furnace batch (Section b) ($b = 1, 2, \cdots, k$).

With the above assumptions and definitions, mathematical model can be established as follows:

$$min(k), \tag{5}$$

$$min(Q, T, C) = \left(\frac{1}{k-1}\sum_{b=1}^{k-1}(S - z_b),\ \frac{1}{k}\sum_{b\in B} T_b,\ \frac{1}{k}\sum_{b\in B} C_b\right), \tag{6}$$

where S is the heating furnace maximum load, z_b is the furnace batch weight (Section b). Eqs. (5) and (6) are the optimization function, aiming at minimizing the furnace batch number, the average furnace loading difference, the average holding temperature and the average holding time.

Assuming:

$$\sum_{b\in B} x_{jb} = 1, \quad j \in J_b\,; \tag{7}$$

$$z_b = \sum_{j\in J} x_{jb} z_j \le S, \quad b \in B\,; \tag{8}$$

$$\bigcap_{j\in J_b}\left[T_{j\,min},\, T_{j\,max}\right] \neq \varnothing, \quad b \in B\,; \tag{9}$$

$$T_b = max\left\{T_{j\,min}\right\}, \quad j \in J_b, \quad b \in B\,; \tag{10}$$

$$\bigcap_{j\in J_b}\left[C_{j\,min},\, C_{j\,max}\right] \neq \varnothing, \quad b \in B\,; \tag{11}$$

$$C_b = max\left\{C_{j\,min}\right\}, \quad j \in J_b, \quad b \in B\,; \tag{12}$$

$$\left\lceil \sum_{j=1}^{n} \frac{z_j}{S} \right\rceil \le k \le n\,; \tag{13}$$

$$x_{jb} = \begin{cases} 1, & j \in J_b \\ 0, & j \notin J_b \end{cases} \quad j \in J, \quad b \in B\,, \tag{14}$$

where n denotes the work-piece number, J denotes aggregate of work-pieces ($J = \{1, 2, \cdots, n\}$), J_b denotes furnace batch number ($b \in B$), B denotes aggregate of charging batches ($B = \{1, 2, \cdots, k\}$), j denotes work-piece number ($j \in J$), j_b denotes aggregate of work-pieces in batch b ($b \in B$), z_j denotes weight of work-piece j, and x_{jb} denotes decision variable, judging whether the work-piece j belongs to the furnace batch b.

Eq. (7) indicates that each work-piece j can only be allocated to one charging batch b.

Eq. (8) is the furnace batch weight constraint, indicating the total weight of work-pieces in a batch shall not exceed the maximum capacity of the furnace.

Eq. (9) shows that the intersection of holding temperature interval of work-pieces in the same batch cannot be empty, i.e. work-pieces in one batch shall meet the temperature compatibility.

Eq. (10) indicates that the final holding temperature of a furnace batch in heating furnace is the minimum temperature that meet the requirements of all work-pieces' holding temperature.

Eq. (11) shows that the intersection of holding time interval of work-pieces in the same batch cannot be empty, i.e. work-pieces in one batch shall meet the time compatibility;

Eq. (12) indicates that the final holding time of a furnace batch in heating furnace is the minimum time that meet the requirements of all work-pieces' holding time.

Eq. (13) defines the quantity interval of charging batches by giving a lower limit for the quantity of charging batches, i.e. $\sum_{j=1}^{n} z_j$, It is assumed that work-pieces can be separated and allocated to different batches, and all work-pieces in any furnace batch can satisfy the temperature compatibility.

Eq. (14) is the decision variables.

4. DSLFA design based on same furnace heating rules

This model is similar to the bin packing problem as well as the multi-knapsack problem[9]. The work-pieces are items while furnace batches are boxes in the model. It's required that total weight of each furnace batch cannot exceed the maximum weight allowed by furnace, and each item can only be put into in a box.

This paper adopts the individual updating ideas from the discrete shuffled frog leaping algorithm in reference [10]: According to the combination optimization problem of work-pieces in different holding temperature and holding time interval sets, the discrete shuffled frog leaping algorithm based on same furnace heating rules is proposed.

Steps are as follows:

1. Coding

Use classic two-dimensional array encoding. The length of individuals is the number of work-pieces, each bit means the sequence number of work-piece, and each block represents a furnace batch.

2. Fitness function selection

Aiming to smaller furnace batch quantity, less average charging difference, smaller average temperature of holding temperature, and smaller average holding time, this paper use the linear weighted comprehensive evaluation to determine the fitness function. The expression is as follows:

$$fitness = w_k \frac{k_{max} - k}{k_{max} - k_{min}} + w_q \frac{q_{max} - q}{q_{max} - q_{min}} + w_T \frac{T_{max} - T}{T_{max} - T_{min}} + w_c \frac{C_{max} - C}{C_{max} - C_{min}}; \qquad (15)$$

$$q = \frac{1}{k-1} \sum_{b=1}^{k-1} \left(S - z_b \right); \qquad (16)$$

$$T = \frac{1}{k} \sum_{b \in B} T_b ; \qquad (17)$$

$$C = \frac{1}{k} \sum_{b \in B} C_b , \qquad (18)$$

where w_k, w_q, w_T, w_C are the weight coefficient of furnace batch number, average charging difference, average holding temperature, average holding time. And they satisfy the equation $w_k + w_q + w_T + w_C = 1$. k_{max}, k_{min}, q_{max}, q_{min}, T_{max}, T_{min}, C_{max}, C_{min} are the maximum and minimum number of furnace batch, the maximum and minimum average charging difference, the maximum and minimum average holding temperature, the maximum and minimum average holding time.

3. Population initialization

BF heuristic algorithm is used to generate the initial population of individuals. In the generation of an individual, a group of work-pieces has not only to satisfy the same furnace heating rules, also cannot exceed the furnace batch weight constraint. Generation of the individual steps are as follows:

Step 1: the work-piece placed in the queue Q in random and numbered sequentially, number is $1, 2, \dots, n$.

Step 2: pick the work-piece j out of the queue Q in order, which weight is z_j holding temperature is T_j, holding time is C_j.

Step 3: pick batch b out of queue Q' that have not been matched with work-piece j, then find out whether the work-piece j matches batch b. The remaining weight space of batch b is $\Delta s_b = S - s$, where S is the maximum load of heating furnace and s_b is the weight of batch b. The holding temperature is T_b, which is the holding temperature interval intersection of all work-pieces, and T_b is not $\varnothing$. The holding time is C_b, which is the holding time interval intersection of all work-pieces, and C_b is not $\varnothing$. If all batches in queue Q' have been operated with work-piece j, a new furnace butch b_{new} is set up with work-piece j in it. Update the remaining weight space of batch b_{new}: $\Delta s_{b_{new}} = S - z_j$, holding temperature: $T_p = T_j$, holding time: $C_{b_{new}} = C_j$. If the queue Q is empty, go to step 4, else go to step 2. If there any butch that not operated with work-piece j, calculate $\Delta s_b' = \Delta s_b + z_j$, $T_b' = T_j \bigcap T_b$, and $C_b' = C_j \bigcap C_b$. If $\Delta s_b' \geq 0$, $T_b' \neq \varnothing$, $C_b' \neq \varnothing$, remove work-piece j into batch b, update the remaining weight space of batch b: $\Delta s_b = \Delta s_b'$ holding temperature: $T_b = T_b'$, holding time: $C_b = C_b'$. If the queue Q is empty, go to step 4, else go to step 2. If anyone of $\Delta s_b' < 0$, $T_b' \neq \varnothing$, $C_b' \neq \varnothing$ is true, then go to step 3.

Step 4: At this time the batches in queue Q' have all work-pieces. This is a partial solution in which individual is in the encoding form talking above.

Using the steps above to generate multiple individuals, the initial population is composed in size r. Please pay attention to eliminating redundant individual.

4. Generating ethnic groups

According to the fitness function in (2), all individuals are in a descending order by fitness values, which means excellent frog is in the front. Then the population is divided into m groups, each group including n frogs. There's totally number is $r = m \times n$.

5. Ethnic group evolution

In each group, the best frogs X_b and the worst frog X_w are chosen, as well as the optimal frog X_g throughout the population, then separately update the worst frog in iteration.

Update individuals based on the idea of individual updates theory in discrete shuffled frog leaping algorithm [11] and the individual update method [12].

Steps are as follows:

Step 1: Select two intersection points from X_b in random. X_b is divided into several fragments.

Step 2: Select intersection points from X_w in random, and insert fragment from X_b into X_w before the intersection point. This means some information X_b is inserted into X_w.

Step 3: delete these furnace batch fragment in X_w that have some redundant work-piece, then transfer these work-pieces in that fragment into the queue Q. Please make sure that the furnace batch fragment is renewed.

Step 4: the work-pieces are ranged in random order. In accordance with the BF method in this paper those work-pieces are insert into X_w, i.e. X'_w.

Step 5: calculate the fitness value of X'_w. If the X'_w is better than X_w, replace X_w, else X_g, which is the best individual in the population should replace X_b in step 1 and start the operation from step 1 to step 4 again. Now if the X'_w is better than X_w, replace X_w, else Generates a random feasible solution to replace X_w.

Step 6: repeat the operation above until the maximum iterations to complete one ethnic group evolution.

Examples are as follows: information of X_b and X_w are shown in Fig. 1. Cross location is shown by arrow. The cross fragment from X_b is plugged into X_w at the cross point. The new individual is shown in Fig. 2. It's shown in Fig. 2 that wherein the work-piece3, 7 and 2 is redundant, so we need to delete the corresponding furnace batch that shown in Fig. 3.

At this time the work-pieces 1, 4, 5, 6 are not in batches, so using the BF method to repartition to get individual shown in Fig. 4.

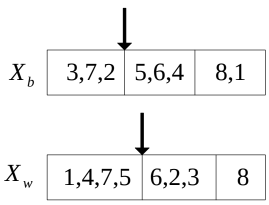

Fig. 1 The individual information and the position of the cross point

1,4,7,5	3,7,2	6,2,3	8

Fig. 2 Individual after insert the cross fragment

3,7,2	8

Fig. 3 Delete the redundant information

1,4,5	3,7,2	6,8

Fig. 4 The individual after adding the missing information

6. The ethnic mixing

After evolution of all ethnic groups, all ethnic groups will be mixed to generate a new population. Then repeat the operation steps of distribution and combination, until the condition is satisfied.

The procedure of the DSFLA based on same furnace heating rules is shown in Fig. 5.

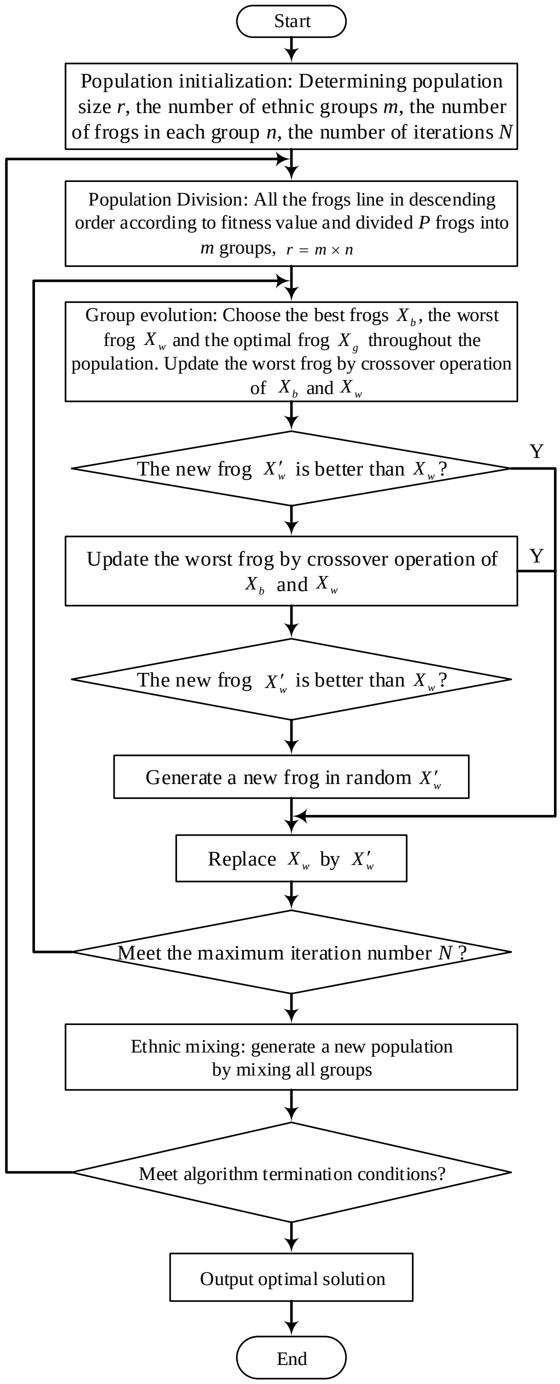

Fig. 5 Flowchart of DSFLA based on same furnace heating rules

5. Case study

5.1. Types of work-pieces to be charged and their parameters

Take multi-tasks charging batch combination form certain forging company as research object. All work-pieces are classified by different weight, holding temperature and holding time. It should be taken into consideration whether these work-pieces could be heated together referring to time compatibility, temperature compatibility and load capacity. The maximum loading amount of the related parameters of the work-piece are shown in Table 1.

Table 1

The work-piece information table

Work-piece type	Quantity of work-piece n, piece	Unit weight of work-piece z_j, kg	Holding temperature T_j, °C	Holding time C_j, min	Work-piece type	Quantity of work-piece n, piece	Unit weight of work-piece z_j, kg	Holding temperature T_j, °C	Holding time C_j, min
J1	7	436	900-950	240-300	J10	19	198	800-850	180-300
J2	2	1180	1300-1350	300-420	J11	6	358	1250-1280	120-200
J3	5	704	1320-1400	280-400	J12	2	627	1320-1380	180-280
J4	14	247	880-940	150-250	J13	4	445	1200-1260	180-300
J5	4	689	950-1000	260-400	J14	10	239	1100-1180	150-270
J6	5	334	1130-1150	120-240	J15	8	482	1200-1280	180-300
J7	3	797	1250-1320	270-390	J16	19	858	1300-1380	300-420
J8	1	1246	1390-1450	320-480	J17	9	571	1250-1300	180-300
J9	12	514	1230-1300	200-280	J18	4	266	1150-1230	120-240

Table 2

A batch program using the traditional manual batching method

Batch number b	1	2	3	4	5	6	7	8	9	10	11	12
Work-piece type J1						7						
Work-piece type J2					2							
Work-piece type J3					5							
Work-piece type J4						14						
Work-piece type J5										4		
Work-piece type J6								5				
Work-piece type J7				3								
Work-piece type J8												1
Work-piece type J9	12											
Work-piece type J10									19			
Work-piece type J11							6					
Work-piece type J12											2	
Work-piece type J13	4											
Work-piece type J14								10				
Work-piece type J15							8					
Work-piece type J16		9	9		1							
Work-piece type J17				9								
Work-piece type J18								4				
Weight of batch s_b, kg	7948	7722	7722	7530	6738	6510	6004	5124	3762	2756	1254	1246
Holding temperature T_j, °C	1250	1300	1300	1250	1320	900	1250	1150	800	950	1320	1390
Holding time C_j, min	200	300	300	270	300	240	180	150	180	260	180	320

5.2. Traditional batching plan

Due to furnace batch weight constraint, temperature compatibility and time compatibility, it's very difficult in practice to use the traditional manual batching.

Table 2 gives a plan by the traditional manual management. Furnace batch quantity is 12. The average furnace loading amount is 5610 kg. The average holding temperature is 1182°C. The average holding time is 240 min.

5.3. Batching plan based on DSFLA

Assuming that the furnace batch quantity weight w_k, the average charging difference weight w_q, the average temperature w_T and the average weight of holding time w_C are 0.50, 0.25, 0.15 and 0.10, repeat the computation 50 times. The batch number in furnace obtained is 11. The average loading amount is 5847 kg. The average temperature is mainly 1163°C. The average holding time is mainly 240 min. Table 3 is a plan of 1170°C average heat preservation temperature and 240 min average holding time. Table 4 is a comparison of traditional manual batching plan and discrete shuffled frog leaping algorithm with furnace based on same furnace heating rules.

Table 3

Batching plan out by DSFLA based on same furnace heating rules

Batch number b	1	2	3	4	5	6	7	8	9	10	11
Work-piece type J1							7				
Work-piece type J2		1	1								
Work-piece type J3					5						
Work-piece type J4										14	
Work-piece type J5							4				
Work-piece type J6								5			
Work-piece type J7					3						
Work-piece type J8											1
Work-piece type J9	9			3							
Work-piece type J10									19		
Work-piece type J11				6							
Work-piece type J12					2						
Work-piece type J13	3			1							
Work-piece type J14								10			
Work-piece type J15	3			5							
Work-piece type J16		7	5			7					
Work-piece type J17		1	4	2		2					
Work-piece type J18	2							2			
Weight of batch s_b, kg	7939	7757	7754	7687	7165	7148	5808	4592	3762	3458	1246
Holding temperature T_j, °C	1230	1300	1300	1250	1320	1300	950	1150	800	880	1390
Holding time C_j, min	200	300	300	200	280	300	260	150	180	150	320

Table 4

Comparison of DSFLA batching and manual batching

Batching plan	Quantity of charging batches b	Average holding temperature T, °C	Average holding time C, min
DSFLA based on same furnace heating rules	11	1170	240
Traditional manual batching method	12	1182	240
Compare DSFLA to manual method	-1	-12	0

6. Conclusions

It can be known from Table 4 that using DSFLA based on the same furnace heating rules is superior to the traditional manual batching in furnace batch number, average loading amount and the average holding temperature. The average holding time of DSFLA is not lower than that of traditional manual batching plan. The energy consumption is related to furnace batch number, average loading amount, the average holding temperature and the average holding time. The influence of the first three indicators of energy-saving effect is more obvious. The traditional manual batching plan has many disadvantages such as difficulty in operation, low efficiency, less arbitrariness and inefficient energy consumption control.

The method proposed in this paper is better than the traditional manual batching in batch efficiency and the energy consumption control. Therefore, the established model with DSFLA solution was effective and better than traditional manual batching method regarding energy saving.

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STUDY ON THE CHARGING COMBINATION OPTIMIZATION FOR FORGING PRODUCTION BASED ON DISCRETE SHUFFLED FROG LEAPING ALGORITHM

S u m m a r y

As a traditional high energy-consuming industry, the forging industry consumes a lot of energy. In order to solve the typical charging optimization problem regarding how to separate work-pieces with different holding temperature intervals and holding time intervals and combine them for charging in forging, a charging combination model for forging is proposed. The discrete shuffled frog leaping algorithm (DSFLA) based on the same furnace heating rules is adopted to optimize and solve the model in order to reduce energy consumption in forging. An instance is illustrated to prove the effectiveness of the proposed model and the algorithm.

Keywords: forgings, combination optimization, shuffled frog leaping algorithm ,energy saving, discrete.

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