Research on multi-objective optimization and simulation to HFSSP hybrid flow-shop scheduling problem for energy saving

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Abstract. To the production scheduling optimization for high energy consumption process, making energy consumption as objective function is relatively less. Using the combinational optimization method of system modeling simulation and improved genetic algorithm, it studies the multi-objective optimization including the least energy cost and shortest maximal flow time to HFSSP(hybrid flow shop scheduling problem). Finally the application example is introduced to verify the feasibility of the method. The proposed method may provide guidance for the enterprise to save energy.

1. Introduction

Developing ultra supercritical units is the most realistic and the most effective way to solve the problems of the power shortage, low efficiency and serious environmental pollution. As key component of the power station equipment, ultra supercritical pressure rotor belonging to large axial forging has high performance requirements and many processes. The high pressure rotor of forming manufacturing includes smelting, casting, forging and heat treatment production [1]. During the process high energy consumption equipment such as the heating furnace is used many times and its energy consumption accounts for a large part of the whole production process, so the effect of saving energy and improving productivity of hot working process is ultimately reflected in the process of heating furnace process. In the modern heavy equipment enterprise, equipment is generally equipped with many sets simultaneously, it is necessary to solve how to reasonably assign each furnace equipment, meeting multi-objective such as the minimum energy consumption, which can be solved using the HFSSP method [2, 3]. HFSSP is usually optimization problem of more constraints, multi-objective, random uncertainty, so it is one of the most difficult combinatorial optimization problem. HFSSP includes many process stages, each stage having several parallel machines. At every stage each workpiece can be processed at a machine, at least one stage exiting many workpieces to be done. The process route of all the work is same, including several working procedure, at least one having parallel machines. As shown in Figure 1, there are n workpieces to process. Qj stands for the j working procedure (j=1,2,3,…,s),which has mj (mj≥1) parallel machines. When the j working procedure is being processed, any machine of the mj parallel machines can be used. The scheduling problem is to decide the assignment of the parallel machines and process sequence at the same machine[4].

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2. Literature review

With a variety of new related disciplines and optimization techniques, in the field of production scheduling, many new optimization methods appear, such as the neural network, simulated annealing method, genetic algorithm, tabu search method, which makes its research methods develop in the direction of diversification [5,6,7]. LIU Lin put forward a kind of mathematical model of the production scheduling problem to minimize the total setup time and designed an improved adaptive hybrid genetic algorithm for solving a "half flow shop" production scheduling problem which exists in the discrete manufacturing industry production line [8]. LEI Wang, etc. proposed an improved adaptive genetic algorithm based on hormone modulation to solve the workshop scheduling problem [9]. LIU Min proposed a variable neighborhood search algorithm based on the critical path, and the continuous PSO algorithm is applied to discrete permutation flow shop scheduling problem, to improve the local search ability of the algorithm [10]. Among the production scheduling problem at home and abroad, most of the research focuses on minimizing the makespan, minimizing delay penalty, maximizing profits, etc., which don’t pay more attention to the energy consumption and environmental protection, leading to the low energy efficiency and serious waste, causing a lot of pressure to the ecological environment, therefore, it is necessary to study the multi-objective scheduling methods and techniques considering the lowest energy consumption.

3. HFSSP mathematical model

3.1. Assumptions and parameters

To HFSSP, there are assumptions as follows: An artifact is an integral whole; One cannot be used twice in the same workpiece processing unit; Artifacts are independent each other, and there is no constraint between different workpiece process; Once process cannot be interrupted; The processing time of parallel machines and all kinds of energy consumption in each working procedure is known [11].

Parameters explanation:
- \( n \): processing work pieces;
- \( s \): the number of working procedure;
- \( \Psi \): collection for process, \( \Psi = \{1, 2, ..., s\} \);
- \( \Omega \): collection for machining, \( \Omega = \{1, 2, ..., \Omega\} \);
- \( M_j \): the number of parallel machines of process \( j \);
- \( N_{jk} \): the number of workpieces of process \( j \) at machining \( k \);
- \( T_{pijk} \): processing time of process \( j \) to the artifacts \( i \) at machine \( k \);
- \( T_{\sigma jik} \): beginning time of process \( j \) to the artifacts \( i \) at machine \( k \);
- \( T_{cijk} \): finishing time of process \( j \) to the artifacts \( i \) at machine \( k \);

![Figure 1. The schematic diagram of hybrid flow shop scheduling problem.](image-url)
Tc: delivery time (completion time);
a_{ijk}: 0, 1 integer variables, when the artifact i is arranged at machine k of the process j, a_{ijk} = 1; when the artifact i is not arranged at machine k of the process j, a_{ijk} = 1.

3.2. The constraint

The main constraints of HFFSP are as follows:

\[ \sum_{j=1}^{n_i} a_{ijk} = 1 \quad \forall j \in \Psi; \quad \forall i \in \{1, 2, \ldots, n_k\} \]  

(1)

\[ \sum_{k=1}^{r_j} n_{jk} = 1 \quad \forall j \in \Psi \]  

(2)

\[ T_{sjk} \leq T_{si(j+1)} \quad \forall j \in \Psi; \quad \forall k \in \{1, 2, \ldots, m_j\}; \quad \forall r \in \{1, 2, \ldots, m_{j+1}\} \]  

(3)

\[ T_{sjk} = T_{si} + T_{pijk} \quad \forall j \in \Psi; \quad \forall i \in \Omega; \quad \forall k \in \{1, 2, \ldots, m_j\}; \]  

(4)

\[ T_{sjk} \leq T_{s(i+1)jk} \quad \forall j \in \Psi \quad \forall i \in \{1, 2, \ldots, n_k-1\}; \quad \forall k \in \{1, 2, \ldots, m_j\} \]  

(5)

\[ \max(T_{cisk}) \leq T_{ci} \quad \forall i \in \{1, 2, \ldots, n_{sk}\}; \quad \forall k \in \{1, 2, \ldots, m_s\} \]  

(6)

Constraints (1) indicates each processes of artifact can only choose one machine for processing; Constraints (2) indicates the total number of the workpieces assigned to the machine is \( r_j \); Constraints (3) indicates the next processing can begin after the completion of the preceding process; Constraints (4) indicates the end time of the workpiece is influenced by its start processing time and processing time; Constraints (5) indicates only when the workpiece is finished at the machine, the next can start, that is, the start time of the next work must be greater than the end time of the being processed work; Constraints (6) indicates the total completion time is not later than the date of delivery \( T \) in the actual production process, for all of the workpiece must be finished in a certain time according to the requirements of the customers [12].

HFSSP must satisfy the above constraints for scheduling. In order to achieve optimal objective and any deviation from the constraints of scheduling is illegal and not feasible.

3.3. Objective function

Considering energy saving problem from the perspective of scheduling, to meet the multi-objective optimization such as minimum energy consumption and shortest maximum process time [13], the objective function is:

\[ \min f = \min(f_1, f_2) \]  

(7)

In the hybrid flow shop, energy consumption is mainly composed of the following aspects:

(1) ES, the energy consumption before the machine starts to process.

(2) Ep, the energy consumption of machining.

\[ E_p = \sum_{j=1}^{r_j} \sum_{k=1}^{m_j} \sum_{i=1}^{n_{jk}} a_{ijk} \times E_{ijk} \]  

(8)

(3) Ew, the energy consumption after a workpiece being finished, waiting for the next workpiece to reach.

(4) Ef, the energy consumption when the machine is shut down.

For the hybrid flow shop, the total energy consumed in the production is the sum of Es, Ep, Ew and Ef, namely E = Es + Ep + Ew + Ef, scheduling goal is: \( f_1 = \min (E) \).

To minimize the maximum the process time as scheduling index [14], the objective function is:

\[ f_2 = \min \{ \max(C_{isk}) \} \quad \forall i \in \{1, 2, \ldots, n_k\}; \quad \forall k \in \{1, 2, \ldots, m_s\} \]  

(9)

Using weight method, the type (7) can be transformed into:

\[ Z = \omega_1 f_1 + \omega_2 f_2 \]  

(10)
Based on energy consumption, under the constraints from (1) to (6), HFFSP is to arrange the artifacts to process on the machine, achieving the aim shown in (10). The mathematical model is a mixed integer nonlinear mathematical programming problem, solving is very complex. Especially when the number and equipment number and parallel machine number is larger, it is very difficult to solve using traditional mathematical methods. Improved genetic algorithm (IGA) is used because of its good performance to solve this problem.

4. Methodology of IGA
Genetic algorithm (GA) is heuristic algorithm appearing earlier, being one of the effective algorithms to solve combinatorial optimization problem which has been proved by a lot of application examples. Local search is often used to solve optimization problems, but if only using local search, the local optimal solution of the problem can be get. In the case of obtaining the global optimal solution the role of local search is limited. To solve the problem, IGA is used combining local search algorithm with GA [15].

4.1. Coding method
Chromosome coding matrix is as follows:

\[
A_{s \times n} = \begin{bmatrix}
a_{11} & \cdots & a_{1n} \\
\vdots & \ddots & \vdots \\
a_{s1} & \cdots & a_{sn}
\end{bmatrix}
\] (11)

Line represents process, column represents workpiece serial number. Chromosome gene \( a_{ij} (i = 1, 2, s; j = 1, 2, n) \) carries the information of the process \( i \) of workpiece that is processed on the machine. Usually \( a_{ij} \) is designed with the two parts of integer and decimal, integer part representing the machine serial number used by process \( i \), fractional part representing the priority of artifacts, the greater the decimal part the higher priority, the earlier processed on the machine. According to the above coding method, chromosome is designed, a matrix corresponding to a chromosome coding, it corresponding to a scheduling scheme. A chromosome is made up of \( s \) small segments, each row of the coding matrix being a small section, with \( \eta \) between segments, each small section containing \( n \) genes. Chromosome can be expressed as \([a_{11}, a_{12}, \ldots, a_{1n}, \eta, a_{21}, a_{22}, \ldots, a_{2n}, \eta, \ldots, a_{s1}, a_{s2}, \ldots, a_{sn}]\).

4.2. Fitness function
The coding matrix is constituted of real numbers \((j=1, 2, \ldots, m)\) generated from the interval \([1, M_j+1]\) randomly, thus constituting the initial population of chromosomes. Fitness function is defined as formulation 12.

\[
F(i)_{fitness} = 2 - R_{\max} + 2 \times (R_{\max} - 1) \frac{x_i - 1}{N - 1}
\] (12)

\( F(i)_{fitness} \) — fitness of the ith individual;
\( R_{\max} \) — Selection pressures, a real number from interval \((1, 2]\);
\( x_i \) — Position of target value to the ith individual(The position of the maximum target value is 1; The position of the minimum target value is \( N \)).

4.3. Local search
Setting a fixed crossover probability \( P_c \) and variation probability \( p_m \), crossover and mutation operation can be carried out. After crossover and mutation, the new individual is obtained. The new individual and the old individual before crossover and mutation constitute the neighborhood space for local search. Mountain climbing is carried out in this space to obtain highly adaptable individuals and replace the original individuals to form a new population.
5. Simulation optimization

5.1. Simulation modeling

Taking rotor production of a heavy equipment manufacturing enterprise for example, production and energy coupling modeling and simulation optimization system is developed, to realize the production and energy coupling visual modeling. Using the discrete event simulation technology of the three sections of scanning method, simulation of the system mode is realized. As shown in Figure 2, to get the performance parameters of the system in the manufacturing process, optimization work is carried out using the IGA by reading the related model information as input parameter, getting the processing scheme of minimum energy consumption.

![Figure 2. The simulation operation of the system model.](image)

5.2. Simulation realizing and result analyzing

During the optimization work, equipment processing strategies don’t need to set by the user, because optimization algorithm can automatically search the optimal strategy of production line with the lowest energy consumption and automatically set the back device of production model after the optimization work. In the window of optimization parameter setting, IGA such as genetic iterative algebra and population size can be set, which can affect the final optimization result.

By selecting a single chromosome in the initial population, the comparison of the optimal chromosome and initial chromosomes can be achieved, getting the optimal scheduling results compared with result of general schedule information, such as changes of the start time and end time of each order before optimization and after optimization, the total time of the order and the total energy consumption in production.
It is assumed that there are 8 artifacts to process, consisting of 3 procedures in each process. The corresponding number of parallel machines in each process is 2, 3, and 2 respectively. The population size is 30. The evolutionary generation number is 160, and the generation gap is 0.9. The cross probability is 0.6. The mutation probability is 0.01. Using genetic toolbox based on MATLAB, simulation was realized. The simulation result can be got as Figure 3. The traditional genetic algorithm does not converge to the global optimal solution, and premature convergence was born. IGA overcomes premature convergence and converges to the global optimal solution quickly. The energy consumption is decreased after optimization.

6. Conclusions
Aiming at energy saving, hybrid flow shop scheduling problem is a kind of important production scheduling. In this paper, according to the characteristics of the ultra supercritical pressure rotor production HFSSP mathematical model is established to realize the lowest energy consumption. Based on the model, in view of the premature convergence problem of GA and slow convergence speed, IGA is used combined GA with local search algorithm, thereby solving HFSSP effectively and quickly. The proposed scheduling method is better than the current artificial scheduling method used in practical production, which has important practical significance for saving energy and reducing consumption to the rotor production.

In the next work, the improved optimization algorithm and more actual data should be used to verify the validity and feasibility of the proposed method.

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