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Optimization of Steelmaking Energy Efficiency Scheduling Based on an Equipment Set Shutdown Strategy

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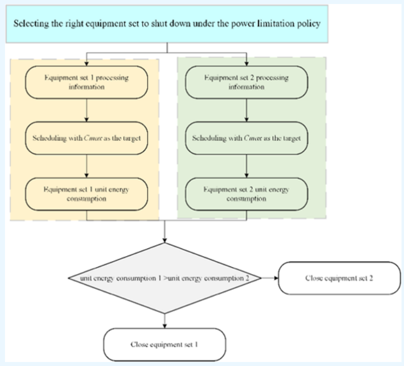
ABSTRACT: The steel industry accounts for a large proportion of power consumption in industries. To greatly reduce the power consumption of production, it is urgent to adjust and optimize the steelmaking production mode. The paper combines production scheduling with equipment energy efficiency indicators, establishing an optimization model for steelmaking energy efficiency scheduling and determining the shutdown strategy of steelmaking equipment sets. Taking two equipment sets of a company processing the same batch of steel as an example, this paper calculates that the unit energy consumption under the optimal scheduling scheme is 79.492 and 22.056 kWh, respectively. The energy consumption of the former to complete the production task is greater than that of the latter. Therefore, by choosing to shut down this equipment set, a total of 65 038.2 kWh of electricity can be saved. Industrial examples were executed to validate the effectiveness of the model, and the results showed that the proposed method can obtain optimal solutions in a short period of time and significantly reduce energy consumption in the workshop. This study first combines scheduling issues with equipment energy efficiency indicators to provide a basis for energy consumption decisions.



1. INTRODUCTION

In recent years, the steel industry has maintained rapid development, and the steel industry has rapidly expanded its production capacity by building multiple sets of process production systems. The rapid economic growth has led to an increase in the power load, and the power grid is facing huge power supply pressure.[1] More and more regions have begun to issue corresponding power curtailment policies, which is undoubtedly a huge challenge for steel companies with huge power consumption.[2] Under the power curtailment policies, production scheduling alone is not enough to greatly reduce power consumption. If some equipment is not shut down, it will greatly affect the production plan of the enterprise and cause planning disorder. Therefore, in order not to affect the production plan, in the case of excess steel production capacity, it is necessary to adopt a strategy of permanently shutting down some redundant equipment sets, which has great practical significance for the steel industry.

The energy consumed by the steel industry occupies a large proportion of energy in the manufacturing industry.[3] How to reduce the energy consumption in production operations has become an urgent problem to be solved. To formulate a reasonable energy efficiency scheduling strategy is of great significance to improve the operation efficiency of the entire workshop and reduce energy consumption. The iron and steel scheduling problem belongs to a hybrid workshop flow (HFS) problem with special constraints, and the research on this problem is of great significance for reducing the energy consumption of the hybrid workshop.[4]

The steel plant scheduling problem is usually regarded as a mixed flow shop scheduling problem with NP-hard characteristics.[5,6] There are multiple parallel processing machines in each processing stage. Many scholars at home and abroad are studying steel production scheduling problems; many solutions are proposed, which have great reference significance in increasing steel production and improving efficiency upstream. A method to quantitatively describe the matching relationship between processing equipment in real production by using the processing weight assignment method of task executable equipment in the production scheduling plan of steelmaking and continuous casting was proposed.[7] An improved migrating birds optimization (IMBO) algorithm to tackle the considered NP-hard problem was proposed.[8] A new nondominated sorting genetic algorithm with an elite strategy (NSGA2)-based production scheduling method for complex steelmaking and continuous casting production process which consisted of multiple refining ways was presented.[9] An effective fruit fly

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optimization algorithm (FOA) to solve the steelmaking casting problem was studied.[10] A general model for the problem of planning and scheduling steelmaking and casting activities obtained by combining common features and constraints of the operations from a real plant and the literature was proposed.[11] A practical steelmaking scheduling problem with batching decisions and energy constraints was studied.[12] Pan et al.[13] proposed an effective artificial bee colony (ABC) algorithm with the job-permutation-based representation for solving the scheduling problem.

Above all, most researchers choose heuristic algorithms as the primary weapon for solving steel scheduling problems.[14,15] In fact, heuristic algorithms not only have excellent performance in steel scheduling but also have been widely applied in oil transportation and refinery scheduling.[16,17] Refinery scheduling also has the characteristics of discrete and continuous processing,[18] and its method can be applied to steel scheduling. Panda and Ramteke[19] proposed a structure-adapted genetic algorithm to prevent crude oil scheduling under demand uncertainty. Pereira[20] proposed a new algorithm that integrates linear and grammar-guided genetic programming concepts with a quantum-inspired approach to create programs that represent a crude oil refinery scheduling solution. Hou et al.[21] solved the problem of processing both low-fusion-point oil (L-oil) and high-fusion-point oil (H-oil) with an adaptive enhanced selection pressure algorithm. Abdellaoui et al.[22] proposed a mixed integer linear programming (MILP) model to satisfy the demands of different distribution centers in oil transportation.

In the actual production process of steelmaking, a large amount of electric power will be consumed, under which steelmaking plants can exchange not only materials but also fuel with other industries to increase energy efficiency.[23] How to reduce the electric power consumption by a large amount in the current situation of an energy shortage has become the focus of current research. Therefore, many scholars have focused on energy consumption and made a lot of research, which provides a theoretical reference for this paper. Scheduling models based on resource-task network (RTN) formulations that incorporate the EAFs' flexibilities to reduce the electricity cost was proposed.[24] An improved multiobjective evolutionary algorithm based on decomposition (IMOEA/D) was proposed.[25] A scheduling solution for electrical load tracking of a steel plant was presented.[3] A new mathematical programming model for the scheduling of the iron and steel scrap steelmaking and continuous casting (ISSSC) that considers energy consumption with time-of-use electricity price and associated carbon emissions in addition to production performance indexes was presented.[26] A scheduling problem to minimize the idle energy consumption of machines was investigated.[27] An integrated scheduling problem from an iron−steel plant equipped with self-generation equipment under time-of-use electricity tariffs was addressed.[28] A scheduling problem of steel plant with strength pareto evolutionary algorithm algorithm (SPEA2) was addressed.[29] A two-stage online scheduling policy that protects the baseline schedule by the slacks provided by intraflow times and casting speeds equipped with self-generation under real-time electricity prices was presented.[30]

To the best of our knowledge, there is no relevant research that combines the optimization problem of hybrid workshop scheduling with the evaluation of equipment set energy consumption indicators at present. Most strategies to reduce energy consumption are to take workshop energy consumption as one of the optimization objectives and schedule the entire workshop. However, this method has certain limitations and cannot greatly reduce workshop energy consumption. In the face of energy scarcity, many countries have introduced a series of policies to limit energy consumption for large electricity consuming enterprises.[31] If the electricity consumption exceeds the specified limit for 1 day, the enterprise will face a cessation of production. Therefore, it is necessary to adjust the production mode of the enterprise and shut down a certain set of equipment to reduce the electricity consumption. The energy consumption and production status are affected by the smelting process and production rhythm. Motivated by these gaps in reviewed literature and power curtailment policy, this paper combines the scheduling method of equipment sets with energy efficiency indicators and is committed to researching scientific equipment set shutdown methods.

It is significant to combine the optimization problem of steelmaking production scheduling with the strategy of equipment set shutdown, which can effectively reduce the energy consumption of production workshops. The main contributions of this article are as follows:

(1) To comply with the power curtailment policy, the unit energy consumption evaluation index of the equipment set is added to the model. And the processing energy consumption and idle energy consumption of different processing production stages are considered.
(2) A mathematical model of steelmaking energy efficiency scheduling optimization is established, and the genetic algorithm of segmented combined coding is used to solve the problem.
(3) Based on the production example of a steel plant, the effectiveness of the proposed method is verified, providing scientific decision-making basis for managers on how to close the equipment set.

2. DESCRIPTION OF THE SHUTDOWN OF STEELMAKING EQUIPMENT

Steelmaking plants can be divided into long-process steelmaking and short-process steelmaking according to different smelting technologies. Long-process steelmaking is the main production mode of steel plants now.[32] Therefore, this paper takes long-process steelmaking as the research object. The main process flow of long-process steelmaking is steelmaking-refining-continuous casting, and each production stage has a corresponding number of parallel converters, refining furnaces (ladle furnace/RH refining), and continuous casting machines. The specific steelmaking process is that the converter smelts the molten iron produced by the blast furnace and the smelting process is usually accompanied by redox reactions, such as desulfurization and dephosphorization. After the specified metal element concentration and temperature requirements are reached, the molten steel is transported to the specified area for refining, and specific elements are added to the steel products with special requirements. In the continuous casting stage, the molten steel that meets the composition requirements of the steel product is injected into the tundish of the continuous casting machine, and after being condensed by the mold, it is pulled out by the dummy bar to form steel products, such as billets. The molten steel produced in the converter smelting process is called charge, which is the smallest unit in the processing and production process.[33] The entire steelmaking process produces a large amount of electrical energy loss. In order to reduce energy consumption, a reasonable production

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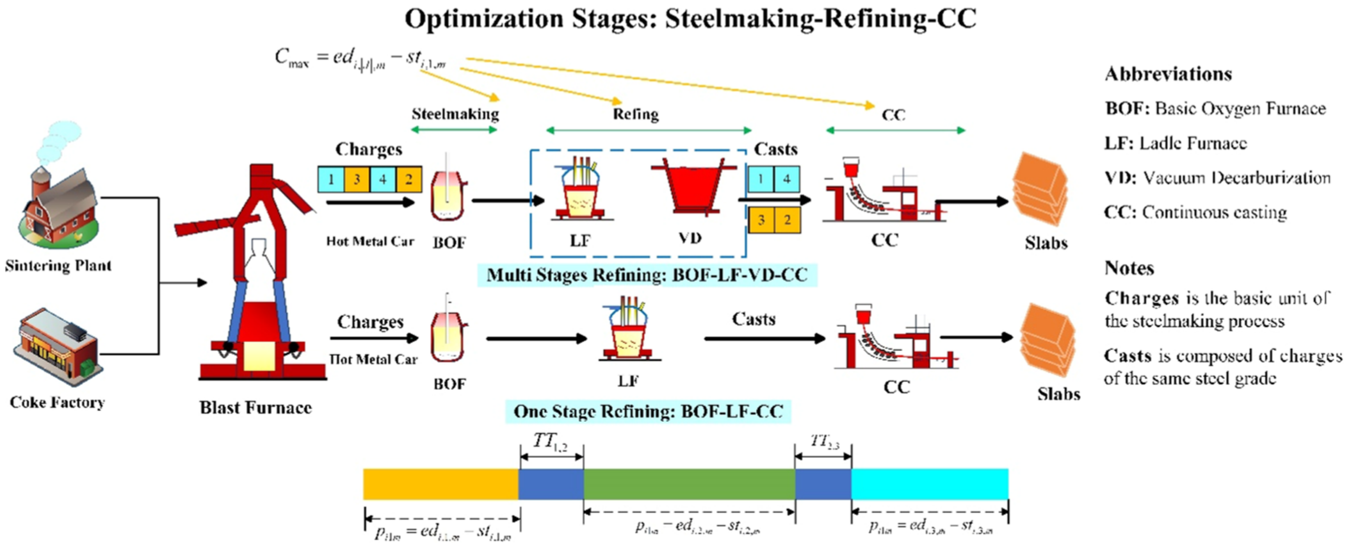

Figure 1. Process of steel production.

plan needs to be arranged. The production process of the steelmaking plant is shown in Figure 1.

The steel industry consumes a lot of energy, which includes the consumption of materials as well as the consumption of fuel exchange with other industries. To respond to the power curtailment policy promulgated and effectively reduce the power consumption of enterprises, it is necessary to adjust the production capacity structure and production mode. In the case of a large degree of power curtailment, all of the equipment sets used for processing and production cannot be put into use, and simple energy consumption scheduling cannot completely solve the problem of power curtailment. A strategy of shutting down less energy-efficient equipment sets when production demands arise. Steel scheduling is based on charge as the basic processing unit, several charges as one pour, and there are several parallel production machines in the steelmaking, refining, and continuous casting production stages. At most, one machine is selected for processing in each stage of each charge, and the pouring schedule has been determined in advance before production. Considering the actual production conditions, the optimization goal is to take the maximum completion time of all processes for each charge as the optimization goal. When the waiting time for a charge is too long, the temperature in the heat will decrease, and the process requirements cannot be met, so the transport time and other constraints should be considered. In the continuous casting stage, the replacement time of the tundish between different pours must be considered.[34] After scheduling the production plan, it is necessary to calculate the energy consumption evaluation index of the equipment set and select the appropriate equipment set to close.

The steelmaking scheduling problem is modeled with the furnace of the steelmaking plant as the research object. This problem has the characteristics of both discrete and continuous production processes and belongs to the mixed-flow workshop problem. Different machines can be selected for processing in each stage of steel production, and the overall processing sequence has been determined.[35] At the same time, the casting plan is finalized before production. In order to better describe the actual production situation of steelmaking and achieve the purpose of greatly reducing the power consumption of the steelmaking plant, this paper adopts the mixed integer programming model to model the production situation from the steelmaking to the continuous casting process to arrange the production plan of the workshop. The unit energy consumption index of each equipment set is introduced to evaluate each equipment set.

3. STEELMAKING ENERGY EFFICIENCY SCHEDULING OPTIMIZATION MODEL BASED ON THE EQUIPMENT SET SHUTDOWN STRATEGY

3.1. Steelmaking Energy Efficiency Scheduling Optimization Model. In order to measure the energy consumption index of each equipment set, the electric energy consumption value per unit time of processing the same steel grade is adopted as the evaluation index and comprehensively considers the energy consumption in idle time and the energy consumption in the processing process. Combined with energy efficiency indicators, a steelmaking energy efficiency scheduling model based on the equipment set shutdown strategy is established, and on the basis of optimal scheduling, the equipment set shutdown strategy is determined. The strategy of equipment set shutdown is shown in Figure 2.

The assumptions of the optimization model of steelmaking energy efficiency scheduling based on the equipment set shutdown strategy are as follows: (1) One machine can only process one charge at the same time, and one charge can be processed by at most one machine at the same time; (2) since the steelmaking process is carried out in a high temperature environment, there is a maximum temperature limit for the waiting processing time of the charge, which is mainly affected by the waiting time; (3) the set of charges in the same cast time is selected to be processed on one machine; (4) each charge is processed according to the technological process, and the transportation time must be considered in the middle; (5) consider the replacement time of tundish for different equipment; (6) the pouring sequence of the charges in the same pouring time is not allowed to be changed, and the cast sequence of the charges is determined in advance; and (7) the influence of other factors on the energy consumption of equipment set is not considered.

3.2. Establishment of Steelmaking Energy Efficiency Scheduling Model. The steel plant scheduling model is a special kind of hybrid flow shop scheduling problem, in which

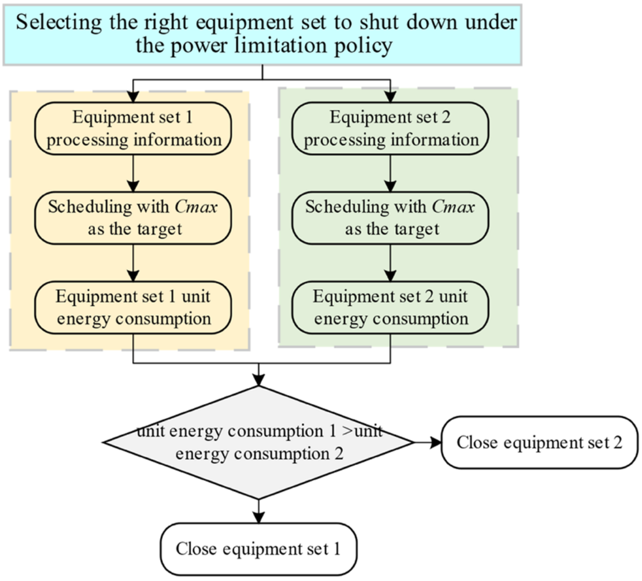

Figure 2. Flowchart of the equipment set shutdown strategy.

the optimization objective is to minimize the maximum completion time of a certain pouring schedule, and the unit energy consumption of the scheduling scheme is solved under this objective as the basis for decision making.

In terms of processing time constraints, to make the maximum completion time of the process as small as possible, the objective function is expressed in eq 1

$$\min f_1 = C_{\max} = ed_{i,|J|,m} - st_{i,1,m} \tag{1}$$

The constraints are as follows:

(1) Equation 2 indicates that one machine can be selected for a certain charge in a certain stage for processing at most due to the limitation of the processing technology.

$$\sum_{m \in M_s} x_{ism} \le 1, \forall i \in I, s \in S \tag{2}$$

where $x_{ism} = 1$ indicates that charge i selects the m_{th} machine for processing on stage s; otherwise, the value is 0.

(2) At the same time in a certain production stage, one machine can process one charge at most at the same time, as expressed in eq 3.

$$\sum_{i \in I} x_{ism} \le 1, \forall s \in S, m \in M_s \tag{3}$$

(3) The maximum waiting time constraint for each charge when the equipment starts processing is expressed in eq 4.

$$WT_i^{s,s+1} \le WT\max_i^{s,s+1}, \forall s = 1, 2, ..., S - 1 \tag{4}$$

In the equation, $WT_i^{s,s+1} = st_{i,s+1,m} - ed_{i,s,m} - TT_{s,s+1}$.

(4) Equation 5 indicates that a charge can only be transported to the next stage after the previous stage is processed.

$$st_{i,s+1,m} - ed_{i,s,m} \ge TT_{s,s+1} \forall i \in I, s = 1, 2, ..., S - 1 \tag{5}$$

(5) Equation 6 presents that the continuous casting machine needs a certain preparation time between adjacent cast times.

$$ed_{H_j^l} + rt \le st_{H_{j+1}^1}, \forall j \in J \tag{6}$$

(6) At the same stage, the processing sequence of the charges in a certain cast on the machine is predetermined, and the constraint is shown in eq 7.

$$x_{ism} = 1, \forall i \in I, \forall m \in M_s \tag{7}$$

(7) In order to change the tundish frequently, the charges on the same cast must be cast continuously, as expressed in eq 8.

$$st_{i+1,s,m} = ed_{i,s,m}, \forall i, i + 1 \in H_s \tag{8}$$

(8) The earliest available time constraint of the equipment is shown in eq 9.

$$st_{i,s,m} - U(1 - x_{ism}) \ge MT_m, \forall m \in M_s \tag{9}$$

(9) The processing time constraint of the process on the equipment is indicated in eq 10.

$$PT_{i,s}^{\min} \le ed_{i,s,m} - st_{i.s,m} \le PT_{i,s}^{\max}, \forall i \in I \tag{10}$$

(10) Equation 11 expresses the transit time constraint between adjacent devices.

$$TT_{s,s+1}^{\min} \le TT_{s,s+1} \le TT_{s,s+1}^{\max}, \forall s \in S \tag{11}$$

(11) Decision variable constraints are shown in eqs 12–14.

$$x_{ism} \in \{0, 1\}, \forall i \in I, \forall s \in S, \forall m \in M_s \tag{12}$$

$$st_{i,s,m} \ge 0, \forall i \in I, \forall s \in S, \forall m \in M_s \tag{13}$$

$$ed_{i,s,m} \ge 0, \forall i \in I, \forall s \in S, \forall m \in M_s \tag{14}$$

After scheduling with the objective of maximum completion time, we generated the scheduling plan with the shortest completion time. This paper calculates the unit energy consumption of each equipment set under this scheme and uses it as an evaluation indicator.

In the construction of the model, this paper assumes that no energy loss occurs when the electric energy is used for processing and production; that is, the electric energy used by the electric furnace for processing and production is all the electric energy actually consumed by the steelmaking plant, and the value is less than the theoretical value in the actual production process.

Equation 15 expresses that energy consumption E for completing the processing of a batch of steel products is divided into the electric energy consumption E^{process} for processing and production and the no-load energy consumption E^{idle} of the machine.

$$E = \sum_{s \in S} (E^{\text{process}} + E^{\text{idle}}) \tag{15}$$

The calculation equation of electric energy consumption for processing and production is shown in eq 16.

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$$E^{\text{process}} = \sum_{i \in I} p_{ism} q_{sm}, \forall\ m \in M_s, \forall\ s \in S \tag{16}$$

Equation 17 expresses the lost energy calculation IEC.

$$E^{\text{idle}} = q_{sm}^{\text{idle}}(it_{i,i+1}) \tag{17}$$

The equation for the electric energy E consumed in the process of processing and production is shown in eq 18.

$$E = \sum_{i \in I} \sum_{s \in S} \sum_{m \in M} (p_{ism} q_{sm} + q_{sm}^{idle}(it_{i,i+1})) \tag{18}$$

where p_{ism} indicates the actual processing time of the charge on the m_{th} machine in the s stage, where $p_{ism} = ed_{i,s,m} - st_{i,s,m}$; q_{sm} is the working power on the m_{th} machine in the s stage; q_{sm}^{idle} represents the idle power on the m_{th} machine in the s stage; $it_{i,i+1,m}$ is the idle time of two adjacent charges on machine m, where $it_{i,i+1} = st_{i+1,s,m} - ed_{i,s,m}$. The target is not included in the process of crossover and mutation of the algorithm.

Because the unit power consumption of each production line is to be measured, the ultimate decision goal of this work is expressed in eq 19.

$$F = E/C_{\max} \tag{19}$$

The smaller the evaluation index, F, the higher the energy efficiency index of the equipment, and vice versa. Low-energy-efficient equipment sets are prone to generating more energy consumption when processing the same steel grade. Therefore, in order to achieve energy-saving purposes, the lower energy-efficient equipment set is turned off, and higher energy-efficient equipment is saved.

In addition to the above methods for evaluating the energy efficiency of equipment sets, this paper also considers another method for evaluating the energy efficiency of equipment sets. The energy consumption of equipment is optimized,[36] that is, the ratio of processing energy consumption used for production to total energy consumption in the production of the same batch of steel grade, as an evaluation indicator of energy efficiency. Considering this objective, a biobjective optimization model can be established.

$$\min f_2 = E^{\text{process}}/E \tag{20}$$

Equation 20 indicates that the larger the objective function value, the more useful work the equipment set does and the better the energy efficiency indicators and the easier it is to save. In the actual production process, enterprises tend to shorten the processing time of idle machines to improve production efficiency, which also means reducing the useless work of the equipment set, consistent with the objective proposed in this paper.

4. MODEL SOLVING METHODS

4.1. Model Solving Algorithm Process. The energy efficiency scheduling model of the equipment set shutdown strategy is solved by an improved genetic algorithm. The algorithm has a fast convergence speed and can search for the optimal solution faster, and then, the model is solved by a piecewise combined coding. The whole problem-solving process is shown in Figure 3. First, the information on processing and production and the basic parameters of the algorithm, such as crossover probability, mutation probability population size, etc., were input to generate the algorithm iterator. Then, a piecewise combinatorial coding was used to generate feasible solutions. In the decoding stage of the algorithm, the reverse order method is used to eliminate the time conflict in the casting stage, and the fitness of each chromosome is calculated. At this stage, the working energy consumption and idle energy consumption of each chromosome are generated, and then, operations such as crossover and mutation are performed to generate a scheduling scheme with the smallest processing time. Then, under this scheme, the optimal energy consumption of each individual is used as the evaluation index and the equipment set with higher energy consumption is selected to be shut down.

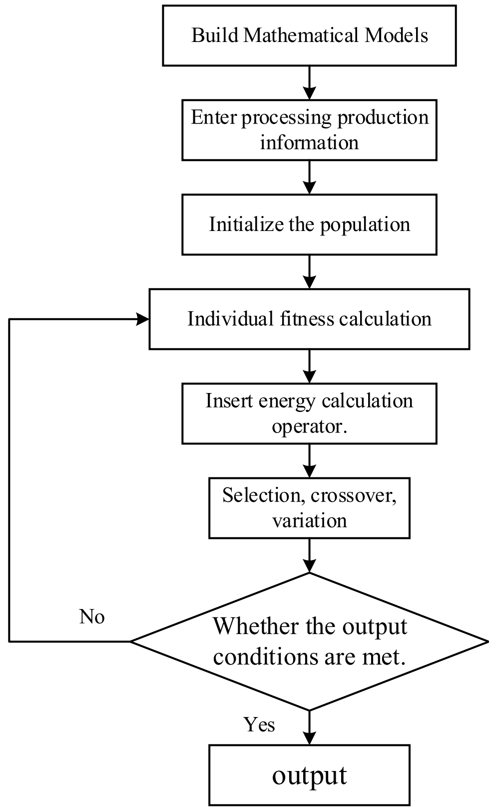

Figure 3. Flowchart of the shutdown strategy of the steel plant equipment set.

4.2. Improved Genetic Algorithm to Solve the Energy Efficiency Scheduling Model. *4.2.1. Encoding.* The first part of this article is the workpiece-based segmented combined coding method (JRBA). The first half represents all of the processing procedures of the charge, and the second half represents the processing machine selected for each charge. For example, ([2,1,3,1,2,3,3,1,2][1,2,2,3,3,4,5,5,5]) means that the processing procedure is three times in three charges and the processing sequence of three stages; the first half is the processing sequence of three charges, and the second half represents the processing machines used for different processes of charges 1, 2, and 3, such as the processing in the refining stage of charges 1, 2, and 3 machines. In addition, the processing sequence of the casting process has been known in advance, so the machine selection of the last process is determined in advance and the machine of this part is unique. The entire encoding process is present in Figure 4.

4.2.2. Decoding. In the decoding stage, the corresponding process is first converted into charge number, and the corresponding process, such as [2,1,3,1,2,3,3,1,2], is converted into [201,101,301,102,202,302,303,103,203]. Then, according to the corresponding process number, the corresponding

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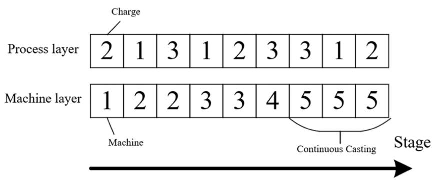

Figure 4. JRBA chromosome coding.

processing machine is randomly generated from the optional machines generated in the other stages, except for the continuous casting stage.

For the time conflict in the continuous casting stage, this paper adopts the method of reverse order to eliminate. First, the discontinuous continuous casting process is generated first, and then, this method is used to eliminate and generate the same continuous casting process as the casting plan.

4.2.3. Fitness Calculation. In the calculation of individual fitness, the reciprocal of the time from steelmaking to the completion of all charge processing is used as the fitness of each individual. Obviously, the shorter the completion time, the greater the fitness of the individual, the greater the probability of being selected, and the easier it is to be preserved and inherited by the next generation.

In the process of individual fitness calculation, this paper introduces the energy consumption calculation operator, which is not considered in the calculation process of the objective function. The energy consumption of each individual includes equipment processing energy consumption and equipment idle energy consumption. Combined with the individual optimization objective, the total energy consumption of each individual is divided by the current individual optimization time as the equipment set energy consumption evaluation index. In the case of processing the same steel grade, the smaller the effective energy consumption per unit time of each equipment set, the higher the power utilization rate of the equipment set. On the contrary, the lower the power utilization rate, the strategy of shutting down the equipment set is adopted.

4.2.4. Operations Such as Selection, Crossover, Mutation. To preserve individuals who have better fitness, the roulette method is adopted to select individuals with better fitness, and individuals with greater fitness are easier to be preserved. The corresponding probability of survival is presented in eq 21.

$$pi(i) = \text{Fitness}(i)/\sum_{i-1}^{n} \text{Fitness}(i)$$

$$\text{Fitness}(i) = 1/\text{Fitness}(i) \tag{21}$$

The crossover operation uses the integer crossover method. First, two individuals are randomly selected, and the crossover position of each individual is randomly generated. First, the first half of the process code is crossed, and then, the machine code of the corresponding position is adjusted. If it is missing, then the redundant process of another individual to the corresponding position is exchanged. In order to generate individuals with as large fitness as possible without destroying the population, the mutation probability is set to 0.01. The mutation operation is similar to the crossover operation. The paper uses the integer mutation method; the operation code is mutated first, and then, the machine code is adjusted with the operation.

4.2.5. Calculation of Evaluation Index of Equipment Set. Two sets of optimal scheduling schemes for equipment sets are generated, respectively, and then, the unit energy consumption under each scheme is calculated. The shutdown strategy is adopted for machines with a higher unit energy consumption that processes the same steel grades.

5. APPLICATION EXAMPLES AND RESULT ANALYSIS

5.1. Case Study. An example of production scheduling planning of a steelmaking plant is used to verify the model and evaluate the application instance. The steelmaking plant mainly has three main production processes: converter steelmaking, LF refining, and continuous casting. Some of the equipment set processing does not include the refining process. The production flow diagram of the steelmaking process is shown in Figure 5. In the picture, CC represents a continuous machine.

The plant mainly includes two sets of equipment; the first set of equipment includes two refining furnaces, two LF refining furnaces, and two continuous casting machines. The second set of equipment mainly includes two main production processes: converter steelmaking and continuous casting. Each production stage has processing machines of the same specifications, and the processing machines of different equipment sets are different in models. The simulation experiment is carried out according to a certain pouring time plan in real production. The prepared pouring time plan is shown in Tables 1 and 2. The parameters of

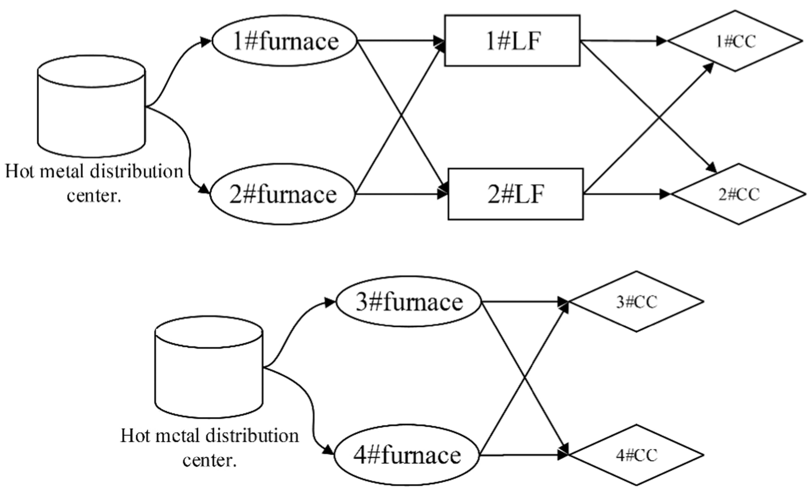

Figure 5. Steelmaking process of equipment set 1 and equipment set 2.

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Table 1. Pouring schedule of Equipment Set 1

cast number	number of charges in the cast	steel grade	routing	continuous cast
1	15	A	BOF-LF-CC	1#
2	8	B	BOF-CC	2#
3	6	C	BOF-LF-CC	2#

Table 2. Pouring schedule of Equipment Set 2

cast number	number of charges in the cast	steel grade	routing	continuous cast
1	8	A	BOF-CC	3#
2	8	B	BOF-CC	4#
3	6	C	BOF--CC	4#

the genetic algorithm are set as population size 40, number of iterations 200, crossover probability Pc = 0.7, mutation probability Pm = 0.1, the steel plant shutdown strategy based on the improved genetic algorithm proposed in this paper is implemented in MATLAB R2021a and is processed in MATLAB R2021a. It runs on a computer with an i5-8300H and 8GB memory. The specific running results are shown in Figures 6 and 7.

The pouring schedule selected for the first equipment set has a total of 29 charges, with a total of three production stages of steelmaking, LF refining, and continuous casting, and each stage has a total of two optional machines. The pouring schedule of equipment set 1 is shown in Table 1.

Scheduling diagram generated by equipment set 1 is as follows.

Different colors in the figure represent different pouring times, and the number represents the heat number of the pouring time obtained by the algorithm. The final solution time is 818.17 min; the energy consumption is 65038.26 kWh. The energy consumption per minute of the obtained equipment set is 79.4924 kWh.

The selected casting schedule for the second equipment set has a total of 22 charges, with a total of two production stages, steelmaking and continuous casting, with a total of two machines available for each stage. The pouring schedule of equipment set 1 is shown in Table 2.

Scheduling diagram generated by equipment set 2 is as follows.

The final solution time is 683.575 min, and the final energy consumption is 5083.41 kWh. The obtained energy consumption per minute of the production line is 22.0568 kWh. Therefore, the 1# furnace, 2# furnace, 1#LF, 2#LF, 1#CC, and 2#CC of the machines in the first equipment set are closed to achieve the purpose of reducing energy consumption.

5.2. Effectiveness Analysis of the Proposed Method.

To further verify the effectiveness of the proposed method, this paper selected three groups of sample data of the steelmaking and continuous casting batch production plan composed of different casting scales of the steelmaking plant. Each group of sample data contains information such as the type of steel to be cast in the current batch plan, the number of casting times of different steel grades, and the number of charges of this steel grade, as shown in Table 3.

Each sample data contains three different steel grades. The processing times of different steel grades in each stage vary within the same range. The basic parameters of the experimental data are shown in Table 4.

With the same settings of all parameters, the improved genetic algorithm is used to carry out simulation experiments on the above three groups of data, which are run independently for 15 times, and the average value of the objective function is taken. The experimental results of the operation are shown in Table 5, where TE represents the total energy consumption of the

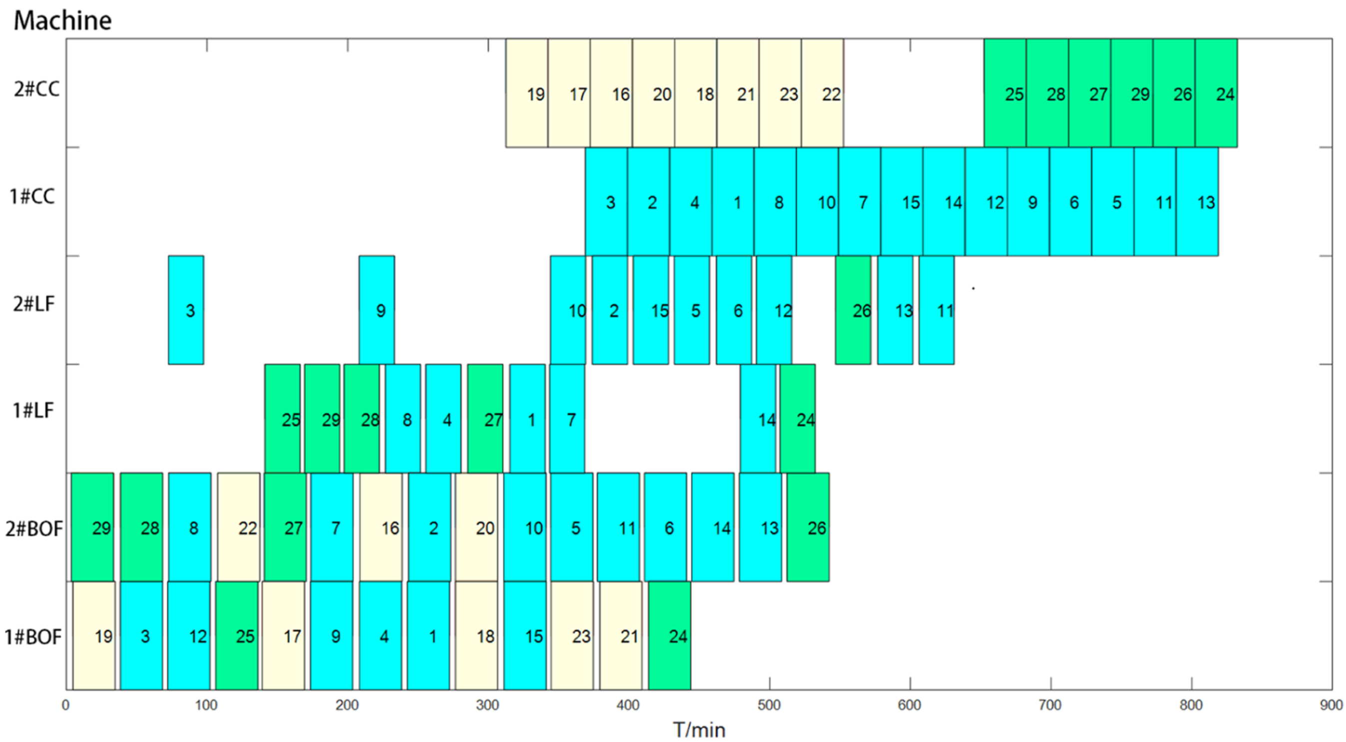

Figure 6. Scheduling diagram of the optimal solution for equipment set 1.

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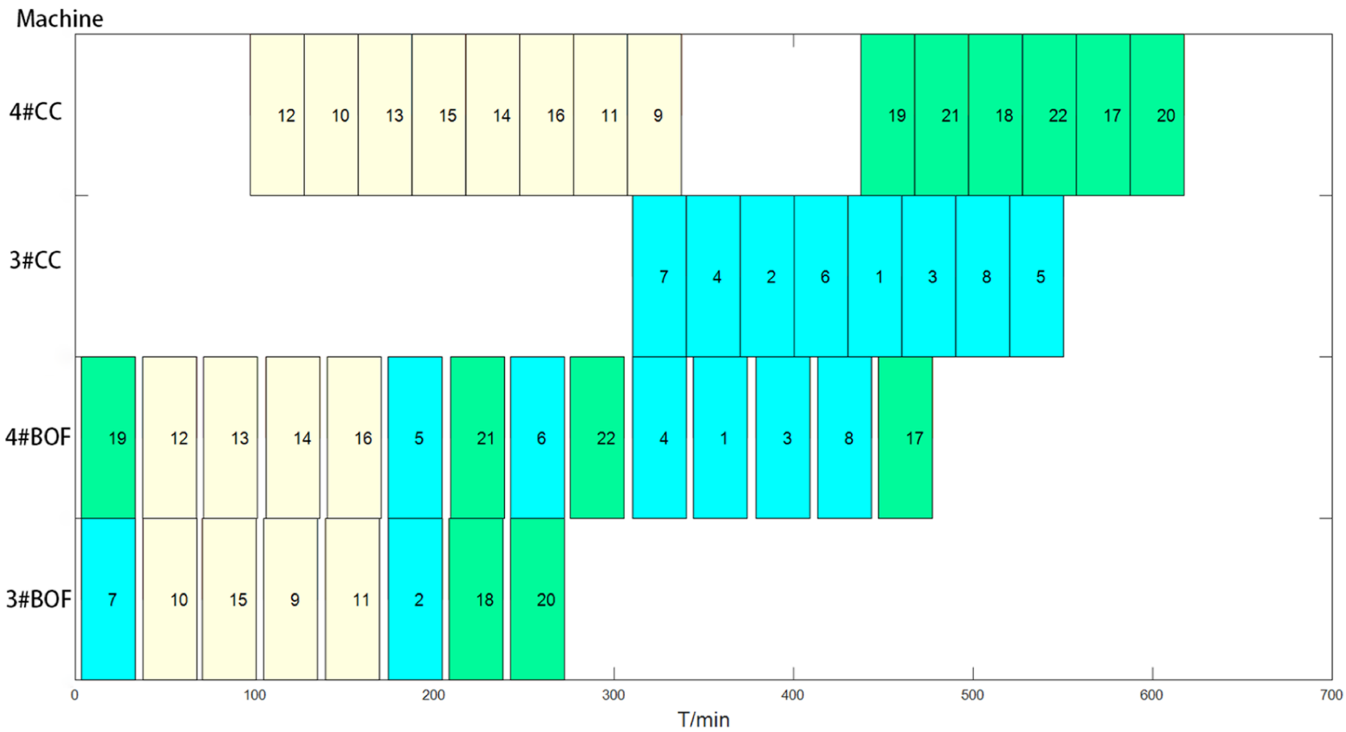

Figure 7. Scheduling diagram of the best solution for equipment set 2.

Table 3. Data of Instance

instance		instance 1	instance 2	instance 3
number of casts	equipment set 1	3	3	3
	equipment set 2	3	3	3
number of charges	equipment set 1	28	49	55
	equipment set 2	20	49	60

Table 4. Instance Parameters

parameters	value
processing time at the steelmaking stage	[27,35]
processing time at the refining stage	[20,30]
processing time at the continuous casting stage	[27,35]
transportation time	[3,5]
setup time between adjacent casts on a same continuous caser	[60,90]

steelmaking plant and UE represents the unit energy consumption.

In terms of size complexity, the model can be analyzed under the number of binary decision variables (NCVs), the number of continuous decision variables (NCVs), and the number of constraints (NCs). The computational statistics of 3 instances are given in Table 5. It can be seen that the size of the model can greatly affect the time required to obtain the optimal solution. The more complex the instance, the longer the time to obtain the optimal solution. All solutions can be obtained within 5 CPU times, which can be considered as a faster solution in actual production environments. The integrality gaps in Table 5 show that the proposed model has a fairly tight LP relaxation.

From Table 5, it can be seen that the unit energy consumption of the first set of equipment for processing and producing the same steel grade is significantly greater than that of the second set of equipment under different casting schedules. Selecting this set of equipment to shut down can greatly reduce the power consumption of the steelmaking plant under the condition of power restriction and meet the production demand. Multiple experiments have achieved the same results. Therefore, the model has good application and popularization value in practical production.

5.3. Results and Discussion. Based on the above analysis, final equipment set 1 will be shut down. To verify the advantages of the proposed model, this paper compares the optimized results with the current operating status of the steel plant. Taking the production plan of a real case as an example, equipment set 1 has 29 charges, and equipment set 2 has 22 charges. This paper selects steel production per unit time, maximum task completion

Table 5. Results of the Model on Different Size Instances

		model size								
instance	equipment set	NBVs	NCVs	NCs	$C_{max/min}$	TE (kWh)	UE (kWh)	integrality gap (%)	time (s)	close or not
1	equipment set 1	140	286	283	730.00	71 502.23	97.9483	1.28	2.02	yes
	equipment set 2	60	106	112	493.04	13 712.93	27.8132	0.18	0.8	no
2	equipment set 1	245	496	360	989.53	115 266.70	116.49	2.64	2.26	yes
	equipment set 2	147	251	257	1633.26	33 537.03	20.5339	0.32	1.7	no
3	equipment set 1	269	556	402	2716.78	140 393.08	51.6766	1.64	3.34	yes
	equipment set 2	180	306	312	1693.16	40 523.07	23.9335	0.18	2.06	no

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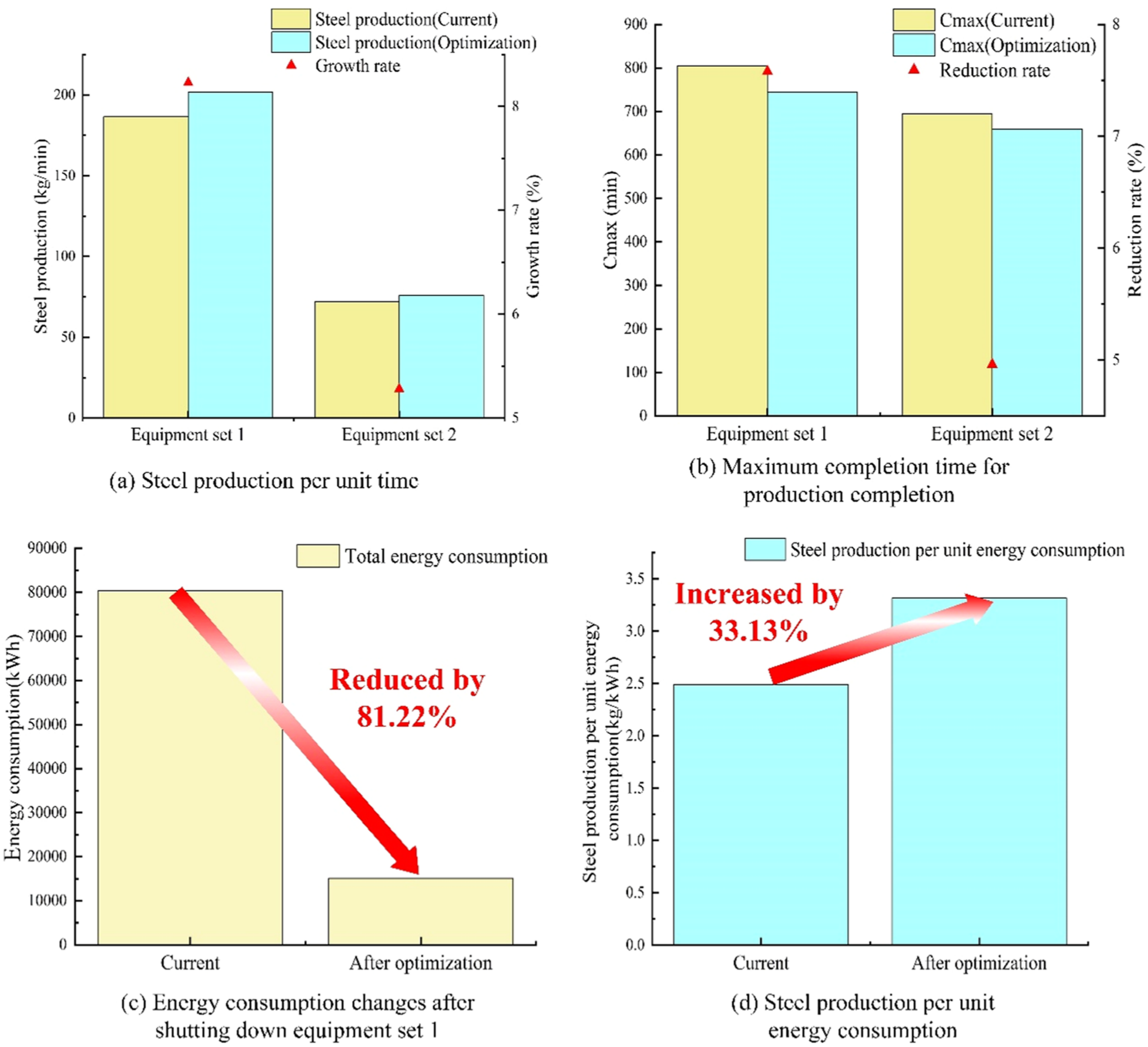

Figure 8. Comparison of the optimized and current methods for effectiveness.

time, total energy consumption, and steel production per unit energy consumption as evaluation indicators.

Figure 8a,b, respectively, shows the changes in the steel production per minute and the maximum completion time for completing the batch production of equipment set 1 and equipment set 2 before and after the application of the scheduling method. After applying the method in this paper, the steel production per unit time of equipment set 1 and 2 increased by 8.23 and 5.28%, respectively. The maximum completion time of equipment set 1 has also been reduced from 804.66 to 743.64 min, with significant changes and significant improvements in energy efficiency, demonstrating the effectiveness of the model proposed in this paper. In addition, Figure 8c,d indicates that the total energy consumption of the steelmaking plant decreased by 81.22% after the shutdown of equipment set 1, while the steel production per unit energy increased from 2.49 to 3.3149 kg/kWh, an increase of 33.13%, resulting in a significant increase. Therefore, under strict power curtailment policies, it is the correct choice to choose to shut down equipment set 1 if there are no specific requirements for steel production.

6. CONCLUSIONS

Aiming at the decision-making problem of how to shut down equipment sets under the premise of not affecting production demand and efficiency under the condition of power curtailment, this paper combines steelmaking production scheduling and energy efficiency strategies to establish a mathematical model of energy efficiency scheduling for an equipment set shutdown strategy. Genetic algorithm is used to solve this problem, and the model and solution methods were verified through practical application cases. For steelmaking in multiple charges, the scheduling plan for the optimal time is first generated and the energy collection of different equipment is calculated. For the equipment set with larger unit energy consumption, the strategy of shutting down is adopted. The equipment set with significant energy efficiency to be saved greatly reduces the power consumption of the enterprise.

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At present, there are no relevant references on the combination of scheduling and equipment set evaluation indicators, which has an important innovative significance for the production decision of enterprises in the current environment of power curtailment. In addition, in terms of energy consumption optimization, the completion time and the energy consumption of the equipment set can be set as the optimization goals at the same time, the influence of other factors can be considered at the same time, and the performance of the equipment set can be comprehensively considered to reduce the energy consumption and improve the economic benefits of the steelmaking plant.

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Notes

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■ NOMENCLATURE

Indices

i =charge
j =cast
s =stage
m =machine
H_j^1 =first charge of the j cast
H_j^l =last charge of the j cast

Sets

I =set of charges
J =set of casts
S =set of all processing stages
M_S =set of all processing machines in the S stage
H_j =set of charges for the j cast

Parameters

$\mathrm{WT\ max}_i^{s,s+1}$ =maximum waiting time from the end of processing in stage s to stage s+1 for charge i
$\mathrm{TT}_{s,s+1}$ =transport time between the s and s+1 stage
rt =preparation time of the same casting on the same caster
U =large enough number
MT_m =earliest available time of the machine
$p_{ism}^{\max}$, $p_{ism}^{\min}$ =maximum processing time and minimum processing time of operation based on historical production data
$TT_{s,s+1}^{\max}$,$TT_{s,s+1}^{\min}$ =maximum transport time and minimum transport time of adjacent operation based on historical production data

Variables

$st_{i,s,m}$ =time when charge i starts processing on the m_{th} machine in stage s
$ed_{i,s,m}$ =time when charge i finishes processing on the m_{th} machine in stage s
$C_{\max}$ =time to finish machining for last batch of final production stage
$\mathrm{WT}_i^{s,s+1}$ =waiting time from the end of processing in stage s to stage s+1 for charge i
$st_{H_{j+1}^1}$ =time when first charge of the j+1 cast starts processing
$ed_{H_j^l}$ =time when last charge of the j cast finishes processing

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