Research Article

Method for Optimizing Energy Consumption in Machining Manufacturing Process

Tengqiao Kong,1 Dong Ren Nhg,2 and Van Tinh Shi2

1GongQing Institute of Science and Technology, Gongqingchengshi, Jiangxi 332020, China
2Saigon University, Ho Chi Minh City 700000, Vietnam

Correspondence should be addressed to Dong Ren Nhg; nhgdr3929088@sg.edu.vn

Received 12 April 2022; Accepted 6 May 2022; Published 23 May 2022

Abstract

With the rapid development of the economy and the continuous maturity of various industries and departments, the total amount of energy required by enterprises in the process of production and operation is also increasing year by year. To achieve sustainable development, it is necessary to adjust the current production and operation mode, reasonably evaluate the current state of resources, use advanced technology to optimize each link of production, and regard low-energy consumption and low carbon as the key to production improvement. In this paper, the integrated realization method of process planning and production scheduling based on intelligent algorithm is adopted, and the integrated model is solved by using the chromosome hierarchical coding genetic algorithm. When the alternative process schemes generated for each part through nonlinear process planning are given, the integrated model can weigh the optimization objectives and decide the suitable process route, machine tool selection scheme, and corresponding production scheduling scheme for each part. In this paper, a case study on the energy-saving effect of energy consumption optimization methods in machining and manufacturing processes is carried out. Taking a manufacturing enterprise as the background, the effectiveness of the proposed energy-saving method is verified by comparing the energy consumption of a batch of mechanical product parts in the process planning and production scheduling integrated mode and the traditional serial working mode.

1. Introduction

With the rapid development of the economy of China, people’s daily living standards have been continuously improved not only reflected in clothing, food, housing, and transportation but the cultural life of the people is also constantly developing and progressing. However, the rapid development of the economy is always based on the development and utilization of resources. Excessive pursuit of the speed of economic development will only lead to waste and shortage of resources. Therefore, in addition to pursuing higher economic profits in the daily production and operation process, more and more people are paying more attention to the rational allocation and utilization of resources in all walks of life, striving to minimize waste and reduce the pressure caused by environmental and resource problems to the long-term and sustainable development of the economy [1–3]. Especially in traditional industries such as mechanical processing and manufacturing, more attention should be paid to the rationalization of energy development and utilization and to achieve sustainable economic development by optimizing energy consumption.

Since the process planning is generally carried out before the workpiece enters the production site for processing, the process routes, process methods, machine tools and process equipment, cutting fluids, and processing parameters involved in the process planning determine the impact of the machining process on the environment. Since the beginning of the research on green manufacturing, people have begun to pay attention to the environmental friendliness of the process and conduct research on process planning for green manufacturing. Munoz et al. proposed an analysis model for evaluating the environmental impact of machining processes, and quantitatively analyzed the energy consumption,
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2.1. Energy Consumption Calculation Model. In order to facilitate modeling and expressing the energy consumption of the machining process in the total completion time of a certain batch of mechanical product parts, some parameters and variables used are first defined and explained. We suppose that there is a batch of \( n \) workpieces, that is, \( n \) processing tasks \( \{J_1, J_2, \ldots, J_n\} \), which are processed by \( m \) plus machines \( \{M_1, M_2, \ldots, M_m\} \). The machine that completes the machining of the workpiece contains \( W \) number of motile types. Each machining task \( i(J_i) \) consists of a series of machining operations \( O_{ij} \), where \( i_l \) represents the number of machining operations included in the machining task \( i \). \( N_k \) represents the number of processing operations corresponding to the operation set \( \{O_{ij}\} \) processed on the machine tool \( k(M_k) \), and the number of processing operations is \( U_{ij} \). For the operation \( O_{ij} \) processed on the machine tool \( k \), the processing time \( T_{P_{ijk}} \) is determined by the machining auxiliary time \( T_{A_{ijk}} \) and the machining process time. The composition of \( T_{P_{ijk}} \) and the processing time varies according to the process characteristics of the process and the selected machine tool. \( S_{ijk} \) represents the processing start time of the process \( O_{ij} \) on the machine tool \( k \), and \( C_{ijk} \) represents the processing end time of the process \( O_{ij} \) on the machine tool \( k \). According to the model assumptions, there is a relationship:

\[
C_{ijk} = S_{ijk} + T_{P_{ijk}}. \tag{1}
\]

Obviously, when the machining process plan and scheduling plan of the workpiece are given, the values of the above input parameters for calculating the energy consumption are determined, and then the energy consumption of the machining process in the total completion time of the workpiece can be calculated. First, we determine the total completion time of this batch of workpieces, which can be expressed as follows:

\[
TC = \max(C_{ijk}). \tag{2}
\]

In the formula: \( TC \) represents the total completion time of this batch of workpieces, that is, the processing end time of the last completed workpiece, \( s \).

For this batch of workpieces, the energy consumption of the machining process is equal to the sum of the energy consumption of the machine tools used in the processing of the batch of workpieces, namely:

\[
E_{\text{total}} = \sum_{k=1}^{m} E_k. \tag{3}
\]

In the formula, \( E_{\text{total}} \) represents the energy consumption of the machining process related to the \( n \) workpieces, \( j; E_k \) represents the energy consumption of the machine tool \( k \) related to the processing task in the total completion time, \( J \). According to the definition of processing time in this paper, for each machine tool, its energy consumption in the total completion time is composed of two parts: the energy consumption in the processing time period and the energy consumption in the nonprocessing time period, which can be expressed as follows:

\[
E_k = EI_k + EM_k. \tag{4}
\]

In the formula, \( EI_k \) represents the total energy consumption of machine tool \( k \) during nonprocessing time, that is, standby time, \( j; EM_k \) represents the total energy
consumption of machine tool $M$ during processing time, $J$. The machine mound has only one state of standby during non-processing time, so there are

$$EIk = Pk^SO_k \times (\max [C_{ijk}] - TP_{ijk}).$$  \hspace{1cm} (5)$$

In the formula, $P_k^SO$ represents the power of the machine tool $k$-standby operation, $W$. The total energy consumption of machine tool $k$ processing time period can be further decomposed as follows:

$$EM_k = EMA_k + EMM_k.$$  \hspace{1cm} (6)$$

In the formula, $EMA_k$ is the total machining auxiliary time energy consumption of the machine tool $k$, $J$; $EMM_k$ represents the total machining process time energy consumption of the machine tool $M$, $J$. According to the modeling assumptions, the machine tool $k$ is also in the standby state during the machining auxiliary time, so it can be expressed as follows:

$$EMA_k = Pk^SO_k \times \sum TAr_{ijk},$$

$$EMM_k = \sum_{i=1}^{U_j} E_{bq,i},$$  \hspace{1cm} (7)$$

where

$$E_{bq,i} = \sum_{x=1}^{\Delta_{kq}} \sum_{y=1}^{W} P_{x+y}\times b_{x+y}^k,$$  \hspace{1cm} (8)$$

where $E_{bq,i}$ represents the energy consumption of the machining process corresponding to the $q$th process performed by the machine tool $k$, $W$, $P_{x+y}^k$ represents the power of the kinematic element $y$ in the corresponding $x$th machining process activity when the machine tool $k$ performs the $q$th process, $W$, $T_{r_{ijk}}$ is the execution time of the corresponding $x$th machining process activity when machine tool $k$ performs the $q$th process, and $b_{x+y}^k$ is the motion element $y$ in the $x$th machining process activity when machine tool $k$ performs the $q$th process. If the motor element $y$ works in the $x$th machining process activity, the value of $b_{x+y}^k$ is 1, otherwise it is 0.

2.2. Expression and Acquisition of Nonlinear Process Planning.

Nonlinear process planning (optional process planning) can be expressed in many ways, such as directed graphs, Petri nets, AND/OR graphs, Tree structures. Using AOS tree to describe nonlinear process planning has the remarkable characteristics of clear and simple structure, easy computerized representation, and easy implementation of basic operation. In this paper, AOS tree theory is used, and the corresponding nonlinear process planning AOS tree is obtained. By traversing the nonlinear process planning AOS tree, we extract the process activities contained in the data nodes, and then analyze the machine tools, process equipment, and process parameters required by the process activities to generate the corresponding processes, so as to obtain various feasible items that meet the requirements of the part design processing route.

According to the geometric information of the feature and the constraint relationship, the entity features to be processed can be connected by relationship nodes. Since the auxiliary feature is attached to the main feature, there is a parent–child relationship between the main feature and the auxiliary feature, and the parent–child relationship is often converted into an $S$ node. There is often a sibling relationship between the main features. If the processing order of several main features is arbitrary, they can be connected by $A$ node; if the processing order is certain, they can be connected by $S$ node. After the main and auxiliary features to be processed are connected with relation nodes, the initial AOS tree can be established. After obtaining the initial AOS tree, we combine the design information and blank information of the part, use feature-mapping technology, and automatically select the feature machining method that meets the machining accuracy and technical requirements from the feature machining method knowledge base, so as to realize the design feature space to process feature space. The automatic mapping of each process feature of AOS tree corresponding to the design features to be processed is established.

2.3. Chromosome Hierarchical Coding Genetic Algorithm.

The basic idea of Genetic Algorithm (GA) comes from Darwin’s theory of evolution and Mendel’s theory of genetics. It expresses the solution of the problem as chromosomes. By forming a group of chromosomes, they are placed in the problem environment, according to the principle of survival of the fittest. Then, we select the chromosomes that adapt to the environment for replication, and then perform chromosomal genetic manipulation through crossover and mutation to generate a new generation of chromosome groups that are more adaptable to the environment, obtaining the optimal solution to the problem. Calculation process of genetic algorithm: evaluate the fitness of the individual corresponding to each chromosome. According to the principle that the higher the fitness, the greater the selection probability, select two individuals from the population as the parent and parent, extract the chromosomes of both parents, cross them, produce offspring, and mutate the chromosomes of the offspring. Repeat the above steps until the optimal solution is generated.

Through nonlinear process planning, each workpiece may have multiple optional process routes. A process route consists of a certain sequence of processes, and the number of processes contained in different process routes may vary. A process consists of one or more process steps. Different processes may have different machine tool selection schemes, and even the same process may have different machine tool selection schemes. Therefore, there are upper-
2.4. Case Analysis. Through the implementation of CNC efficiency enhancement and a series of digital engineering projects, a manufacturing enterprise already has a good foundation for digitalization and informatization applications. The proportion of CNC machine tools in the entire enterprise’s machine tools and the CNC rate of machining processes have reached a high level. It is suitable for the production of multivariety and small batch parts and can coordinate the business process between departments to effectively collect and store machine tool status information in the enterprise workshop. The typical mechanical product parts produced by the manufacturing company selected in this paper have three A-type parts \( J_1-J_3 \) and two B-type parts \( J_4, J_5 \). These five parts belong to the same processing batch, and A and B are the same. The materials of the three types of parts are all No. 45 steel. Table 1 shows the processing energy consumption when different machine tools are selected for each process in different schemes of A and B parts.

### Table 1: Processing energy consumption when different machine tools are selected for each process in different schemes.

| Part category | Machining task | Routing | Employee ID | Machine type | Machine tool processing energy consumption (\( M_{ijk} \)) |
|---------------|----------------|---------|-------------|--------------|--------------------------------------------------------|
| A \( i = 1, 2, 3 \) | 1 | M1 | 107960 | M2 | 123580 |
| | 2 | M2 | 112060 | M3 | 126985 |
| | 3 | M3 | 110650 | M4 | 4891 |
| B \( i = 4, 5 \) | 1 | M4 | 1089100 | M5 | 1120910 |
| | 2 | M5 | 542351 | M4 | 548920 |
| | 3 | M4 | 512680 | M5 | 124510 |
| | 4 | M5 | 98264 | M4 | 1089100 |

3. Results and Discussion

3.1. Comparison of Energy-Saving Effects of Energy-Consumption Optimization Methods in Different Mechanical Processing and Manufacturing Processes. In order to better verify the effect of optimizing the energy consumption of mechanical manufacturing process through the integration of process planning and production scheduling, this paper analyzes the energy consumption of typical mechanical product parts in the process planning and production scheduling integrated environment and nonintegrated environment. Comparisons are made and discussed in four cases:

Case 1: In a nonintegrated environment of process planning and production scheduling, according to the existing process arrangement, all processing tasks are added in the order of job serial numbers.

Case 2: In a nonintegrated environment of process planning and production scheduling, according to the existing process arrangement, the activity scheduling mechanism is used for production scheduling.

Case 3: In the integrated environment of process planning and production scheduling, the semiactive
scheduling mechanism is used for production scheduling in combination with the given optional process plans generated for each workpiece through nonlinear process planning.

Case 4: In the integrated environment of process planning and production scheduling, combined with the given optional process plan for each workpiece through nonlinear process planning, the activity scheduling mechanism is used for production scheduling.

In addition, when the process route selected for each processing task is determined, the process planning and production scheduling integration problem degenerates into a flexible job shop scheduling problem. Further, if the machine tool selected for each process is also determined, the process planning and production scheduling integration problem are further degraded for the traditional job shop scheduling problem. Therefore, the method based on the chromosomal hierarchical coding genetic algorithm proposed in this paper to solve the integrated model of process planning and production scheduling for low-carbon manufacturing is also suitable for solving the production scheduling problem considering energy consumption in case 2. Since in case 1 and case 2, the process route and machine tool selected for each processing task are known, corresponding to the integrated mathematical model of process planning and production scheduling established in this paper, the decision variable and the sufficient value can be determined first, and the value of the decision variable $S$ shot is determined.

For case 1, there is no need to run the genetic algorithm, and it is only necessary to decode the chromosome corresponding to the semiactive scheduling decoding mechanism. For case 2, there is more than one individual corresponding to the best fitness obtained by running the genetic algorithm 50 times, and an energy-saving production scheduling scheme obtained after decoding is randomly selected. For cases 3 and 4, the genetic algorithm is run 50 times, respectively, and there is more than one individual corresponding to the best fitness obtained after the algorithm runs. In these two cases, an individual with the best fitness is randomly selected, and the energy-saving process route, machine tool selection scheme and corresponding production scheduling scheme of each processing task are obtained after decoding. Since the initial population is randomly generated each time the genetic algorithm runs, the results obtained after the operation are not the same. Under multiple schemes with the same energy consumption, the scheme with the shortest processing time is selected.

However, from an evolutionary point of view, with the increase of evolutionary algebras, the average fitness of individuals in the population increases as a whole, and eventually tends to be stable. Comparing the best fitness individuals obtained in the third and fourth cases, it is found that the fitness of the best fitness individuals obtained under the semiactive scheduling decoding mechanism is the same as that of the best fitness individuals obtained under the active scheduling decoding mechanism. However, it is not certain that in the integrated environment of process planning and production scheduling, considering the optimization goal of energy consumption in the machining process of all processing tasks, there is no difference in the problem-solving effect between the semiactive scheduling decoding mechanism and the active scheduling decoding mechanism. For the research case given in this paper, the reason why the solution results are the same under the two scheduling and decoding mechanisms is mainly because the scale of the case problem is small and the combination situation is limited. For other problems in the integrated environment of process planning and production scheduling, the appropriate decoding mechanism still requires specific solutions and comparative analysis.

According to Figures 1 and 2, comparing case 1 and case 2, it can be seen that under the given conditions of each processing task, process route, and machine tool, there is no difference in the energy consumption of the machine tool during the processing time period, indicating that the consumption is regarded as a fixed cost, and it is reasonable to ignore it in production scheduling. In case 2, the total standby energy consumption of machine tools is reduced by nearly 83% on the basis of case 1. Effective measures to carry out production scheduling that considers energy consumption can help reduce machine tool standby energy consumption, reduce energy waste, and then reduce energy consumption.
consumption in the machining and manufacturing process of all parts. Comparing cases 2, 3, and 4, it can be seen that the total energy consumption of machine tool standby in cases 2, 3, and 4 is 0. In nonlinear process planning, the flexibility of production control are further improved, and each processing task has not only alternative processing machine options but also alternative process routes.

3.2. The Results and Analysis of the Ensemble Model Based on the Chromosomal Hierarchical Coding Genetic Algorithm. When solving a multiojective optimization problem, it is necessary to first determine the weight of each optimization objective. For the integrated model of process planning and production scheduling for low-carbon manufacturing proposed in this paper, the three optimization objective weights, namely, the comprehensive average state of the machine tool, the total completion time, and the energy consumption of the machining and manufacturing process, are all selected by the AHP for all processing tasks. The weights of these three optimization objectives are 0.20, 0.48, and 0.32, respectively. We assume that the evolution cycle number of the genetic algorithm is 400, the initial population is 50, the crossover probability in the genetic operation is 0.74, and the mutation probability is 0.26. For the actual production case given in this paper, due to the small scale of the problem, the active scheduling decoding mechanism and the semiactive scheduling decoding mechanism have no obvious effect difference. Therefore, this paper chooses the active scheduling decoding mechanism to solve the problem and considers three optimizations at the same time. We take the optional process plan generated for three types of parts through nonlinear process planning as input, run the genetic algorithm 50 times, get more than one individual with the best fitness, and randomly select a process route for each processing task after chromosome decoding. The machine tool selection scheme and the corresponding production scheduling scheme are shown in Table 3. Correspondingly, the total completion time B makespan of this batch of parts is 3391 s, and the total energy consumption of the machining process is 5776512 J (the total energy consumption of the machine tool processing time is 5424356 J, and the total standby energy consumption is 35216 J).

According to the current production arrangement of the enterprise, in case 2, by only considering the optimization objective of energy consumption in the mechanical processing and manufacturing process of all processing tasks and the optimization objective function values when considering three optimization objectives at the same time, it is found that the calculation results are the same. On the one hand, this is because the total processing time of the B-type parts according to the current process arrangement of the enterprise is much larger than that of the other two types of parts, which is the dominant factor affecting the total completion time of all parts. On the other hand, Figures 1 and 2 show that the energy consumption of machine tool processing time is the main body of energy consumption in the machining process of all processing tasks. However, under the current process arrangement, the total energy consumption of machine tool processing time is a fixed value, so the energy consumption optimization of the machining process can only be aimed at the standby of the machine tool. The total energy consumption is carried out, but the scale of the case problem is small and the combination situation is limited.

When given an optional process scheme generated for each part through nonlinear process planning, we compare the optimization objective of only considering the energy consumption of all machining tasks in the machining process and the objective functions obtained by simultaneously considering the three optimization objectives in case 4. It can be seen that with the reduction of the weight of the energy consumption optimization objective and the increase of the weight of the other two optimization objectives, the energy consumption of the machining and manufacturing process of all processing tasks has increased, and the total

### Table 2: The process route, machine tool selection scheme, and production scheduling scheme of each processing task obtained by weighing the three optimization objectives.

| Machining tasks | Selected process route | Machine tools selected for each process | Start processing time of each process, (s) |
|-----------------|------------------------|----------------------------------------|------------------------------------------|
| J1              | 1                      | M3-M3-M5                               | 169-256-2153                             |
| J2              | 2                      | M3-M3-M5                               | 0-78-1121                                |
| J3              | 2                      | M3-M3-M5                               | 352-415-2451                             |
| J4              | 2                      | M4-M5-M5                               | 0-1121-1598                              |
| J5              | 3                      | M5-M5                                 | 0-1841                                   |

According to the current production arrangement of the enterprise, each typical mechanical product part has a unique and definite process route, and the machine tool selected for each processing procedure is determined. The average value of the comprehensive evaluation of the state of the machine tool for task processing selection is determined, which is 0.5769, so this time can be regarded as a special case of the integrated model of process planning and production scheduling for low-carbon manufacturing, that is, the integrated model degenerates to only consider all processing tasks. The three optimization objective weights of the established ensemble model are still taken as 0.20, 0.48, and 0.32, respectively. After running the genetic algorithm 40 times, more than one individual with the best fitness is obtained, and an energy-saving production scheduling scheme obtained after chromosome decoding is randomly selected as shown in Table 3. Correspondingly, the total completion time B makespan of this batch of parts is 3391 s, and the total energy consumption of the machining process is 5776512 J (the total energy consumption of the machine tool processing time is 5424356 J, and the total standby energy consumption is 35216 J).
completion time of all processing tasks has decreased. The average value of the comprehensive evaluation of the condition of the machine tool has increased. According to Figures 1 and 2, the energy consumption of the machine tool processing time is the main energy consumption in the machining process. Therefore, when considering only the optimization goal of energy consumption, in order to reduce the energy consumption of the machine tool processing time, the selection of machine tools with lower-energy consumption for process processing leads to higher frequency of use of certain machine tools.

However, after considering the other two optimization objectives, since each machining task has an optional process scheme, among the results obtained by weighing the three optimization objectives, the number of operations performed by some machine tools remains the same, and the number of operations performed by some is reduced. The average value of the comprehensive evaluation of the state of the selected machine tools for all processing tasks is increased from 0.5769 to 0.6132. The total completion time of all processing tasks is also optimized, the optimization range is the highest, and its value is shortened by 24.43% compared with the energy consumption optimization objective. Comparing the parts with optional process plans and the objective function values obtained by weighing the three optimization objectives according to the current production arrangement of the enterprise, it can be seen that, due to the consideration of the state of the machine tool, some processes of the processing task select a machine tool with a better state under the same processing capacity, improving the on-site processing environment. Although some processes have higher-energy consumption when they are processed on machine tools in better condition, there are also processes that reduce process energy consumption (such as force processes) because energy-saving machine tools are selected from the energy consumption optimization goal. In general, although the energy consumption value of the batch of parts obtained when each part has an optional process plan increases, the scheduling operation space is improved when each part has an optional process plan, and all processing in the optimization goal is improved. The total completion time of the task is given the highest weight, so the optimization of the total completion time of all parts is further improved, which is shortened by 32.31% on the basis of the current production arrangement.

### Table 3: Energy-saving production scheduling scheme obtained by weighing three optimization objectives under the existing production arrangement.

| Machining tasks | Selected process route | Machine tools selected for each process | Start processing time of each process, (s) |
|-----------------|------------------------|----------------------------------------|------------------------------------------|
| J1              | 1                      | M1-M2-M5                               | 92-221-1601                              |
| J2              | 1                      | M1-M2-M5                               | 0-125-1428                               |
| J3              | 1                      | M1-M2-M5                               | 165-312-1652                             |
| J4              | 1                      | M4-M4-M4-M4                            | 1529-3587-3265-3391                      |
| J5              | 1                      | M4-M4-M4-M4                            | 0-892-1625-3156                          |

3.3. Discussion and Suggestion. In the process of machining and manufacturing, there are many links and contents involved, so we should apply the energy consumption optimization method to each link scientifically and reasonably in combination with the actual situation. This is not only conducive to the scientific and reasonable judgment of the use of link energy consumption but also can put forward targeted control measures in combination with the actual situation, which can ensure the optimization effect of energy consumption. According to the state evaluation index of machine tool equipment, it is necessary to obtain the state of machine tool equipment, the state of production workshop, and the state of its production unit. In the actual production and transportation, the workpiece with known volume and weight adopts a fixed transportation mode, so the transportation distance from the current machine tool equipment to the destination machine tool equipment has become the main factor affecting the transportation time. The layout of machine tools in the workshop determines the distance between machine tools and equipment, so that the transportation time of different parts between different machine tools and equipment can be calculated. When the process route of machining is determined, the integration problem is mainly reflected in the scheduling problem of workshop machine tools, but if the machine tools are also determined, this problem will become the scheduling problem of traditional workshop.

### 4. Conclusion

1. Based on the analysis of energy consumption characteristics of machine tool equipment, this paper studies the method of reducing energy consumption in machining and manufacturing process by integrating process planning and production scheduling based on nonlinear process planning. Based on the existing research on flexible job shop scheduling, combined with the quantitative analysis of machine tool equipment status and the analysis and calculation of energy consumption in the machining process, the comprehensive average state, total completion time, and machining manufacturing process of selecting machine tools for all machining tasks are established.

2. Energy consumption can be used as an independent optimization target for the integration of process planning and production scheduling. The integration of process planning and production scheduling for low-carbon manufacturing is not only conducive to the optimization of energy consumption in the machining and manufacturing process but also helps
to improve the workshop Live production operations.

**Data Availability**

The figures and tables used to support the findings of this study are included in the article.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

The authors would like to show sincere gratitude to those techniques which contributed to this research.

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