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REGULAR PAPER

A High Efficiency and Low Carbon Oriented Machining Process Route Optimization Model and Its Application

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Abstract

This paper aims to reduce the carbon emission of the manufacturing process and to achieve the low carbon optimization decision of the machining process route. Carbon emission was analyzed from the perspective of material flow, energy flow and environmental flow, and the machining process route carbon efficiency model was established based on the one from per unit cutted-volume. A multi-objective machining process route optimization model was established based on the genetic algorithms (GA), and the minimum processing time (high efficiency) and the optimal carbon efficiency (low carbon) were set as the optimization objectives. An experiment case study was performed on grinding carriage box, and a comparison was given between the optimized process and traditional process. The results indicate the resultant process route from the proposed algorithm, which verifies to reduce the processing time and increase the carbon efficiency.

Keywords Machining process route · Three flows model · Carbon efficiency · High efficiency and low carbon · Genetic algorithms

Abbreviations

$Q_{process}$	Carbon efficiency of machining process
$C_{process}$	Carbon emissions generated in machining process
ΔV	Material removal volume in machining process
M	Material flow consumption
E	Energy flow consumption
W	Environmental flow consumption
$i(i=1, 2\ldots i0)$	Each process
$j(j=1, 2\ldots j0)$	All kinds of materials
$k(k=1, 2\ldots k0)$	All kinds of energy
$l(l=1, 2, \ldots l0)$	All kinds of pollutants
C_M,C_E,C_W	The carbon emission from material flow/energy flow/environmental flow
f_M^N,f_E^N,f_W^N	Carbon emission factor of the corresponding material flow/energy flow/environmental flow
N	The natural number
$C_M^{rmc},C_M^{clc},C_M^{ctc},C_M^{fc}$	The carbon emission from raw materials consumption/coolant liquid consumption/cutting tools consumption/fixtures consumption
Δm	The removed quality of the material
$f_M^{rmc},f_M^{clc},f_M^{ctc},f_M^{fc}$	The carbon emission factor of removed material consumption/coolant fluid consumption/cutting tool consumption/fixture consumption
$T_{process}$	The processing time
T_{rct}	The replacement cycle time of coolant fluid
ρ_{cf}	The coolant fluid density,
V_{rvf}	The replaced volume of coolant fluid
T_{tl}	The tool life

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m_{ct}	The quality of cutting tool
T_{rcf}	The replacement cycle time of fixture
m_f	The quality of fixture
P_e	The machine input power
P_u	No-load power
P_c	Cutting power
P_a	Additional load loss power
$T_{no\text{-}load}$	The no-load time of machine tool
f_E^{eec}	The carbon emission factor of electric energy consumption
f_W^{ad}, f_W^{wd}	The carbon emission factor of attle disposal/liquid waste disposal
F	Machining features
P	Machining methods
F_a	The a_{th} feature element
$M_b^{'}$	The b_{th} machine
$T_c^{'}$	The c_{th} tool
me_a	The set of all the machining elements
T_{total}	The total processing time
T_{ppt}	Part processing time
T_{mrt}	Machine replacement time
T_{trt}	Tool replacement time
T_{emrt}	Each machine replacement time
T_{etrt}	Tools replacement time
$RC_i(x)$, $OC_i(x)$	The rationality constraints/optimal constraints
Ω	The set of all the solutions in the component processing elements
S_i	Machining procedure code
ω_1, ω_2	The weight coefficients

1 Introduction

The process route plays an important role during the whole process design, it determines the production cost, processing time, product quality, production resources and environmental impact of the whole product. Greenhouse gas emission has become a recent global concern for green manufacturing, as product low-carbon process route design is an essential approach to achieve low-carbon manufacturing [1]. Carbon emission of manufacturing process includes the carbon emission from material flow, energy flow and environmental flow in the production and machining processes. Hence, it is of great significance to perform a study on process route optimization model for low carbon manufacturing, such that the carbon emission in the manufacturing process could be reduced.

Process route sequencing is considered as the key technology for computer aided process planning (CAPP) and is very complex and difficult. Some researchers focused their work on the traditional objective optimization. The shortest processing time [2], the minimum number of steps [3], and the minimum machining cost [4] were considered as the optimization goal. Multi-objective optimization was also carried out by many researchers. A mathematical model of IPPS is proposed based on the methodology of NLPP, the process plan of every job and the scheduling plan are generated simultaneously in this model, and the selection of process plan and generation of scheduling plan are guided by the objectives (such as minimizing makespan or cost) [5]. An evolutionary algorithm was presented to solve a multi-objective FMS process planning (MFPP) problem with various flexibilities. The MFPP problem simultaneously considers four types of flexibilities related to machine, tool, sequence, and process and takes into account three objectives: balancing the machine workload, minimizing part movements, and minimizing tool changes [6]. A process route optimization model was proposed to solve the decision-making problems of the process route in a Computer Aided Process Planning (CAPP) system based on the ant colony algorithm, Then generated and optimized by using the modified ant colony algorithm under the taboo criterion and constraints [7].

With the growing problem of resources and environment, the energy consumption was taken into account as the optimization goals in the process route optimization research. Based on this background the developed concept realizes the optimization of the energy consumption of a forging process chain by adaptation of its energetic relevant parameters [8]. Some multi-objective optimization model were established, which takes the minimum total processing time and the lowest total carbon emissions as the optimization objectives, and the optimization model is solved based on NSGA-II (Non-dominated sorting genetic algorithm II) [9, 10]. A similar work was carried out by Li et al. [11] with the emphasis on the batch splitting flexible job shop scheduling model, with the optimization objectives of minimizing energy consumption and makespan. An energy-saving optimization method was proposed that considers machine tool selection and operation sequence for flexible job shops [12]. Similar work can be found in Zhang et al. (2016) (which gives a detailed introduction of) the objective of minimizing energy consumption into a typical production scheduling model, i.e., the job shop scheduling problem, based on a machine speed scaling framework [13]. The manufacturing process of an automotive crankshaft was systematically investigated via a numerical simulation approach towards energy savings. The aim of this work is to propose potential solutions for improving the energy efficiency of the forging process chain in which energetically relevant parameters are optimized variables [14]. An algorithm was developed that optimally arranges EPS process, to control the stability of the craft, wherein the center of gravity is used as an object function [15].

Toward the development of process plans with reduced environmental impacts (carbon emissions et al.), A proposed method is presented for environmentally conscious process planning, which identifies impactful process steps, and associated design features, in terms of manufacturing cost and environmental impact [16]. Then Yin et al. [17] presented a new process planning method based on a carbon emission function model is that integrates both economic and environmental considerations. The method is demonstrated using an example part and the benefits of the method in terms of energy consumption and carbon emissions are evaluated. An optimization model for low carbon oriented Modular Product Platform Planning (MP3) is presented by Qi et al. [18], which is developed for solving the optimization problem by Adaptive Memetic Algorithm (AMA).

While the literature seems abundant, and some significant studies on the quantitative analysis and evaluation carbon emissions has been performed in manufacturing system. However, these studies have focused on optimizing energy consumption, economic benefits or carbon emissions. But considering the differences of each task of processing, production plan, material and energy consumption characteristics, the green degree of machining process could not be evaluated only by carbon emissions. The relationship between carbon emissions and efficiency should be introduced, considering the carbon efficiency of the whole machining process. In our previous work [19, 20], the concept of carbon efficiency (The carbon efficiency was defined as the produced carbon emissions per unit cutted-volume) was proposed, and the optimization of grinding process parameters was carried out taking the carbon efficiency and processing time as the optimization objective. At the same time, carbon emissions caused by changes in material flow, energy flow and environmental emissions flow should be taken into account in the process of quantifying carbon emissions.

Therefore, in this paper, a research was given on low carbon manufacturing oriented machining process route. The following part was outlined as follows: Sect. 2 analyzed the carbon emission of the production process in detail, and the carbon efficiency model of the machining process route was established based on the material flow, energy flow and environmental flow. In Sect. 3, A machining process route optimization model for low-carbon manufacturing was established based on genetic algorithms, under considering the constraint conditions that need to be satisfied in the process. An experiment case study was performed on grinding carriage box, and a comparison was given between the optimized process and traditional process, the validity and practicability of the model were verified in Sect. 4. The conclusions were discussed in Sect. 5.

2 Carbon Efficiency Model of Production Process

2.1 Carbon Efficiency Model

In order to analyze the carbon emissions and evaluate the optimization of carbon efficiency during the machining process, a feasible low-carbon optimization model must be established. According to the characteristics of carbon emissions, this paper established a carbon emissions quantitative model of the machining process. In the model, the removed volume of machining process was connected to the carbon efficiency, the carbon efficiency (produced carbon emissions per unit volume which was cutted) as the low carbon manufacturing comprehensive evaluation index, as shown in Eq. (1):

$$Q_{process} = \frac{C_{process}}{\sum_{i=1}^{i_0} \Delta V_i} \tag{1}$$

Where $Q_{process}$ is carbon efficiency of machining process, $C_{process}$ is the carbon emissions generated in a machining process, ΔV is the material removal volume in machining process, $i(i=1, 2\ldots i_0)$ means each process.

2.2 Carbon Emission Quantification of Machining Process Route

The whole input and output process of the machining process should be considered to quantify carbon emissions. Input includes materials (raw materials, auxiliary materials, etc.) and energy (electricity, coal, natural gas, etc.). The output includes energy (electric energy, thermal energy) and emissions (exhaust gases, attle, and liquid waste). Therefore, the carbon emission of the whole machining process can be analyzed from the perspective of “three flows” (energy flow, material flow and environmental flow). The direct carbon emission from the production of materials was included, and indirect carbon emission from waste disposal was also generated through energy consumption.

Component processing is the most important stage of workblank production and workblank forming. Materials, energy and environmental emissions were included in the process. The consumption of materials includes raw materials, coolant, tools and fixtures; Energy consumption includes the consumption of electricity; Environmental emissions include attle, and liquid waste. Therefore, Material flow consumption M, Energy flow consumption E and Environmental flow consumption W of each process should be considered. Material flow consumption materials include all kinds of materials $j(j=1, 2\ldots j_0)$; Energy flow consumption includes all kinds of energy $k(k=1, 2\ldots k_0)$; Environmental flow consumption includes all kinds of pollutants $l(l=1, 2, \ldots l_0)$.

The carbon emission model of the machining process route based on material flow, energy flow and environmental flow is shown in Fig. 1.

During the process, an analysis model was performed for energy flow, material flow and environmental flow. The total amount of carbon emission could calculated in Eq. (2):

$$C(M, E, W) = C_M + C_E + C_W \tag{2}$$

Carbon emission from machining process is shown in Eq. (3):

$$C_{process} = C(M, E, W) = \sum_{i=1}^{i_0}\sum_{j=1}^{j_0} M_{j_i} \times f_M^N + \sum_{i=1}^{i_0}\sum_{k=1}^{k_0} E_{k_i} \times f_E^N + \sum_{i=1}^{i_0}\sum_{l=1}^{l_0} W_{l_i} \times f_W^N \tag{3}$$

Where C_M is the carbon emission from material flow, C_E is the carbon emission from energy flow, C_W is the carbon emission from environmental flow, f_M^N is carbon emission factor of the corresponding material flow, f_E^N is carbon emission factor of the corresponding energy flow, f_W^N is carbon emission factor of the corresponding environmental flow. N is the natural number. The relevant carbon emission factors can be obtained through the literature [21–23].

2.2.1 Carbon Mission from Material Flow

Material consumption is mainly concentrated in raw materials consumption C_M^{rmc}, coolant liquid consumption C_M^{clc}, cutting tools consumption C_M^{ctc} and fixtures consumption C_M^{fc}, as shown in Eq. (4):

$$C_M = \sum_{i=1}^{i_0}\left(C_{M_i}^{rmc} + C_{M_i}^{clc} + C_{M_i}^{ctc} + C_{M_i}^{fc}\right). \tag{4}$$

1. Raw materials consumption

   The carbon emission from raw material consumption refers to those caused by materials consumed during the mechanical processing system. The machining system will be processed into products and excised materials. Then the part of the material entering the product will enter the next stage with the product. The carbon emission from the excision materials were taken into account during machining process system. As shown in Eq. (5).

   $$C_M^{rmc} = \Delta m \times f_M^{rmc} \tag{5}$$

   where Δm is the removed quality of the material, f_M^{rmc} is the carbon emission factor of removed material consumption.
2. Coolant liquid consumption

   In the machining process, coolant fluid will return to the box after used. At the same time, coolant fluid will evaporate and stick on the workpiece or attle. Therefore, the fluid consumption of machining process should be calculated by using the standard time and converted to the replacement cycle time. The calculation formula is as the following Eq. (6).

   $$C_M^{clc} = \frac{T_{process}}{T_{rct}} \rho_{cf} V_{rvf} \times f_M^{clc} \tag{6}$$

   where $T_{process}$ is the processing time, T_{rct} is the replacement cycle time of coolant fluid,ρ_{cf} is the coolant fluid density, $Vrvf$ is the replaced volume of coolant fluid, f_M^{clc} is the carbon emission factor of coolant fluid consumption.
3. Cutting tools (grinding wheel) consumption

   Generally speaking, the direct environmental impact caused by the cutting tools is relatively small during the machining process, mainly the caused by the indirect influence (the environmental impact of the tool preparation process was assessed in the tool use process). Thus,

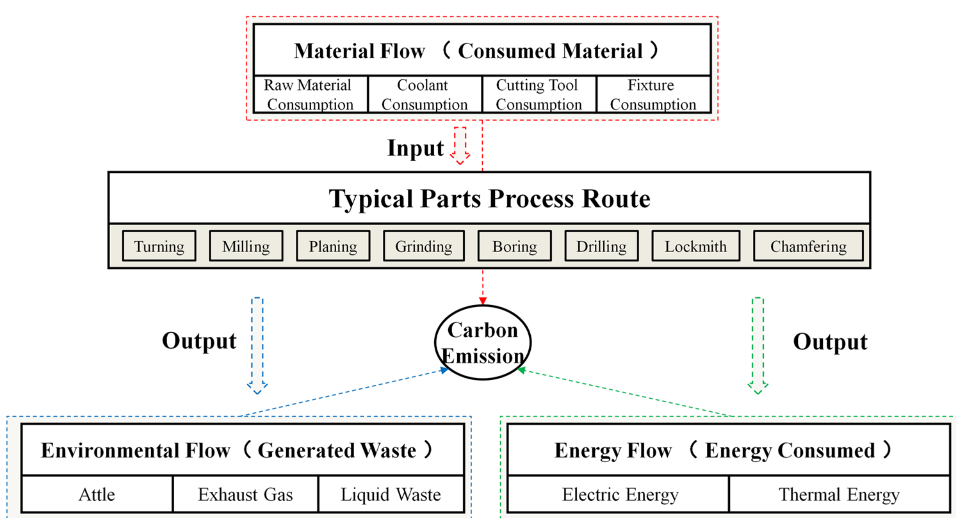

Fig. 1 Machining process route carbon emission model based on “Three flows” model

for a certain process, the carbon emission of cutting tool is calculated in a similar way to that of the coolant fluid, which also employs a conversion distribution method according to time.

$$C_M^{ctc} = \frac{T_{process}}{T_{tl}} m_{ct} \times f_M^{ctc} \tag{7}$$

where T_{tl} is the tool life, m_{ct} is the quality of cutting tool, f_M^{ctc} is carbon emission factor of cutting tool consumption.

4. Fixture consumption

The carbon emission of fixture is calculated in a similar way to that of the coolant fluid, which also employs a conversion distribution method according to time.

$$C_M^{fc} = \frac{T_{process}}{T_{rcf}} m_f \times f_M^{fc} \tag{8}$$

Where T_{rcf} is the replacement cycle time of fixture, m_f is the quality of fixture, f_M^{fc} is carbon emission factor of fixture consumption.

2.2.2 Carbon Emission from Energy Flow

The energy consumption of machine tool mainly includes basic startup part, transmission part, processing part and auxiliary device. The energy consumption of the machining part includes No-load energy consumption, processing energy consumption and additional load loss energy consumption.

Generally, the machine input power P_e consists of three parts:No-load power P_u, Cutting power P_c and Additional load loss power P_a [24]. The power balance equation is shown in Eq. (9):

$$P_e = P_u + P_c + P_a. \tag{9}$$

The total output power and the no-load power of the machine will be maintained at a certain stable value when the spindle speed of the machine is maintained at the steady-state operation. The no-load energy consumption can be regarded as a quadratic function relation with the rotational speed, furthermore the additional load loss is in a linear proportional relation to the load (The proportionality coefficient is often set to between 0.15 and 0.25, in this paper, the value was set as 0.2 in calculation). The cutting power is related to the product of force and feed rate.

Therefore, The carbon emission from energy consumption can be calculated as the following Eq. (10):

$$C_E = \sum_{i=1}^{i_0} \left(\int_0^{T_{no-load}+T_{process}} P_u dT + \int_0^{T_{process}} 1.2 P_c dT \right)_i \times f_E^{eec} \tag{10}$$

where $T_{no\text{-}load}$ is the no-load time of machine tool, f_E^{eec} is the carbon emission factor of electric energy consumption.

2.2.3 Carbon Emission from Environmental Flow

Environmental emissions are mainly attle and liquid waste products after processing. Thus, carbon emissions from attle and liquid waste disposal were included. As shown in Eq. (11):

$$C_W = \sum_{i=1}^{i_0} \left(C_{W_i}^{ad} + C_{W_i}^{lwd} \right). \tag{11}$$

1. Attle disposal C_w^{ad}

$$C_W^{ad} = \Delta m \times f_W^{ad} \tag{12}$$

2. Liquid waste disposal C_w^{lwd}

$$C_W^{lwd} = \frac{T_{process}}{T_{rct}} \rho_{cf} V_{rvf} \times f_W^{lwd} \tag{13}$$

Where f_W^{ad} 、f_W^{lwd} are the carbon emission factor of attle disposal/liquid waste disposal (include waste recycle part and the waste treatment part).

3 Machining Process Route Multi-Objective Optimization Model Based on GA

The process decision of parts process is a very complicated process, which is influenced by many factors such as the selection of machining methods, machine tools and tools, etc. During the whole manufacturing process, the development of process route of parts not only affects the processing energy consumption, carbon emission was also influenced. Therefore, reasonable planning process route can reduce energy consumption effectively, thus reducing the carbon emission of manufacturing process.

After the determination of the feature, processing technology and processing methods of each processing unit, which takes the minimum processing time and the optimal carbon efficiency as the optimization objectives, and the machining process route was determined by GA. The technology roadmap is shown in Fig. 2.

3.1 Feature of mechanical parts

In order to better describe the optimization of process route, two concepts named feature element and machining element were introduced [10]. Each machining feature of the part was defined as a feature element, and all machining features of the parts were expressed as the Eq. (14):

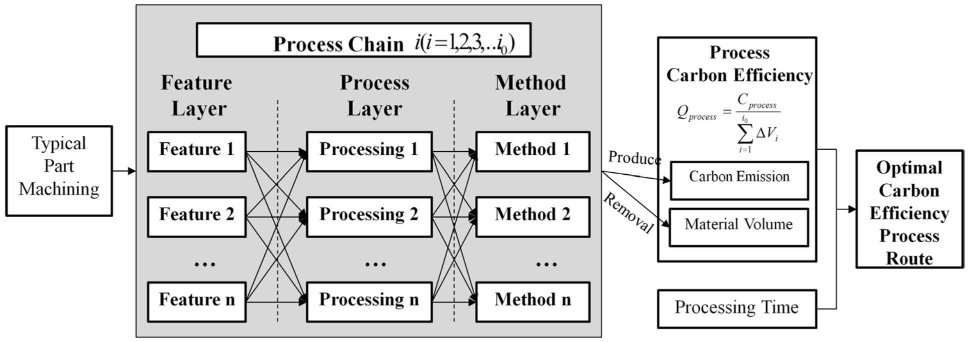

Fig. 2 High efficiency and low carbon machining process route optimization technology road-map based on genetic algorithm

$$F = \{F_1, F_2, F_3, \dots F_a\} \tag{14}$$

Each machining element, as an information entity required by the core feature of the parts, has a uniform processing technique which contains machining features F, machining process i and machining methods P. The machining element can be expressed as the Eq. (15):

$$ME = \{F_a, i, P\} \tag{15}$$

Generally speaking, the machining method can be composed of different resources in mechanical processing, which the compilations of machine, tools and other resources were included. The compilations of machine were set as: $M' = \{M'_1, M'_2, \dots, M'_b\}$, the compilations of tools were set as: $T' = \{T'_1, T'_2, \dots, T'_c\}$.

The compilations of process route can be written as the Eq. (16):

$$ME = \{me_1, me_2, \dots, me_a\} \tag{16}$$

where F_a is the a_{th} feature element, M'_b is the b_{th} machine, T'_c is the c_{th} tool. me_a is the set of all the machining elements of F_a. Process line is a random combination of all components in the set of machining elements for parts. For example $x = \{me_{a1}, me_{a2}, \cdots, me_{ai}\}$ means process route from begin at me_{a1} and end with me_{ai}. Hence, the problem of process route optimization can also be considered as the selection and sequencing of machining elements.

3.2 Multi-Objective Optimization Model

From the above discussion about the machining element analysis, the crux problem of the process route optimization design is to analysis the part feature structure, select the machining method, machining equipment and tool information, such that it can optimize the structure size of the parts and determine the sequential optimization design of machining methods. Note that it is essential to take carbon efficiency and processing time into consideration, hence, the process route should be a multi-objective optimization.

In order to realize the whole process line, the generalized carbon efficiency and processing time are optimized simultaneously, the machining process route optimization for low-carbon manufacturing is actually a selection and sorting of processing elements. The selection of processing elements includes the selection of machining methods, machines, tools etc. The general mathematical model of the optimization of process route can be expressed as a constrained combinatorial optimization problem, and the variable of combinatorial optimization is the process element sequence. Therefore, the optimization objective function for low-carbon manufacturing can be expressed as:

$$\min f(x) = y(Q_{process}, T_{total}) \tag{17}$$

3.2.1 Carbon Efficiency Function

Based on Eq. (1) and synthesizing the Eq. (2)–(13), carbon efficiency comprehensive calculation model could be established as the following Eq. (18):

$$\begin{aligned} Q_{process} &= \frac{C_{process}}{\sum_{i=1}^{i_0} \Delta V_i} = \left(\sum_{i=1}^{i_0} \sum_{j=1}^{j_0} M_{j_i} \times f_M^N + \sum_{i=1}^{i_0} \sum_{k=1}^{k_0} E_{k_i} \times f_E^N + \sum_{i=1}^{i_0} \sum_{l=1}^{l_0} W_{l_i} \times f_W^N \right) \Big/ \sum_{i=1}^{i_0} \Delta V_i \\ &= \sum_{i=1}^{i_0} \left[\begin{array}{l} \Delta m \times (f_M^{rmc} + f_W^{ad}) + \frac{T_{process}}{T_{rct}} \rho_{cf} V_{rvf} \times (f_M^{clc} + f_W^{lwd}) + \frac{T_{process}}{T_{tl}} m_{ct} \times f_M^{ctc} \\ + \frac{T_{process}}{T_{rcf}} m_f \times f_M^{fc} + \left(\int_0^{T_{no-load} + T_{process}} P_u dT + \int_0^{T_{process}} 1.2 P_c dT \right) \times f_E^{eec} \end{array} \right]_i \Big/ \sum_{i=1}^{i_0} \Delta V_i \end{aligned} \tag{18}$$

3.2.2 High Efficiency Function

The high efficiency of the process route can be defined as the shortest processing time, then the total processing time T_{total} of process route was taken as another optimization objective, which include part processing time T_{ppt}, machine replacement time T_{mrt} and tool replacement time T_{trt}. It can be described in detail as shown in Eq. (19):

$$T_{total} = T_{ppt} + T_{mrt} + T_{trt}. \tag{19}$$

1. Part processing time. The no-load time $T_{no\text{-}load}$ and processing time $T_{process}$ were included in parts processing time, as shown in Eq. (20):

$$T_{ppt} = \sum_{i=0}^{i_0} (T_{no-load_i} + T_{process_i}). \tag{20}$$

2. Machine replacement time

   If different machines are required for two adjacent processes, it is necessary to replace the machine. The parts were removed from the machine and then loaded into the next one. It can be obtained by the replacement time of each process machine. Therefore, the replacement time was as follows:

$$T_{mrt} = T_{emrt} \times \sum_{i=0}^{i_0-1} \left(M'_{i+1} - M'_{i} \right) \tag{21}$$

$$\left(M'_{i+1} - M'_{i} \right) = \begin{cases} 1, & M'_{i} \neq M'_{i+1} \\ 0, & M'_{i} = M'_{i+1} \end{cases} \tag{22}$$

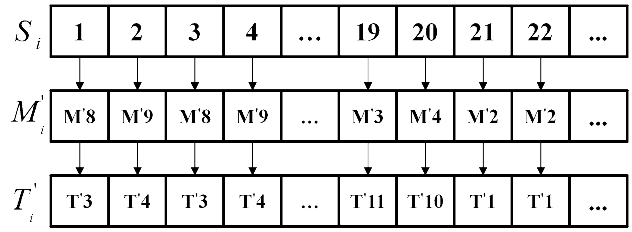

Fig. 4 Encoding method

where T_{emrt} is each machine replacement time, M'_i is the machine that the ith stage used. If two adjacent processes ith and $(i+1)$th were processed on the same machine, the result was $\left(M'_{i+1} - M'_{i} \right) = 0$, otherwise the answer was 1.

3. Tool replacement time

   The tool replacement time is calculated in a similar way to that of the machine, which also depends on the replacement according to time. As shown in Eq. (23), (24):

$$T_{trt} = T_{etrt} \times \sum_{i=0}^{i_0-1} \left(T'_{i+1} - T'_{i} \right) \tag{23}$$

$$\left(T'_{i+1} - T'_{i} \right) = \begin{cases} 1, & T'_{i} \neq T'_{i+1} \\ 0, & T'_{i} = T'_{i+1} \end{cases} \tag{24}$$

where T_{etrt} is tools replacement time, T_i' is the tools that the i_{th} stage used. If two adjacent processes ith and $(i+1)_{th}$ were processed on the same tool, the result was $\left(T'_{i+1} - T'_{i} \right) = 0$, otherwise the answer was 1.

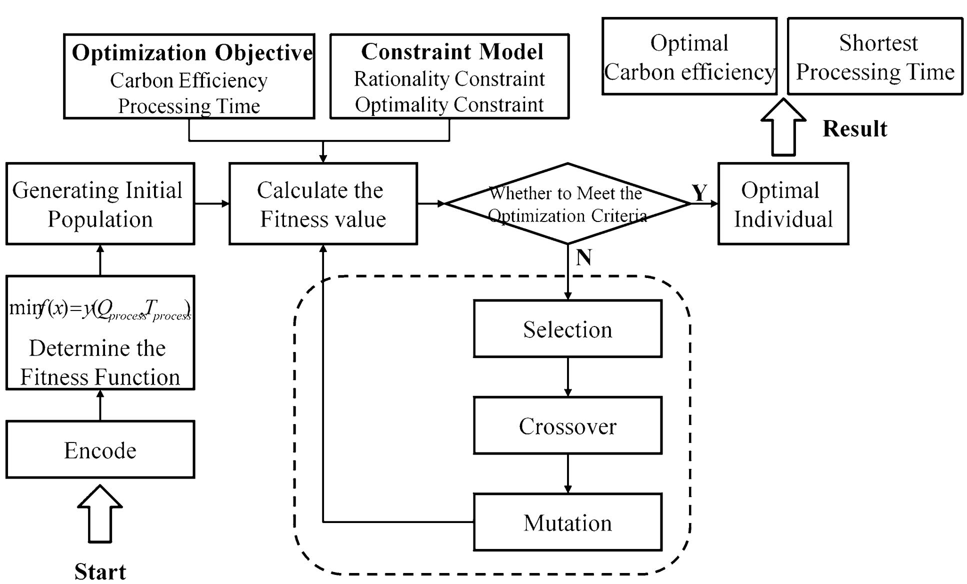

Fig. 3 Genetic algorithm flowchart

In conclusion, the total processing time of the process route can be expressed as:

$$T_{total} = \sum_{i=0}^{i_0} (T_{no-load_i} + T_{process_i}) + T_{emrt} \times \sum_{i=0}^{i_0-1} \left(M'_{i+1} - M'_i \right) + T_{etrt} \times \sum_{i=0}^{i_0-1} \left(T'_{i+1} - T'_i \right) \tag{25}$$

3.3 Constraint Model

The machining process of parts can be divided into rationality constraints and optimal constraints according to their mandatory differences. One optimal solution of process route optimization must satisfy rationality constraints and try to gratify optimal constraint as far as possible.

The rationality constraints include: (1) Coarse-to-precise, that is, first rough machining, then semi-finishing, and finally finishing machining; (2) Primary-to-secondary, that is, the main surface is processed first and the secondary surface is processed later; (3) The datum is processed before other surfaces. When there is geometric tolerance relationship between two machining features, the processing features including the benchmark are processed first. (4) Nondestructive constraint, that is, to ensure that the subsequent processing does not destroy the attributes generated during the previous processing. (5) In addition, the general rationality constraint should also meet the principles of non-destructive constraint relationship (the processing characteristics of the previous process cannot be destroyed in the subsequent processing process), and the processing order determined by the feature attribute itself (for example, the drilling of the inner hole must be done before the reaming process).

The optimal constraints are generally out of consideration for the optimization goal, including how to shorten the machining time, reduce costs, ensure the quality of machining precision, etc., The optimal constraints mainly including minimize the replacement of machines, tools and fixtures subject to the principles of processes concentration and processing economy.

The mathematical model of the constraint process through the following equations is as follows:

$$S.T. \begin{cases} RC_i(x) = 0, & i = 1, 2, \dots i_0 \\ OC_i(x) = 0, & i = 1, 2, \dots i_0 \\ x \in \Omega, & \Omega = x_1, x_2, \dots x_{i_0!} \end{cases} \tag{26}$$

Among them, $RC_i(x)$, $OC_i(x)$ are the rationality constraints and optimal constraints discussed above. Ω is the set of all the solutions in the component processing elements, which comprises of $i_0!$ process route. Due to the constraints, the practical process route plan should be far less than i_0.

3.4 Optimization Model Based on Genetic Algorithm

Genetic algorithm is a random search algorithm, which referenced from biology natural selection and natural genetic mechanism, and aims to search the optimal solution by simulating the natural evolution process. In this paper, an improved multi-objective genetic algorithm was used to solve the optimization of the machining process route. In order to meet the needs of practical problems, a coding method based on processing characteristics was adopted, and genetic operations such as crossover and mutation are adjusted accordingly to adapt to the coding mode and various constraints in actual machining process. The carbon efficiency and processing time are taken as the optimization objective and fitness equation to make evolutionary choices about the population.

The genetic algorithm optimization flowchart for the machining process route is shown in Fig. 3.

3.4.1 Encode

According to machining feature, every complete process route is represented by a chromosome, which includes machining sequence, machining machines, machining tools, etc. Chromosome is shown in Fig. 4, including machining procedure code S_i, machining machines code M'_i and machining tools code T'_i.

Each gene X in the substring represents the machining feature X of the part, while in the middle of S_i, the previous process will be machined prior to the subsequent process. Both M'_i and T'_i were coded according to the machining number of machines, of whose genes correspond to those in S_i.

3.4.2 Basic Operation of Genetic Algorithm

Genetic algorithm can be divided into three basic operations: selection, crossover and variation. We set up the corresponding coding for the process-machine-tool when encoding, The MATLAB functions (PemCom etc.) was used in this article to implement substitution to satisfy the sequence constraint of processing sequence (Coarse-to-precise, Primary-to-secondary etc.).

Selection is based on the fitness value of each individual, and individuals with better processing time and carbon efficiency in the current population were selected to perform genetic operation.

The crossover operation in this paper can be divided into the machining procedure, machines and tools. The operation

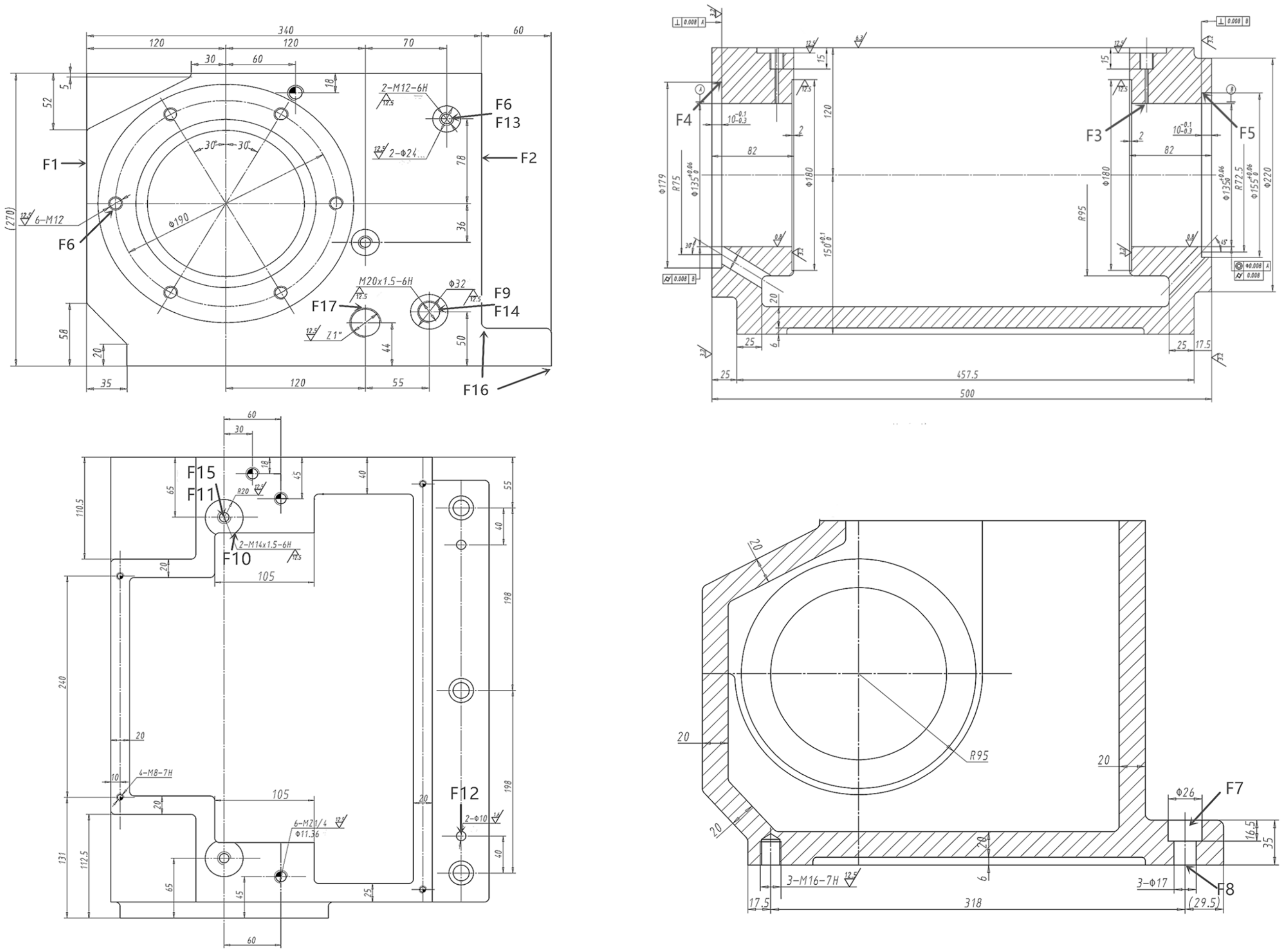

Fig. 5 Grinding carriage box

of generating new individuals by replacing and recombining parts of the two parent individuals by cross operations.

In order to adapt to the above mentioned encoding method based on processing characteristics, the improved block crossover method is adopted in this paper. The main steps are as follows: Chromosomes were divided into block cross point according to the processing sequence. The genes other than the intersections of parent chromosomes were copied to the same position of offspring chromosomes. Then, the genes outside the intersection are checked. If they do not conflict with the changed gene fragments, they are retained directly. If there is a conflict, they are replaced by mapping. The same gene in machining procedure of parental chromosome was deleted, and the remaining gene sequence of was maintained to copy it to the uncrossed position. The generation of illegal individuals and exchanges according to the mapping relationship in the matching region were avoided by this crossover scheme, so that the process sequence (work step) ordering is theoretically possible.

More genes were exchanged within a single chromosome to form new offspring under certain mutation probability through mutation operation. The main steps are as follows: A chromosome was randomly selected from the current population. Multiple random positive integers are generated as switching points within the interval of chromosome length n. More genes were exchanged at the switching point to form a new individual. The new individual was judged whether meets the constraint conditions. If satisfied, join the next generation group, otherwise return to the step.

3.4.3 Fitness function evaluation and operation parameters

Fitness function is a measurement tool to measure the quality of chromosomes. Its value is the basis of selection and operation, which directly affects the convergence performance and is an important factor of genetic optimization. The carbon efficiency and total processing time of the process route were optimized, and the Eqs. (18) and (25) were selected as

Table 1 Feature processing scheme of grinding carriage box

Machining feature	Feature name	Process	Process description
F1	Hole Φ135 × 2	Heavy boring–Finish boring	The shaving surface is location datum, boring(finish boring) Φ135 hole to request, deep 144 mm
F2	Hole Φ175	Heavy boring–Finish boring	Boring(finish boring)φ175 × 10 hole to request, deep 10 mm
F3	Hole Φ155	Heavy boring–Finish boring	Boring(finish boring)φ155 × 10 hole to request, deep 10 mm
F4	Upper end-surface	Heavy Planing–Finish Planing	Heavy planing upper end-surface size to 270, leave a remainder of 2–2.5 mm; finish planing to machining requirements
F5	Lower end-surface	Heavy Planing–Finish Planing	Heavy planing lower end-surface size to 270, leave a remainder of 2–2.5 mm; finish planing to machining requirements
F6	Hole Φ12 × 15	Drilling	Drilling bottom hole to15- Φ12, deep 20 mm
F7	Hole Φ26 × 3	Drilling	Drilling 3- Φ26, deep 16.5 mm
F8	Hole Φ16 × 3	Drilling	Drilling 3- Φ16, deep 18 mm
F9	Hole Φ20 × 2	Drilling	Drilling bottom hole to 2- Φ20, deep 25 mm
F10	Hole Φ40 × 2	Drilling	Drilling 2- Φ40, deep 9 mm
F11	Hole Φ14 × 2	Drilling	Drilling bottom hole to 2- Φ14, deep 6 mm
F12	Hole Φ10 × 2	Drilling	Drilling 2- Φ10, deep 35 mm
F13	Hole ΦM12 × 15	Tapping	Tapping 15-M12, deep 20 mm
F14	Hole ΦM40 × 2	Tapping	Tapping 2-M20, deep 25 mm
F15	Hole ΦM14 × 2	Tapping	Tapping 2-M14, deep 6 mm
F16	Chamfering	Finish turning	Machining to request chamfering
F17	Hole chamfering	Finish turning	Machining to request chamfering

Table 2 Machine list

Machine number	Types of machine	No-load power (kw)	Processing power (kw)	Workpieces handling time (s)
M′1	Common Lathe CA6140	5.2	5.3	30
M′2	Numerical Control Lathe CY500	3.1	3.5	30
M′3	Horizontal Machining Center KURAKI	9.89	10.7	100
M′4	Vertical Machining Center GF1220P	6.9	7.2	100
M′5	CNC Milling Planer VMC3030	9.68	10.2	100
M′6	Horizontal Milling and Boring Machine TX611D	3.0	8.3	90
M′7	Radial Drilling Machine Z3063	4.2	4.23	20
M′8	Shaper BY60100C	8.7	9.45	80
M′9	Planer BM2015	5.1	7.2	170

fitness functions to calculate the carbon efficiency and total processing time of each individual chromosome, based on which genetic algorithm optimization was carried out.

The weight coefficient transformation method was used to transform the multi-objective optimization problem into a single-objective optimization method. Then the linear weighting calculation is carried out. The linear weighted sum function is the fitness function.

Aiming at the objective function of the high efficiency and low carbon grinding optimization model, according to the corresponding sub-targets importance to determine weights, the weighted functions of the two sub-objective functions are expressed as:

$$func_{fit} = \omega_1 \times Q_{process} + \omega_2 \times T_{process} \tag{27}$$

where ω_1 and ω_2 are the weight coefficients.

The MATLAB computing software was used to implement the genetic algorithm. Then the GA randomly generated population and defined a fitness function based on the objective function after set the GA parameters. New individuals were then generated by using some genetic operators. The optimized results which meet the requirements would be output after the crossover, selection and mutation. Because

Table 3 Tool list

Tool number	Types of tool	Tool material	Tool type	Tool life (min)	Tool quality (g)
T′1	Common Turning Tool 1	High-carbon steel	C20-SPK30-150L chamfering knife	60	9
T′2	Common Turning Tool 2	High-carbon steel	C20-SPK25-150L chamfering knife	120	12
T″3	Common Planing Tool 1	Cemented carbide	YG8: JBD01	60	15
T′4	Common Planing Tool 2	Cemented carbide	YG8: JBD03	120	20
T′5	Common Drilling Tool 1	Cemented carbide	BIG: SCMP060204EFM	60	9
T′6	Common Drilling Tool 2	Cemented carbide	BIG: SCGA060204FN	90	9
T′7	Drilling Bit 1 (Diameter 10–20 mm)	Alloy	YG-1: D1201000; D1201025 D1201120; D1201160; D1201175	60	350
T′8	Drilling Bit 2 (Diameter 26 mm)	Alloy	YG-1: D1201260	75	450
T′9	Drilling Bit 3 (Diameter 40 mm)	Alloy	YG-1: D1201400	110	600
T′10	Screw Tap 1 (Diameter 12 mm, 14 mm)	High speed steels	RUIZHI: T1121502; T1121542	60	250
T′11	Screw Tap 2 (Diameter 40 mm)	High speed steels	OSG: 2322	120	500

the genetic algorithm is a random method and the approximate solution is obtained, the results of each calculation in the MATLAB environment will be slightly different.

4 Case Study

In order to verify the feasibility of carbon efficiency quantification method and the reliability of the process route optimization conclusion, we conducted an example study on manufacturing a grinding carriage box of CNC camshaft grinder. The grinding wheel box body was made of castings, and its dimensions and machining features are shown in Fig. 5.

4.1 Machining Feature and Experiments Analysis

The grinding carriage box contains many typical machining characteristics, such as upper end-surface, lower end-surface, hole, chamfering and hole chamfering. The main features and process description were shown in Table 1.

The machine to be used in the processing is shown in Table 2. Lathe (M′1/M′2), Machining Center (M′3/M′4), Milling and Boring Machine (M′5/M′6), Drilling Machine (M′7) and Planer (M′8/M′9) in the workshop. The machine power and the workpiece handing time were measured by experiment.

The relative parameters of machine tools can be found in the literature [25]. The replacement time of the tools is about 10 s. Since the hole size of the part is not consistent, the drill and the tap used are not the same. According to the small difference between the quality and life of some tools, the smaller ones were combined to simplify the calculation in this paper. All those machine tools and machines are always available for certain process procedure. The detailed tool information is shown in Table 3.

According to the above optional machines and tools, the experiment was carried out with the usual processing parameters of the enterprise, and the AWS2013S Power Analyser digital power meter was used to measure power. The carbon emission and carbon efficiency can be calculated through the established model. The experimental data obtained by selecting the machine and the tool for each machining feature of the parts, as shown in Table 4.

The traditional machining process route of enterprise is as follows:01 M′03T′05 → 02 M′03T′06 → 03 M′03T′05 → 04 M′03T′06 → 05 M′03T′05 → 06 M′03T′06 → 07 M′09T′04 → 08 M′09T′04 → 09 M′09T′04 → 10 M′09T′04 → 11 M′07T′07 → 12 M′07T′07 → 13 M′07T′07 → 14 M′07T′07 → 15 M′07T′07 → 16 M′07T′07 → 17 M′07T′07 → 18 M′07T′07 → 19 M′07T′07 → 20 M′07T′07 → 21 M′01T′01 → 22 M′01T′01.

4.2 Optimization Result

The key parameters of the genetic algorithm were set as follows: NIND (Number of individuals) = 500, MAXGEN (Maximum number of generations) = 500, Crossover = 0.9, Mutation = 0.1. The MATLAB computing software was used to implement the genetic algorithm to get the optimal process route, and the minimum processing time and optimal carbon efficiency were set as the optimization objectives. High efficiency and low carbon optimization convergent graph are shown in Fig. 6.

The optimal machining process route form generated by genetic algorithm optimization is shown in Fig. 7.

The above optimal performance form is compiled into machining process route as shown in Table 5.

Table 4 Machining feature, machining sequence and machining resources list

Machining feature	Feature name	Process	Process Step	Machining parameters	Machine	No-load time (s)	Processing Time (s)	Energy consumption (KW·h)	Carbon emission (Kg)	Carbon efficiency (g/cm^3)
F1	Hole Φ135×2	Heavy boring	1	Spindle speed: 67.5 r/min	M′3T′5	142	750	2.62	4.28	35.87
				Feed: 0.17 mm	M′3T′6	142	750	2.62	4.26	35.71
				Back cutting depth: 4 mm	M′5T′5	95	750	2.38	4.16	34.87
					M′5T′6	95	750	2.38	4.14	34.71
					M′6T′5	60	750	1.78	3.86	32.35
					M′6T′6	60	750	1.78	3.84	32.20
		Finish boring	2	Spindle speed: 88 r/min	M′3T′5	265	1400	4.89	4.32	141.95
				Feed: 0.07 mm	M′3T′6	265	1400	4.89	4.28	140.81
				Back cutting depth: 1 mm	M′5T′5	177	1400	4.44	4.09	134.60
					M′5T′6	177	1400	4.44	4.06	133.47
					M′6T′5	112	1400	3.32	3.53	116.16
					M′6T′6	112	1400	3.32	3.50	115.02
F2	Hole Φ175	Heavy boring	3	Spindle speed: 67.5 r/min	M′3T′5	10	52	0.18	0.35	31.97
				Feed: 0.17 mm	M′3T′6	10	52	0.18	0.34	31.85
				Back cutting depth: 4 mm	M′5T′5	6	52	0.16	0.34	31.11
					M′5T′6	6	52	0.16	0.33	30.99
					M′6T′5	4	52	0.12	0.32	29.25
					M′6T′6	4	52	0.12	0.31	29.13
		Finish boring	4	Spindle speed: 88 r/min	M′3T′5	18	97	0.34	0.31	113.70
				Feed: 0.07 mm	M′3T′6	18	97	0.34	0.31	112.83
				Back cutting depth: 1 mm	M′5T′5	10	97	0.30	0.29	107.10
					M′5T′6	10	97	0.30	0.29	106.23
					M′6T′5	6	97	0.23	0.26	93.72
					M′6T′6	6	97	0.23	0.25	92.84
F3	Hole Φ155	Heavy boring	5	Spindle speed: 67.5 r/min	M′3T′5	10	52	0.18	0.32	33.66
				Feed: 0.17 mm	M′3T′6	10	52	0.18	0.32	33.52
				Back cutting depth: 4 mm	M′5T′5	6	52	0.16	0.31	32.68
					M′5T′6	6	52	0.16	0.31	32.55
					M′6T′5	4	52	0.12	0.29	30.58
					M′6T′6	4	52	0.12	0.29	30.44
		Finish boring	6	Spindle speed: 88 r/min	M′3T′5	18	97	0.34	0.30	125.38
				Feed: 0.07 mm	M′3T′6	18	97	0.34	0.30	124.40
				Back cutting depth: 1 mm	M′5T′5	10	97	0.30	0.29	117.97
					M′5T′6	10	97	0.30	0.28	116.98
					M′6T′5	6	97	0.23	0.25	102.93
					M′6T′6	6	97	0.23	0.25	101.94

Table 4 (continued)

Machining feature	Feature name	Process	Process Step	Machining parameters	Machine	No-load time (s)	Processing Time (s)	Energy consumption (KW·h)	Carbon emission (Kg)	Carbon efficiency (g/cm^3)
F4	Upper end-surface	Heavy Planing	7	Spindle speed: 2100 r/min	M′8T′3	105	970	2.80	7.88	23.50
				Feed rate: 0.4 mm/r	M′8T′4	105	970	2.80	7.89	23.52
				Planing width: 0.4 mm	M′9T′3	450	970	2.58	7.77	23.16
				Planing depth: 5 mm	M′9T′4	450	970	2.58	7.78	23.19
		Finish Planing	8	Spindle speed: 2100 r/min	M′8T′3	42	390	1.13	2.19	26.16
				Feed rate: 0.4 mm/r	M′8T′4	42	390	1.13	2.20	26.20
				Planing width: 0.4 mm	M′9T′3	180	390	1.04	2.15	25.62
				Planing depth: 2 mm	M′9T′4	180	390	1.04	2.15	25.66
F5	Lower end-surface	Heavy Planing	9	Spindle speed: 2100 r/min	M′8T′3	189	1700	4.92	13.71	23.55
				Feed rate: 0.3 mm/r	M′8T′4	189	1700	4.92	13.72	23.58
				Planing width: 0.4 mm	M′9T′3	790	1700	4.52	13.51	23.21
				Planing depth: 5 mm	M′9T′4	790	1700	4.52	13.52	23.23
		Finish Planing	10	Spindle speed: 2100 r/min	M′8T′3	78	700	2.03	3.85	26.42
				Feed rate: 0.3 mm/r	M′8T′4	78	700	2.03	3.85	26.46
				Planing width: 0.4 mm	M′9T′3	325	700	1.86	3.77	25.85
				Planing depth: 2 mm	M′9T′4	325	700	1.86	3.77	25.89
F6	Hole Φ12×15	Drilling	11	Spindle speed: 250 r/min	M′3T′7	150	360	1.48	2.55	103.27
				Feed rate: 0.2 mm/r	M′4T′7	150	360	1.01	2.32	93.68
				Tool diameter: 10.25 mm	M′5T′7	150	360	1.42	2.53	102.08
					M′7T′7	150	360	0.60	2.11	85.40
F7	Hole Φ26×3	Drilling	12	Spindle speed: 250 r/min	M′3T′8	36	75	0.32	0.95	36.10
				Feed rate: 0.16 mm/r	M′4T′8	36	75	0.22	0.90	34.15
				Tool diameter: 26 mm	M′5T′8	36	75	0.31	0.94	35.87
					M′7T′8	36	75	0.13	0.85	32.46
F8	Hole Φ16×3	Drilling	13	Spindle speed: 250 r/min	M′3T′7	30	65	0.28	0.59	54.09
				Feed rate: 0.2 mm/r	M′4T′7	30	65	0.19	0.54	50.04
				Tool diameter: 16 mm	M′5T′7	30	65	0.26	0.58	53.60
					M′7T′7	30	65	0.11	0.51	46.53
F9	Hole Φ20×2	Drilling	14	Spindle speed: 250 r/min	M′3T′7	24	75	0.29	0.65	54.37
				Feed rate: 0.16 mm/r	M′4T′7	24	75	0.20	0.61	50.51
				Tool diameter: 17.5 mm	M′5T′7	24	75	0.28	0.65	53.88
					M′7T′7	24	75	0.12	0.57	47.18

Table 4 (continued)

Machining feature	Feature name	Process	Process Step	Machining parameters	Machine	No-load time (s)	Processing Time (s)	Energy consumption (KW·h)	Carbon emission (Kg)	Carbon efficiency (g/cm^3)
F10	Hole Φ40×2	Drilling	15	Spindle speed: 250 r/min	M′3T′9	28	33	0.18	0.64	28.15
				Feed rate: 0.13 mm/r	M′4T′9	28	33	0.12	0.61	26.92
				Tool diameter: 40 mm	M′5T′9	28	33	0.17	0.63	28.01
					M′7T′9	28	33	0.07	0.58	25.86
F11	Hole Φ14×2	Drilling	16	Spindle speed: 250 r/min	M′3T′7	20	15	0.10	0.13	97.94
				Feed rate: 0.2 mm/r	M′4T′7	20	15	0.07	0.12	86.31
				Tool diameter: 12 mm	M′5T′7	20	15	0.10	0.13	96.73
					M′7T′7	20	15	0.04	0.10	76.09
F12	Hole Φ10×2	Drilling	17	Spindle speed: 320 r/min	M′3T′7	24	82	0.31	0.57	102.80
				Feed rate: 0.16 mm/r	M′4T′7	24	82	0.21	0.52	93.74
				Tool diameter: 10 mm	M′5T′7	24	82	0.30	0.56	101.63
					M′7T′7	24	82	0.12	0.47	85.95
F13	Hole ΦM12×15	Tapping	18	Spindle speed: 250 r/min	M′3T′10	150	550	2.05	2.82	272.00
				Feed rate: 0.13 mm/r	M′4T′10	150	550	1.39	2.49	240.18
				Thread: M12	M′5T′10	150	550	1.96	2.78	267.89
					M′7T′10	150	550	0.82	2.21	212.85
F14	Hole ΦM40×2	Tapping	19	Spindle speed: 250 r/min	M′3T′11	20	90	0.32	0.49	138.45
				Feed rate: 0.13 mm/r	M′4T′11	20	90	0.22	0.44	123.75
				Thread: M40	M′5T′11	20	90	0.31	0.48	136.52
					M′7T′11	20	90	0.13	0.39	111.14
F15	Hole ΦM14×2	Tapping	20	Spindle speed: 250 r/min	M′3T′10	20	20	0.11	0.12	254.31
				Feed rate: 0.13 mm/r	M′4T′10	20	20	0.08	0.11	217.52
				Thread: M14	M′5T′10	20	20	0.11	0.12	250.29
					M′7T′10	20	20	0.05	0.09	185.38
F16	Chamfering	Finish turning	21	Spindle speed: 3200 r/min	M′1T′1	60	608	0.98	1.12	311.05
				Feed rate: 0.1 mm/r	M′1T′2	60	608	0.98	1.10	306.89
				Cutting depth: 2 mm	M′2T′1	60	608	0.64	0.95	263.97
					M′2T′2	60	608	0.64	0.94	259.80
F17	Hole Chamfering	Finish turning	22	Spindle speed: 3200 r/min	M′1T′1	79	432	0.75	1.36	44.46
				Feed rate: 0.1 mm/r	M′1T′2	79	432	0.75	1.35	44.11
				Cutting depth: 2 mm	M′2T′1	79	432	0.49	1.22	40.16
					M′2T′2	79	432	0.49	1.21	39.81

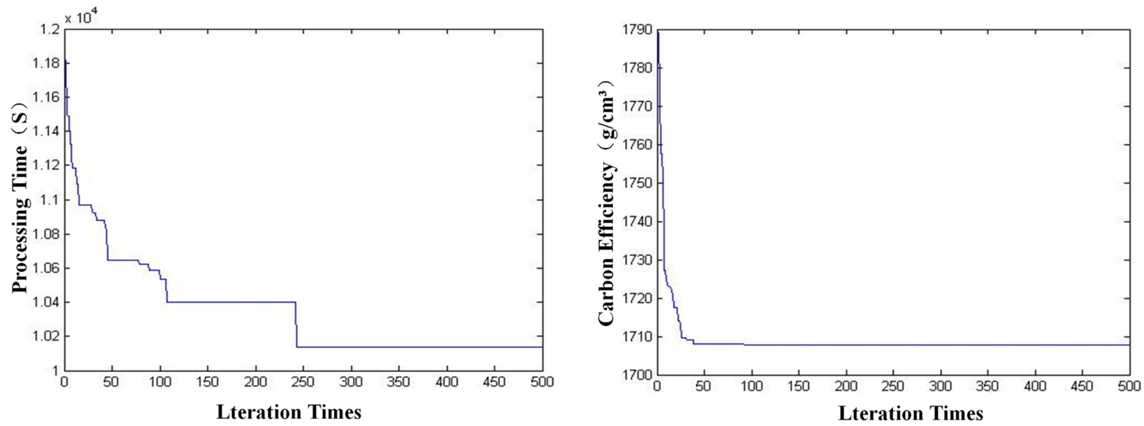

Fig. 6 High efficiency and low carbon optimization convergent graph

S_i	07	09	08	10	01	05	03	02	06	04	11	13	14	16	17	12	15	18	20	19	21	22
M'_i	08	08	08	08	06	06	06	06	06	06	07	07	07	07	07	07	07	07	07	07	02	02
T'_i	03	03	03	03	06	06	06	06	06	06	07	07	07	07	07	08	09	10	10	11	02	02

Fig. 7 Optimal machining process route performance chart

Table 5 Optimal machining process route

Machining feature	Processing technology	Processing scheme	Machine	Tool
F4 Upper end-surface F5 Lower end-surface	Planing	1. Heavy Planing (07)–F4 Upper end-surface 2. Heavy Planing (09)–F4 Upper end-surface 3. Finish Planing (08)–F5 Lower end-surface 4. Finish Planing (10)–F5 Lower end-surface	M′08	T′03
F1 Hole Φ135 × 2 F3 Hole Φ155 F2 Hole Φ175	Boring	5. Heavy Boring (01)–F1 Hole Φ135 × 2 6. Heavy Boring (05)–F3 Hole Φ155 7. Heavy Boring (03)–F2 Hole Φ175 8. Finish Boring (02)–F1 Hole Φ135 × 2 9. Finish Boring (06)–F3 Hole Φ155 10. Finish Boring (04)–F2 Hole Φ175	M′06	T′06
F6 Hole Φ12 × 15 F8 Hole Φ16 × 3 F9 Hole Φ20 × 2 F11 Hole Φ14 × 2 F12 Hole Φ10 × 2	Drilling	11. Drilling (11)–F6 Hole Φ12 × 15 12. Drilling (13)–F8 Hole Φ16 × 3 13. Drilling (14)–F9 Hole Φ20 × 2 14. Drilling (16)–F11 Hole Φ14 × 2 15. Drilling (17)–F12 Hole Φ10 × 2	M′07	T′07
F7 Hole Φ26 × 3	Drilling	16. Drilling (12)–F7 Hole Φ26 × 3	M′07	T′08
F10 Hole Φ40 × 2	Drilling	17. Drilling (15)–F10 Hole Φ40 × 2	M′07	T′09
F13 Hole ΦM12 × 15 F15 Hole ΦM14 × 2	Tapping	18. Tapping (18)–F13 Hole ΦM12 × 15 19. Tapping (20)–F15 Hole ΦM14 × 2	M′07	T′10
F14 Hole ΦM40 × 2	Tapping	20. Tapping (19)–F14 Hole ΦM40 × 2	M′07	T′11
F16 Chamfering F17 Hole Chamfering	Turning	21. Turning Chamfering (21)–F16 Chamfering 22. Turning Hole Chamfering (22)–F17 Hole Chamfering	M′02	T′02

Table 6 Experimental results of optimal machining process route

Processing scheme	Carbon emission from material flow	Carbon emission from energy flow	Carbon emission from environmental flow	Carbon efficiency
1	5.50	1.40	0.9864	23.50
2	1.39	0.56	0.2466	26.16
3	9.54	2.46	1.7111	23.55
4	2.41	1.01	0.4282	26.42
5	2.56	0.89	0.3926	32.20
6	1.67	1.66	0.1672	115.02
7	0.22	0.06	0.0346	29.13
8	0.13	0.11	0.0134	92.84
9	0.20	0.06	0.0310	30.44
10	0.12	0.11	0.0125	101.94
11	1.72	0.30	0.0927	85.40
12	0.71	0.07	0.0814	32.46
13	0.41	0.06	0.0355	46.53
14	0.47	0.06	0.0395	47.18
15	0.48	0.04	0.0683	25.86
16	0.08	0.02	0.0048	76.09
17	0.39	0.06	0.0207	85.95
18	1.73	0.41	0.0610	212.85
19	0.31	0.06	0.0154	111.14
20	0.06	0.02	0.0026	185.38
21	0.57	0.32	0.0444	259.80
22	0.86	0.24	0.1137	39.81

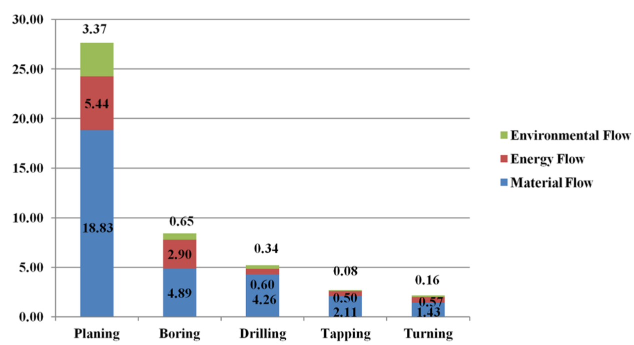

Fig. 8 Analysis process route of carbon emission based on "three flow"

4.3 Result Analysis

The carbon emission and carbon efficiency of the optimal process route were analyzed. The detailed experimental result was shown in Table 6. The results were as shown in Figs. 8 and 9.

It can be seen from Fig. 8 that the influence of "three flows" on carbon emission in the whole machining process route is: material flow > energy flow > environmental flow. The reasons for those were as follows: (1) The carbon emission from material were related to machining allowance;

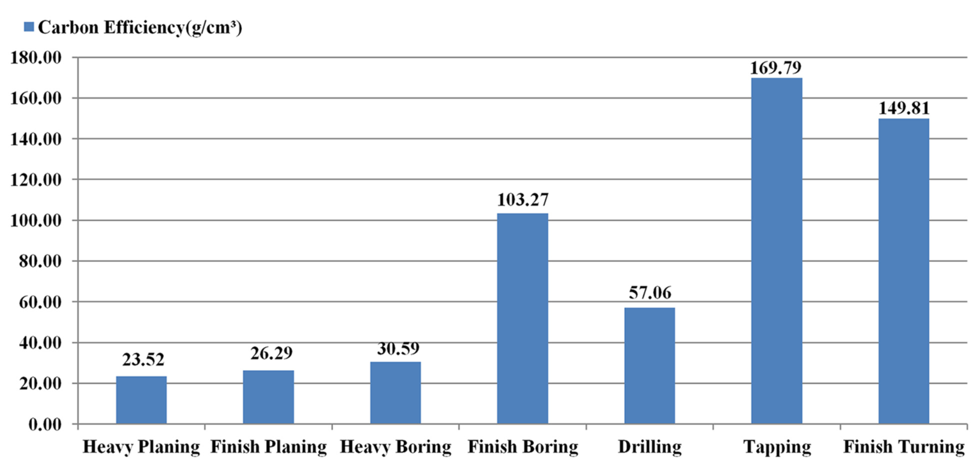

Fig. 9 Analysis process of carbon efficiency

Table 7 Comparison table of different processing route

Processing scheme	Processing time (s)	Energy consumption (KW·h)	Carbon efficiency (g/cm^3)
Tradition	12052	25.72	32.21
Optimized	10160	20.00	29.52
Optimized proportion (%)	15.70	22.24	8.35

(2) Material consumption of machining process is larger; (3) The processing time is not long; (4) This process lack of precision machining (such as grinding). Those factors lead to the carbon emission impact of material consumption more than the energy consumption and environmental consumption.

As shown in Fig. 9, the carbon emission of planing is obviously better than boring, drilling and tapping and turning, in addition, the carbon efficiency of heavy machining is better than that of precision machining, and the carbon efficiency of tapping and turning is worse. Compared with Fig. 8, carbon emission of planning is the biggest but carbon efficiency is the best. Instead, the turning process has less carbon emission but less carbon efficiency. It is because the planing process removes a lot of material, and the amount of finish turning and tapping is very small. It can be seen from the results that the processing efficiency should be improved, and the removal quantity should be increased to reduce the carbon emission and optimize the carbon efficiency.

In order to verify the feasibility of optimized result, the traditional process route of the enterprise was compared with the optimized process route, the comparison results are shown in Table 7.

Figure 10 shows the comparison of processing time, carbon emissions and carbon efficiency before and after the optimization, the results revealed clearly that the processing time and carbon emissions has been significantly reduced and the carbon efficiency has reached a better value after the optimization.

To achieve high efficiency and low carbon, the relatively concentrated tools and machine were used to reduce the change times of tools and machine in comparison to other case correspond in to less time processing. The process route optimization model has a better trade-off between carbon efficiency and processing time with decrease of the energy consumption and the increase of the carbon efficiency. It saved 15.7% processing time and increased 8.25% carbon efficiency on average, compared with traditional process route.

5 Conclusion

1. The carbon efficiency model (the produced carbon emissions per unit cutted-volume) of the machining process route was established based on the material flow, energy flow and environmental flow, and the process route optimization model of minimum processing time and optimal carbon efficiency were set up.
2. Based on the genetic algorithm, the optimization of the high efficiency and low carbon optimization model of the above process route was carried out, which realizes the optimization steps of different process characteristics, and the feasible and optimized process route was obtained.
3. With the established carbon efficiency model, it could effectively understand the carbon emission of different stages.
4. The optimized technological route was compared with the traditional one of the enterprises, and the results indicated that takes a reasonable process planning can effectively reduce carbon emission.

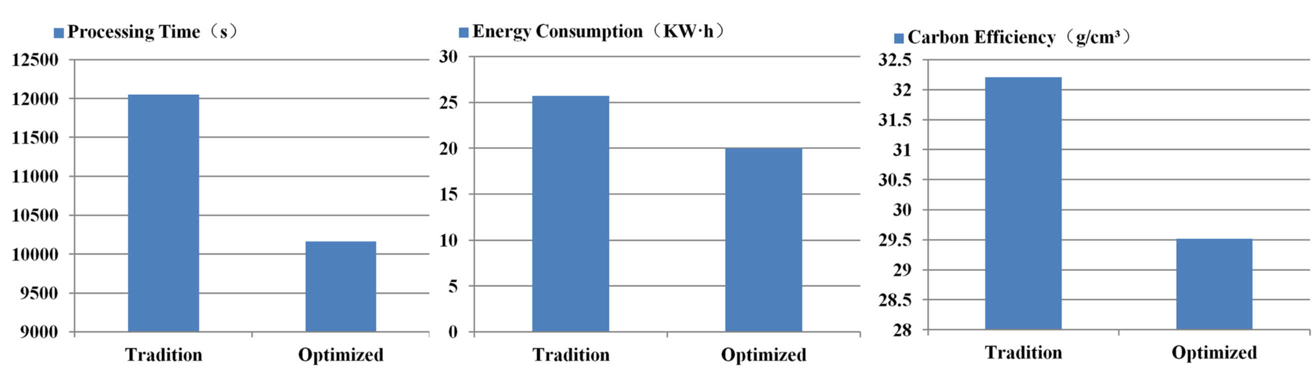

Fig. 10 Comparison diagram of different process route

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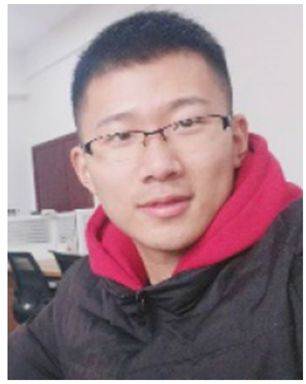

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