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ORIGINAL ARTICLE

CAD-based identification of product low-carbon design optimization potential: a case study of low-carbon design for automotive in China

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Abstract

The low-carbon design strategy that most Chinese manufacturers evaluate and improve in the product's life cycle in the late stage of product development extends the product development cycle. This paper combines low-carbon design theory with 3D design software, in the early stage of product design, by identifying low-carbon design optimization potential, the feedback mechanism of evaluation results and design recommendations is established to guide designers' conduct in low-carbon design in real time. Taking low-carbon design of Chinese automobile for instance, based on the life cycle carbon emission analysis of automobile products and the construction of a quantification model of the life cycle carbon emission, from the viewpoints of the structure, material, process, disassembly, and recycling of automobile products, this paper constructs the low-carbon evaluation index of automobile products; puts forward the method of identifying low-carbon design optimization potential of automobile parts, which is used to develop a low-carbon design integrated system for automobile products; and explains the workflow and theoretical realization scheme of the integrated system. Finally, taking the design process of automobile engine as an example, through the analysis results of the integrated system, it can be seen that the raw material acquisition stage of the engine has the largest carbon emission, and the carbon emission of the cylinder block is the largest. Based on the established evaluation model, the optimization suggestions are given on the structure and materials, and the feasibility of the integrated system is verified.

Keywords Low-carbon design · Optimization potential · Automotive carbon emissions · Computer-aided design · Integrated system

1 Introduction

In recent years, environmental issues have become increasingly valued and due to the improvement of some environmental regulations, many companies begin to consider low-carbon design. At present, the low-carbon design strategy has been adopted by most automobile manufacturers; it is used to identify the main influencing factors of product life cycle evaluation in the late stage of product development and then to improve the design based on the evaluation results. The strategy delays the product development cycle. On the one hand, the data associated with life cycle assessment (LCA) tools cannot be communicated and integrated with each other. On the other hand, designers need to spend more time analyzing complex environments and assessing their impact, which will substantially increase the time for product development. Therefore, more and more enterprises and manufacturers need a tool that can analyze product life cycle at design stage and integrate 3D computer-aided design (CAD) software and LCA analysis tools.

There have been some related studies in this field, which mainly focuses on the analysis of carbon emission performance, low-carbon design method, and low-carbon process planning and optimization. Firstly, in aspect of product carbon emissions performance analysis, according to the basic information of product life cycle, Haapala K et al. [1, 2] constructed the energy consumption forecasting model of product manufacturing process, so as to analyze the environmental impact of products and improve the environmental performance of products. Based on the life cycle theory, Song J-S et al. [3] proposed the model of carbon emission estimation based on the greenhouse gas emission equivalent of parts and developed the low-carbon design system of electronic products based on g-BOM and carbon emission estimation model. He B et al. [4] presented a carbon footprint model and a low-carbon conceptual design framework

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where the environmental impacts throughout the life cycle of a product can be assessed. A feature-based life cycle modeling approach was proposed by Tao J et al. [5] to address life cycle representation, retrieval, and integration of valuable data from current computer-aided engineering tools and formulation of relations between various product and process design factors and product environmental impact indicators for sustainability improvement analysis. Zhang C et al. [6] proposed an approach integrating structural optimization and material selection to reduce the carbon emissions of mechanical parts from the perspective of manufacturing system.

Second, in terms of low-carbon design methods, Bank JVD et al. [7] aimed to validate the LCA-CAD integrated system through commercial product to make the ecological design during the design phase, a comparative analysis of two CAD integrated SLCA tools and a dedicated LCA tool were performed to determine the accuracy of the tool. Gaha R et al. [8] proposed a system for implementing CAD/CAM integration based on feature technology, the system was used to select the minimum environmental impact process and production mode, with a typical box type parts to verify the feasibility and effectiveness of the system. Ostad-Ahmad-Ghorabi H et al. [9] summarized the CAD model data needed in the LCA analysis and describes the possibility of integrating LCA in CAD based on the link between the model information data and the LCA database. Finally, an environmental assessment tool for the early design phase was developed. Chen Z et al. [10] proposed a CAD-LCA software integration approach based on feature technology and a feature-based LCA system prototype tool which has the capabilities of processing product feature models, generating the life cycle process model based on product-to-operation feature mapping, and performing life cycle inventory (LCI) and impact assessment. Lu Q et al. [11] presented an allocation method of carbon emissions based on the product's temperature field to support the low-carbon design. The result showed carbon emissions of the usage stage had a close connection with the temperature distribution and gradient. In addition, the effective allocation method provided a theoretical basis for the target parts or components decision in the low-carbon design. Viñoles-Cebolla R et al. [12] proposed a method to estimate the principal types of emissions throughout a vehicle's life cycle based on primary data and the proposal had been validated by analyzing three different fuels of internal combustion engine vehicles.

In addition, in terms of low-carbon process planning and optimization, Zhang X et al. [13] developed an integrated system that automates part process planning in Pro/E environment, expounded the theoretical design of the functional modules of the development system, and carried out an in-depth study on the key technologies of the integrated system. Zhang H et al. [14] built the technological characteristics of libraries through the group technology and used knowledge engineering theory to express the feature library, develop integrated system which supports process decisions, and CNC programming based on process feature library. Li CB et al. [15] used the characteristic and the processing elements to express the geometric and process characteristics of the parts. Time and carbon emission were taken as the optimization objectives to construct the multi-objective optimization design model of the processing route, and the genetic algorithm was used to solve the problem. To reduce carbon emissions of process routes of parts and simultaneously consider economic and high-efficiency factors, Zhou GH et al. [16] proposed a low-carbon multi-objective process route optimization method.

At present, the related researches on integrating LCA into CAD software mainly focus on carbon emission assessment at a certain stage of the product life cycle or simply based on the feature recognition technology, put forward some theoretical solutions of product process design and establish the product process model library, and the research about integrated system is less. This paper presents a product low-carbon design-integrated system that differs from Dassault System's SolidWorks in providing CAD-embedded SolidWorks Sustainability software. SolidWorks Sustainability uses LCA standards and the Gabi environmental impact database, designers, and engineers can perform real-time environmental assessments during the low-carbon design of their products. However, due to the different low-carbon design capabilities of different designers, they often lack the guidance of low-carbon design advice when implementing low-carbon improvement, which resulting in inefficient low-carbon design. Product low-carbon design-integrated system discussed in this paper generates environmental performance evaluation result; it will also give many suggestions for improving low-carbon design to guide engineers to select the appropriate low-carbon design process technology and parts, which can enhance the low-carbon properties of products, and then products meet the relevant green standards. On the other hand, instead of using the GaBi database directly like SolidWorks Sustainability, this system uses data from Chinese automotive companies in the raw materials, manufacturing, shipping, and use phases. Therefore, the product low-carbon design integrated system is more in line with the actual Chinese enterprises.

2 The research object and its system boundary

2.1 The choice of research object

The manufacture of automobiles mainly includes blank forming, heat treatment, machining, welding, painting, and assembly [17]. Because the components of automobiles are numerous and the manufacturing processes of parts are different, therefore, this paper chooses the metal component that have a great impact on the carbon emission as the research object.

2.2 System boundary

The life cycle of automobile mainly includes the acquisition of raw materials and energy, production, transportation, use, maintenance, recovery, and processing. Considering the life cycle carbon emission in the design stage, it is difficult to evaluate the response of the parts materials, structure, and manufacturing process on the use of the later products in the design stage. In addition, in view of the difficulty of data collection in the sales and maintenance stages, there are still many uncertainties which exerts little influence on the overall result so it will not be considered temporarily. Therefore, according to the international standard ISO14041 and the research objective, the boundary of the life cycle system of the typical automobile parts is determined; it is shown in Fig. 1.

3 Study on the quantitative methods of automobile carbon emissions

3.1 Raw material stage

Material consumption is the main factor affecting the carbon emissions at the acquisition stage of components. Carbon emissions can be calculated according to Eq. 1 [18]. As the parts have different losses in the manufacturing process, this paper studies the manufacturing process of the automobile manufacturing enterprises by setting the material loss rate from 2 to 5%, for some processes that are difficult to obtain their loss rate through research, the default value of 5% is adopted. Carbon emission factors are material-driven and can be obtained through production emissions date of primary materials released by the Intergovernmental Panel on Climate Change, National Bureau of Statistics and GaBi's own database.

$$G_{\text{material}} = \sum_{i=1}^{n} (M_i \times EF_i) = \sum_{i=1}^{n} [\rho_i V_i \times (1+\eta) \times EF_i] \quad (1)$$

where

G_{material} is GHG emissions for raw material acquisition phase (kg CO_2e)
M_i is the mass of the i-type material contained in the component (kg)
EF_i is the ith substance emission factor (kg CO_2e/kg)
ρ_i is the density of the ith substance (kg/m^3)
V_i is the volume of the ith substance (m^3)
η is the loss rate of the material

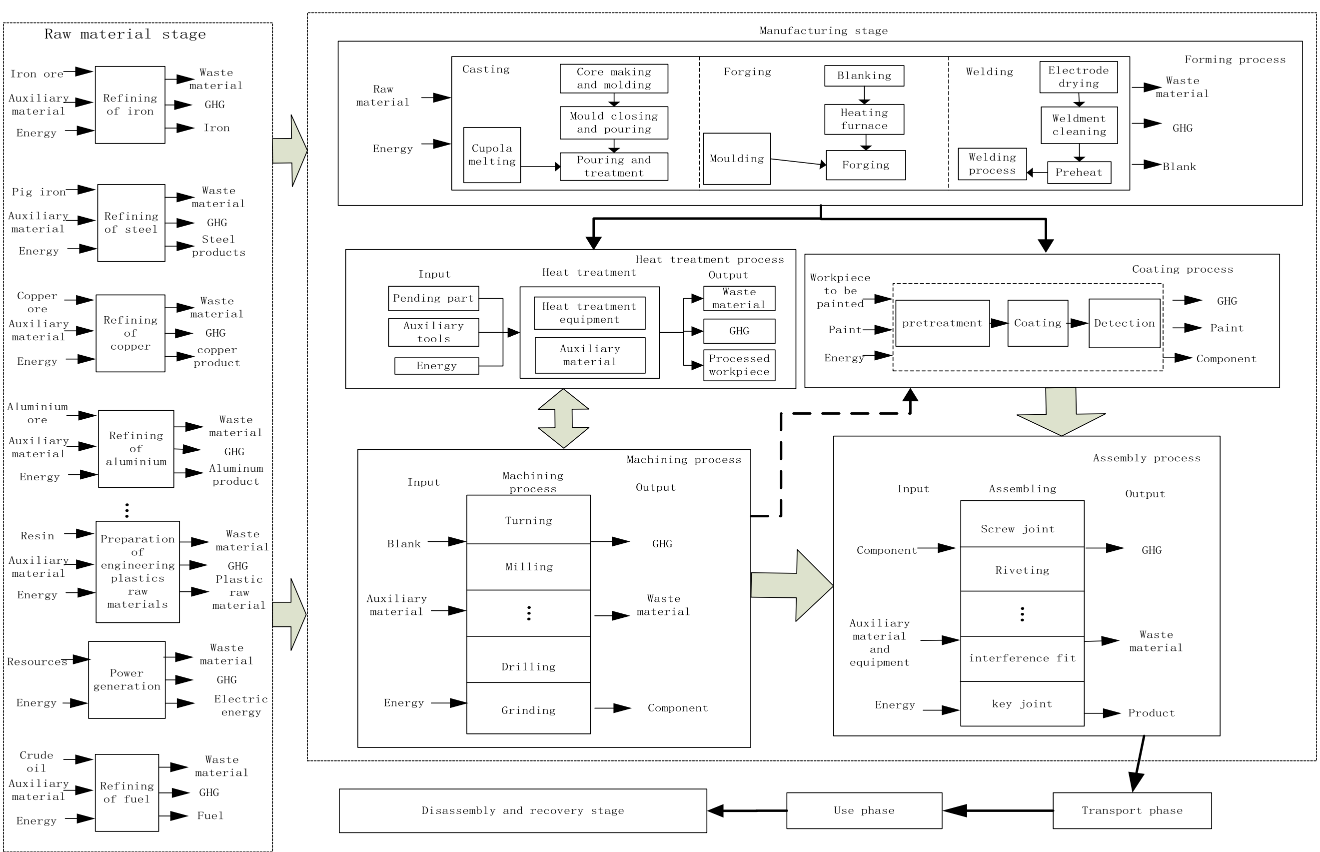


Fig. 1 System boundary

3.2 Manufacturing stage

The manufacturing phase of automotive components includes parts processing (including rough forming, parts heat treatment, mechanical processing); parts welding process; parts painting process; and parts assembly process. In the manufacturing stage, each process is considered as an independent system in the process of calculating carbon emissions, and the carbon emissions of each system are separately calculated, and the total emissions in the manufacturing stage are accumulated sequentially. Therefore, the quantitative model is

$$\begin{aligned} G_{\text{manufacture}} &= G_{\text{Machining}} + G_{\text{welding}} + G_{\text{paining}} + G_{\text{assembly}} \\ G_{\text{Machining}} &= G_{\text{forming}} + G_{\text{heating}} + G_{\text{cuting}} \end{aligned} \tag{2}$$

3.2.1 Automobile parts processing technology

Typical forming process

1. Casting process

The blanks of the key parts of automobiles are produced by sand casting. Therefore, sand casting was taken as the research object. The carbon emission assessment boundary of the process is shown in Fig. 2.

Calculation formula of carbon emission in cupola melting

$$CM\Delta t = \eta m q \tag{3}$$

where

- C is the specific heat capacity of the workpiece (J/kg °C)
- M is the quality of the workpiece (kg)
- Δt is the temperature difference between metal inlet and outlet furnace (°C)
- η is the heat utilization rate, which is usually 60%
- m is the quality of standard coal (kg)
- q is the calorific value of coal derived from the general rules of comprehensive energy consumption (GB/T 2589–2008), is 29,307 kJ/kg

The amount of standard coal consumed in the process of smelting can be calculated by the upper model:

$$m = \frac{CM\Delta t}{\eta q} = \frac{CM\Delta t}{29,307 \times 60\%} = \frac{CM\Delta t}{17,584.2} \tag{4}$$

According to reference [19], limestone accounts for 0.042 kg in the list of each kilogram cast iron. Because the reaction of limestone in high-temperature environment will produce carbon dioxide ($CaCO_3 \rightarrow CaO + CO_2$), the direct discharge of calcium carbonate in the melting process is

$$G_{CaCO_3} = \frac{44 \times 0.042}{100} M = 0.0185M \tag{5}$$

In the process of sand casting, the sand can be reused; the power consumption of molding and falling sand is small. To simplify the quantitative difficulty, this paper will not consider these secondary factors. In conclusion, the approximate formula of carbon emission in sand casting process is concluded

$$G_{\text{casting}} = m \times EF_{\text{coal}} + 0.0185M \tag{6}$$

2. Forging process

Automotive parts are small in size and complex in structure, so the die forging is widely used. The evaluation boundary of die forging is shown in Fig. 3.

The blank is generally heated by induction furnace, and the formula of carbon emission caused by the consumption of electric energy is calculated

$$G_h = \frac{CM\Delta t}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{7}$$

The main factors of the forging process are the emissions caused by the energy consumption of the forging press. Therefore, the total amount of carbon emissions during forging process is the accumulation of emissions during the heating and forging process:

$$G_{\text{forging}} = \frac{CM\Delta t}{3.6 \times 10^6} \times EF_{\text{elc}} + P_f T \tag{8}$$

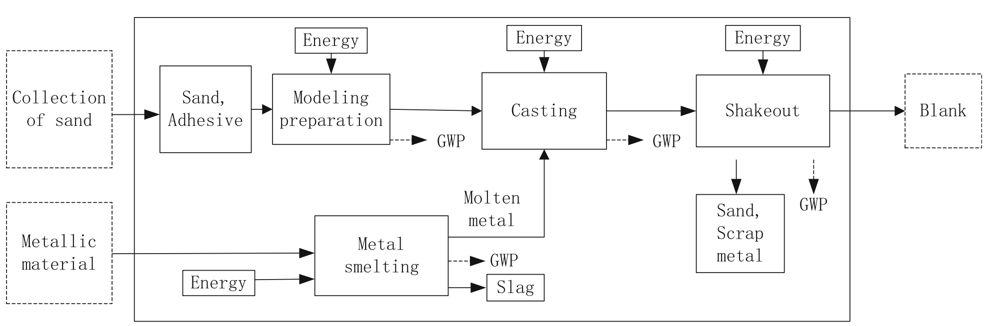
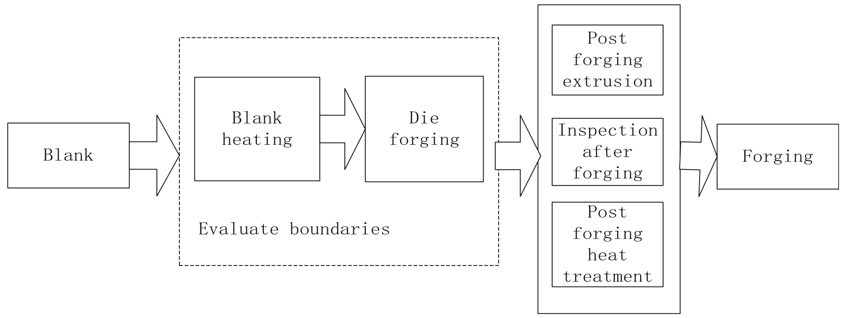


Fig. 2 Evaluation boundary of carbon emission during sand casting process

Fig. 3 Carbon emission evaluation boundary of forging process



where

P_f is the average power for the forging press (kW)
T is the working cycle (6 s) of the forging press

3. Powder metallurgy process

The process of powder metallurgy is shown in Fig. 4 [19]. The main carbon emissions are process equipment energy consumption and energy consumption during sintering process.

The carbon emission formula of the process:

$$G_{\text{powder}} = \left(P_h t_h + P_y t_y\right) \times EF_{\text{elc}} + \frac{CM\Delta t}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{9}$$

where

P_h is the power of mixer (kW)
t_h is the powder mixing time (h)
P_y is the power of press (kW)
t_y is the press forming time (h)
C is the specific heat capacity of compact blank (J/kg °C)
M is the quality of compact (kg)
Δt is the temperature difference (°C)

Heat treatment process During the heat treatment process, the cleaning liquid and cooling medium can be used repeatedly and less affectedly; thus, the carbon emissions of these parts can be ignored and indirect carbon emissions caused by energy consumption during heating and insulation processes are only considered. According to the national standard GBT17358-2009 heat treatment production power consumption calculation and determination method, a heat treatment process energy consumption can be calculated

$$N_i = N_b \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \tag{10}$$

where

N_i is the ith heat treatment process consumes electricity (kWh/kg)
N_b is the standard process power consumption (0.28 kwh/kg)
k_1, k_2, k_3, k_4, and k_5 are the conversion coefficient of the heat treatment process, the heating mode coefficient, the production mode coefficient, the workpiece material coefficient and the loading factor. k_1, k_2, k_3, k_4, and k_5 can be obtained by the national standard GBT17358-2009 lookup according to the actual situation of the heat treatment

The process of carbon emissions can be calculated:

$$G_{\text{heating}} = \sum_{i=1}^{n} N_i \times m_i \times EF_{\text{elc}} \tag{11}$$

where

m_i is the quality of the ith heat treatment process (kg)
n is the total number of heat treatment processes

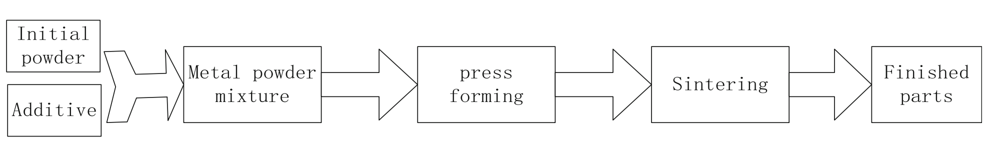
Typical machining process The parts machining process carbon footprint model is shown in Fig. 5. Therefore, taking a single step system as the core, carbon emissions of parts machining process can be solved by accumulation:

$$G_{\text{cutting}} = \sum_{i=1}^{n} G_{\text{ci}} \tag{12}$$

1. Turning

Turning carbon emissions are based on material and energy carbon emissions. Cutting power can be calculated according

Fig. 4 Carbon emission assessment boundary of powder metallurgy process



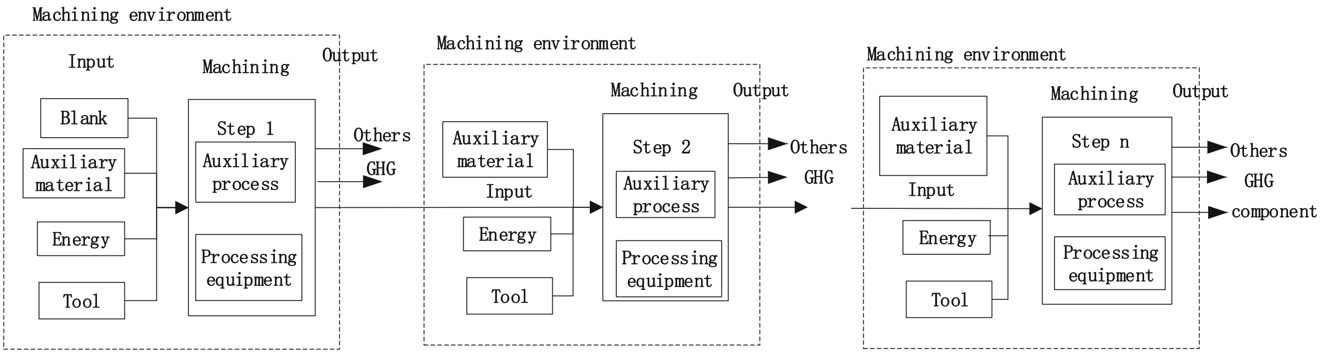


Fig. 5 Carbon footprint model of machining process

to the rated power of the processing equipment. For cutting time, this paper only considers the processing time, it can be calculated

$$t = \frac{v}{r} \tag{13}$$

where

t is the processing time
v is the volume of the material to be removed
r is material removal rate

Thus, the quantitative expression of carbon emissions from parts turning can be approximated

$$G_C = \left(\frac{L\Delta}{60 \times nfa_p}\right) \times p_c \times EF_{\text{elc}} \tag{14}$$

where

n is the spindle speed (r/min)
L is the turning length (mm)
Δ is the working allowance (mm)
f is the feed (mm/r)
a_p is the amount of knifing
p_c is lathe power (kW)

2. Milling

According to the milling characteristics, the carbon emissions in the process is summarized

$$\begin{aligned} Z_X &= a_p a_e v_f \\ G_X &= \left(\frac{S\Delta}{60 \times Z_X}\right) \times P_X \times EF_{\text{elc}} \end{aligned} \tag{15}$$

where

Z_X is the milling metal cutting rate [20] (mm^3/min)
v_f is the feed rate (mm/min)
a_p is the milling depth (mm)
a_e is the milling contact depth (mm)
S is the milling area (mm^2)
P_X is milling machine power (kW)

3. Grinding

As an example, the energy consumption of excircle grinding is analyzed

$$\begin{aligned} Z_M &= \pi d_m n_m a_e f_l \\ G_M &= \left(\frac{S\Delta}{60 \times Z_M}\right) \times P_M \times EF_{\text{ele}} \end{aligned} \tag{16}$$

where

Z_M is the grinding metal cutting rate [20] (mm^3/min)
d_m is the diameter of the part to be machined (mm)
n_m is the speed of parts to be machined (r/min)
a_e is the grinding contact depth of the arc (mm)
f_l is the vertical feed (mm/r)
S is the surface area of the part to be machined (mm^2)
P_M is the power of the grinder (kW)

4. Drilling

Quantitative expression of carbon emissions in drilling process

$$G_Z = \left(\frac{H}{60 \times fn}\right) \times N \times p_z \times EF_{\text{elc}} \tag{17}$$

where

H is the machining depth along the axis (mm)
f is the tool feed (mm/r)
n is the spindle speed (r/min)
N is the number of holes machined
P_z is the power of the equipment used (kW)

3.2.2 Welding process

1. Spot welding

The main influential factor of carbon emission in spot welding is the consumption of electric energy. Approximate formula for carbon emission:

$$G_{\text{welding}} = I^2 R t_{\text{weld}} \cdot N \times \text{EF}_{\text{elc}} = I^2 R t_{\text{weld}} \cdot \left(\frac{l}{d}+1\right) \times \text{EF}_{\text{elc}} \quad (18)$$

where

I is the average current through welding area (A)
R is the welding area resistance (Ω)
t_{weld} is the through the welding current time (s)
N is the solder joint quantity
l is the welding length
d is the distance between two solder joints

2. Electrode arc welding

According to reference [21], the approximate expression of carbon emission in welding process is known:

$$G_{\text{welding}} = m_{\text{welding}} \times EF_{\text{welding}} + E_{\text{welding}} \times EF_{\text{elc}} \quad (19)$$

where

m_{welding} is the electrode consumption during welding (kg)
EF_{welding} is the carbon emission factor of welding rod (kg CO_2e/kg)
E_{welding} is the energy consumption of the welding process (kWh)
EF_{elc} is the carbon emission factor of power grid (kg CO_2e/kg)

The parameter calculation expression is shown in the following Tables 1 [21] and 2 [22].

3. CO_2 gas shielded arc welding

The major carbon emission factors in the preparation process before welding are the consumption of acid bath and electrical energy and direct and indirect carbon emissions during the welding process. Quantitative expression of approximate carbon emission in welding process based on reference [21]:

$$G_{\text{welding}} = m_{\text{welding}} \times EF_{\text{welding}} + E_{\text{welding}} \times EF_{\text{elc}} + m_{co_2} \times EF_{co_2} \quad (20)$$

where

m_{welding} and E_{welding} are the amounts of welding wire (kg) and electric energy consumed (kWh) during welding
EF_{welding}, EF_{elc}, and EF_{co2} are the carbon emission factors (kg CO_2e/kg) for welding wire, power grid, and carbon dioxide, respectively
m_{co2} is the direct emissions of carbon dioxide during welding (kg).

The solution of m_{welding} and E_{welding} are the same as the electrode arc welding

For the direct carbon emissions caused by the use of carbon dioxide gas in the welding process, the emissions are

$$m_{co_2} = T_{\text{welding}} \times Q_{CO_2} \times \rho_{CO_2} \quad (21)$$

where

T_{welding} is the welding time (s)
Q_{co2} is the flow rate of CO_2 gas during welding (cm^3/s)
ρ_{co2} is the density of CO_2 gas during welding (g/cm^3)

3.2.3 Coating process

The main influencing factors of carbon emission in coating process are coating and energy consumption. According to the characteristics of different coating materials, the consumption of coatings with different coatings was calculated, respectively

$$M = S \times K \times n \quad (22)$$

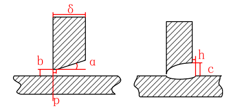
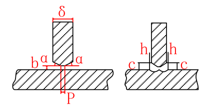
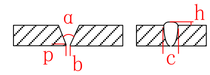
where

M is the consumption of paint (g)
S is the surface area of the parts (m^2)
K is the quality of the paint per square meter (g/m^2)
n is the number of road paint

Table 1 Welding parameters of electrode arc welding

Parameter	Formula	Remarks
m_{welding}	$m_{\text{welding}} = A \times L \times \rho_{\text{welding}}$	A is the cross-sectional area of the groove (cm^2); L is total length of welding (cm); ρ_{welding} is the density of electrode (g/cm^3)
E_{welding}	$E_{\text{welding}} = T_{\text{welding}} \times U \times I$	T_{welding} is welding time (s);U is welding voltage (V); I is welding current (A)
T_{welding}	$T_{\text{welding}} = 225 \times m_{\text{welding}}$	The welding time is proportional to the electrode consumption

Table 2 Cross-sectional area of groove

Groove type	Calculation of cross-sectional area	Cross-sectional view of groove
Unilateral *T* type	$A=\delta b+\frac{(\delta-p)^2\tan\alpha}{2}+\frac{2}{3}hc$	
Bilateral *T* type	$A=\delta b+\frac{(\delta-p)^2\tan\alpha}{4}+\frac{3}{4}hc$	
V type butt joint	$A=\delta b+(\delta-b)^2\tan\frac{\alpha}{2}+\frac{2}{3}hc$	

As a result, the amount of carbon emissions caused by the consumption of the paint can be calculated

$$G_{\text{coating}}=\sum_{i=1}^{3}M_i\times EF_i \tag{23}$$

where

M_i is the quality of paint used in layer i
EF_i is the carbon emission factor corresponding to the ith layer coating

The spraying robot will consume a great deal of electric energy in the process of painting

$$G_{\text{elc}}=PT\times EF_{\text{elc}}=P\frac{nS}{S_0}\times EF_{\text{elc}} \tag{24}$$

where

P is the power of spraying equipment (W)
T is the spraying time (s)
S is the surface area of the sprayed material (m^2)
S_0 is the spraying area per unit time of spraying equipment (m^2/s)
EF_{elc} is the carbon emission factor of power grid

Therefore, the total carbon emission during the coating process is

$$\begin{aligned}G_{\text{paining}}&=G_{\text{coating}}+G_{\text{elc}}\\&=\sum_{i=1}^{3}M_i\times EF_i+P\frac{nS}{S_0}\times EF_{\text{elc}}\end{aligned} \tag{25}$$

3.2.4 Assembly process

The carbon footprint model of the assembly process is shown in Fig. 6. The carbon emission equation is

$$G_{\text{assembly}}=\sum_{i=1}^{n}G_{ai} \tag{26}$$

In order to simplify the quantization process, all energy consumption is unified into electrical energy consumption. The carbon emission of each connection is shown as following, where formulas 27–33 refer to the literature [23].

1. Threaded connection: According to reference [23], the process of carbon emissions quantification is studied by taking an ordinary screw thread connection as an example.

$$\begin{aligned}G_s&=\frac{M\theta}{3.6\times10^6}\times EF_{\text{elc}}\\M&=KDF\times10^{-3}\\\theta&=360\times\frac{F}{P}\times\left(\frac{1}{C_1}+\frac{1}{C_2}\right)\end{aligned} \tag{27}$$

where

M is the tightening torque
θ is the thread angle
K is the resistance coefficient, which is related to the diameter of thread and the coefficient of friction, with a general value of 0.2
F is the pretightening force, which is generally 70–80% of the thread failure load, and the failure load generally takes the product of the yield limit of the thread and the effective area of the thread
D is the nominal diameter of the thread
C_1 and C_2 are, respectively, the connected parts and the stiffness of the connected parts
P is the pitch

2. Interference connection

$$\begin{aligned}&G_i=\frac{PS}{3.6\times10^6}\times EF_{\text{elc}}=\pi fLi\frac{E_1E_2}{(C_1E_2+C_2E_1)\times3.6\times10^6}\times EF_{\text{elc}}\\&C_1=\frac{D^2-d^2}{D^2+d^2}+\mu_1\qquad C_2=\frac{d^2-{d_0}^2}{d^2+{d_0}^2}+\mu_2\end{aligned} \tag{28}$$

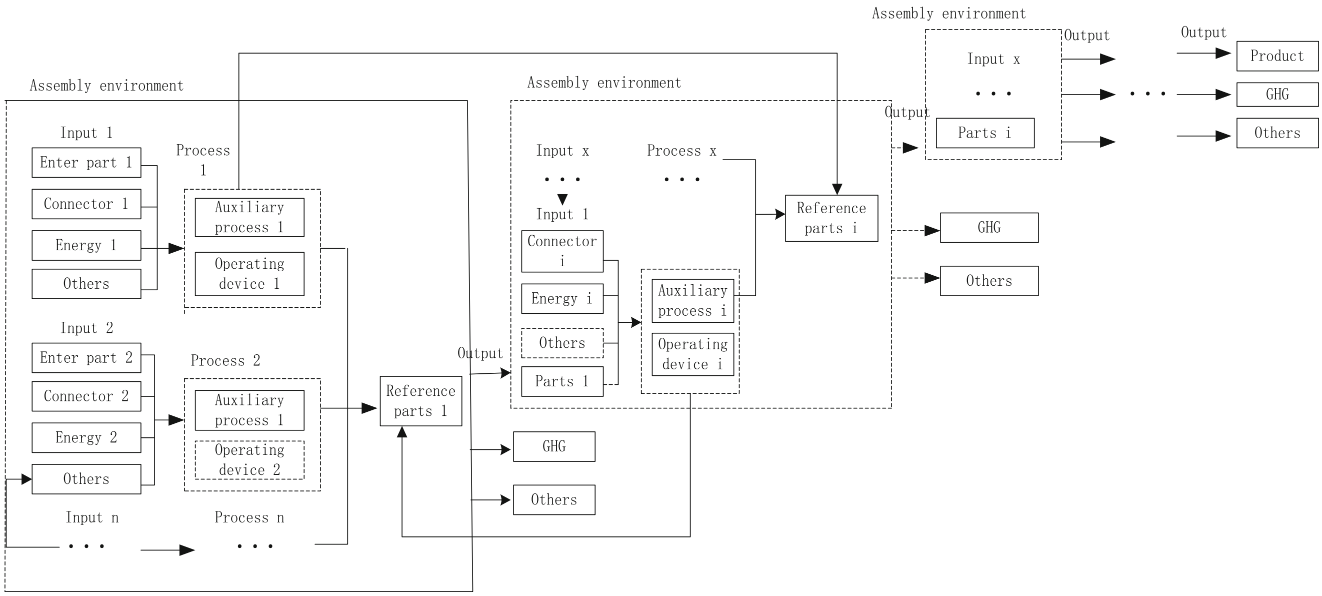


Fig. 6 Carbon footprint model of assembly process

where

f	is the coefficient of friction between assembly parts
L	is the length of the pressed parts
i	is the amount of interference
D	is the outer diameter of the outsourced part
d	is the aperture of the covered part
d_o	is the diameter of the pressing piece
μ_1	is the Poisson's ratio of steel, $\mu_1 = 0.3$
μ_2	is the Poisson's ratio of cast iron, $\mu_2 = 0.3$
E_1 and E_2	are the elastic modulus of the outsourcing and the package parts, respectively
C_1 and C_2	are the rigid coefficients of the contained parts and components

3. Riveting

$$G_r = \frac{\sum_{i=1}^{n} T_i(L_{bi} - L_{e0})}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{29}$$

where

T	is the rivet machine pressure
L_{bi}	is the initial length of the ith rivet
L_{e0}	is the termination length of the ith rivet

4. Key joint

Loose key joint:

$$G_k = \frac{FS}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{30}$$

Tight key joint:

$$\begin{aligned} G_K &= \frac{PL}{3.6 \times 10^6} \times EF_{\text{elc}} \\ &= \pi f S i \frac{E_1 E_2}{(\mu_1 E_2 + \mu_2 E_1) \times 3.6 \times 10^6} \times EF_{\text{elc}} \end{aligned} \tag{31}$$

where

F	is the loose key bonding force
S	is the keyway height
P	is the tight key bonding force
L	is the length of key assembly

5. Pin joint

Loose joint:

$$G_k = \frac{FS}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{32}$$

Tight joint:

$$G_K = \frac{PL}{3.6 \times 10^6} \times EF_{\text{elc}} \tag{33}$$

where

F	is the clearance fit force
P	is the interference fit force
S and L	are the assembly lengths of pin

3.3 Transport stage

Transportation takes place at all stages of vehicle's life cycle, which is an important consideration in the life cycle impact of products. Therefore, it can be assumed that the transportation process of automobile manufacturing raw materials is truck road transportation and the consumption is diesel. The transportation distance is 192 km of the average transportation distance of highway freight transportation in Anhui Province in 2015 [24]. Therefore, the quantitative formula is

$$G_{\text{transport}} = \rho \text{VL} \times EF_{\text{elc}} \tag{34}$$

where

- ρ is the density of fuel
- V is the automobile comprehensive fuel consumption per hundred kilometers (L/100 km) (according to some specific calculation models)
- L is the average distance (km)

3.4 Use stage

Due to the complex situation of automobile use stage, according to the "standard for compulsory vehicle scrapping," the non-operating car runs 600,000 km, which is a scrap standard, and the car's mileage is assumed to be 600,000 km, in the car use phase, main carbon emissions are derived from fuel consumption. Its quantification formula is:

$$G_{\text{use}} = \rho \text{VL} \times EF_{\text{elc}} \tag{35}$$

Different energy carbon emission factors are shown in Table 3 below:

3.5 Recovery stage

The steps of the auto recycling technology are the recycling of waste cars, the recovery of parts and components, the recovery of liquid, the pretreatment, the disassembly, and the recovery and burial of garbage. At present, the waste recycling industry for car recycling dismantling, recycling, and processing are mainly divided into three steps. The first step is to filter the liquid of the waste car. In the second step, the outer and interior of the waste car are recovered, processed, and reused. The third step is mainly to dismantle and recover the core power of the car. Because the current car scrap recycling work is not standardized, the availability of dismantling energy data is poor, GREET model built-in data is used. According to the literature [25], the energy consumption of a recuperation recovery stage for a conventional gasoline car with a curb weight of 1100 kg is 1,193,896 kj.

Table 3 Carbon emission factors of typical energy

Serial number	Energy types	Carbon emission factor
1	Electric energy	0.7035
2	Gasoline	2.492
3	Natural gas	1.744
4	Diesel oil	2.632

The carbon emission factor is kg CO_2e/kg; the data is from the GaBi database

4 Low-carbon optimization potential quantification and improvement

4.1 Low-carbon optimization potential quantification

he parts are designed via the CAD, how to evaluate products' carbon emission performance, quantify its low-carbon optimization potential, and generate a proposal for guiding designers to optimize low-carbon design based on the design requirements are key points of low-carbon design integration system. In this paper, the low-carbon evaluation index of parts is constructed from the aspects of structure, material, process, disassembly, and recovery performance: $M_1 k_{\text{ce,i}}$, $M_2 k_{\text{joint,i}}$, $M_3 k_{\text{process,i}}$, and $M_4 k_{\text{position,i}}$, based on these indicators, the calculation method of low-carbon optimization of parts is established:

$$K = M_1 \cdot k_{\text{ce,i}} + M_2 \cdot k_{\text{joint,i}} + M_3 \cdot k_{\text{process,i}} + M_4 \cdot k_{\text{position,i}} \tag{36}$$

where

- K is the low-carbon optimization potential of parts, the higher the K value is, the greater the potential for low-carbon optimization is
- $M_1 \sim M_4$ are the weight set by the designer according to its importance and its value ranges from 1 to 10
- $M_1 k_{\text{ce,i}}$ is the measure of the impact of carbon emissions on the material and structure of part i
- $k_{\text{ce,i}}$ is the proportion of the carbon emissions caused by the material and structure of the part i in the total amount of carbon emissions

$$k_{\text{ec,i}} = \frac{CE_{\text{component,i}}}{\sum CE_{\text{component}}} = \frac{M_i \cdot EF_i}{\sum CE_{\text{component}}} \tag{37}$$

- $M_2 k_{\text{joint,i}}$ and $M_4 k_{\text{position,i}}$ are the measures of the impact on carbon emissions in assembly, disassembly and recycling of part i
- $k_{\text{joint,i}}$ is the proportion of carbon emissions caused by the assembly connection of part i in the total amount of carbon emissions

Table 4 Corresponding carbon emission levels for each connection type

Serial number	Connection type	Carbon emission level	Serial number	Connection type	Carbon emission level
1	Welding	5	4	Threaded connection	3
2	Riveting	4	5	Key joint	3
3	Interference joint	4	6	Pin joint	2

The emission level of the connection characteristics is evaluated according to the difficulty of assembly and disassembly

$$k_{\text{joint,i}} = \frac{\text{joint}_{\text{component,i}}}{\sum \text{joint}_{\text{component}}} \quad (38)$$

$\text{joint}_{\text{component,i}}$ refers to the carbon emissions caused by the assembly connection of part i, which can be obtained by counting the number of connection types querying Table 4.

$k_{\text{position,i}}$ is the proportion of carbon emissions caused by the dismantling and recovery of part i in the total amount of carbon emissions

$$k_{\text{position,i}} = \frac{\text{position}_{\text{component,i}}}{\sum \text{position}_{\text{component}}} \quad (39)$$

Table 5 Recommendations for low-carbon optimization under scenarios

Condition	Design suggestion
$M_1k_{\text{ce,i}}$ is larger relative to the other three terms	1. Use a substance with lower carbon emission factor 2. Structural optimization or use lightweight materials to achieve the same quality 3. Use existing materials more efficiently and effectively to avoid waste
$M_1k_{\text{ce,i}}$ and $W_2k_{\text{joint,i}}$ are large relative to the other two terms	1. Use a substance with lower carbon emission factor 2. Structural optimization or use lightweight materials to achieve the same quality 3. Use existing materials more efficiently and effectively to avoid waste 4. Use a lower carbon level connection or assembly process
$M_1k_{\text{ce,i}}$ and $M_3k_{\text{process,i}}$ are large relative to the other two terms	1. Use a substance with lower carbon emission factor 2. Structural optimization or use lightweight materials to achieve the same quality 3. Use existing materials more efficiently and effectively to avoid waste 4. Perform process optimization to control manufacturing emissions
$M_1k_{\text{ce,i}}$ and $M_4k_{\text{position,i}}$ are large relative to the other two terms	1. Use a substance with lower carbon emission factor 2. Use light materials 3. Structural optimization 4. Perform disassembly sequence optimization
$M_2k_{\text{joint,i}}$ and $M_3k_{\text{process,i}}$ are large relative to the other two terms	1. Use a lower carbon level connection and assembly process 2. Perform process optimization to control manufacturing emissions
$M_2k_{\text{joint,i}}$ and $M_4k_{\text{position,i}}$ are large relative to the other two terms	1. Perform structural optimization, reduce the number of adjoining parts, or improve the joining process 2. Perform disassembly sequence optimization
$M_3k_{\text{process,i}}$ and $M_4k_{\text{position,i}}$ are large relative to the other two terms	1. Perform process optimization to control manufacturing emissions 2. Optimize the structure 3. Perform disassembly sequence optimization
$M_1k_{\text{ce,i}}$, $M_2k_{\text{joint,i}}$, and $M_3k_{\text{process,i}}$ are large relative to $M_4k_{\text{position,i}}$	1. Use a substance with lower carbon emission factor 2. Use a lower-carbon level connection and assembly process 3. Perform process optimization to control manufacturing emissions
$M_1k_{\text{ce,i}}$, $M_2k_{\text{joint,i}}$, and $M_4k_{\text{position,i}}$ are large relative to $M_3k_{\text{process,i}}$	1. Use a material with a lower carbon emission coefficient 2. Optimize the structure to reduce the number of adjacent parts 3. Perform disassembly sequence optimization
$M_2k_{\text{joint,i}}$, $M_3k_{\text{process,i}}$, and $M_4k_{\text{position,i}}$ are large relative to $M_1k_{\text{ce,i}}$	1. Optimize the structure to reduce the number of adjacent parts 2. Perform process optimization to control manufacturing emissions 3. Perform disassembly sequence optimization
$M_1k_{\text{ce,i}}$, ,$M_2k_{\text{joint,i}}$, $M_3k_{\text{process,i}}$ and $M_4k_{\text{position,i}}$ are all about the same	1. Use a substance with lower carbon emission factor 2. Remove the component/change its design 3. Use lightweight alternative materials
Others	Redesign on the basis of all the above suggestions

position$_{component,i}$ refers to the number of parts adjacent to part *i*

$M_3 k_{process,i}$ is the degree of carbon emissions in the manufacturing process;

$k_{process,i}$ is the proportion of carbon emissions in the manufacturing process of part *i* in the total amount of carbon emissions

$$k_{process,i} = \frac{\text{process}_{component,i}}{\sum \text{process}_{component}} \tag{40}$$

4.2 Recommendations for improvement of low-carbon design

After the evaluation of the carbon emission of the parts under the assembly environment, the low-carbon optimization potential is calculated according to the corresponding evaluation index, and the corresponding low-carbon improvement design proposal is generated. If the low-carbon optimization potential is greater than the set threshold, in accordance with the design requirement and improvement design proposal, the designers improve the design of the parts in the integrated system.

As shown in Table 5, when $M_1 k_{ce,i}$ is too large, the product design can be adjusted in terms of materials and structures, such as using materials with a lower carbon emission coefficient, using materials that are relatively lighter with the same effect, optimizing the appropriate structural, and utilizing existing materials efficiently. When $M_2 k_{joint,i,}$ is too large, the parts adopt lower carbon emission level connection or assembly process. When $M_3 k_{process,i}$ is too large, the optimized manufacturing process can be used. When $M_4 k_{position,i}$ is too large, the

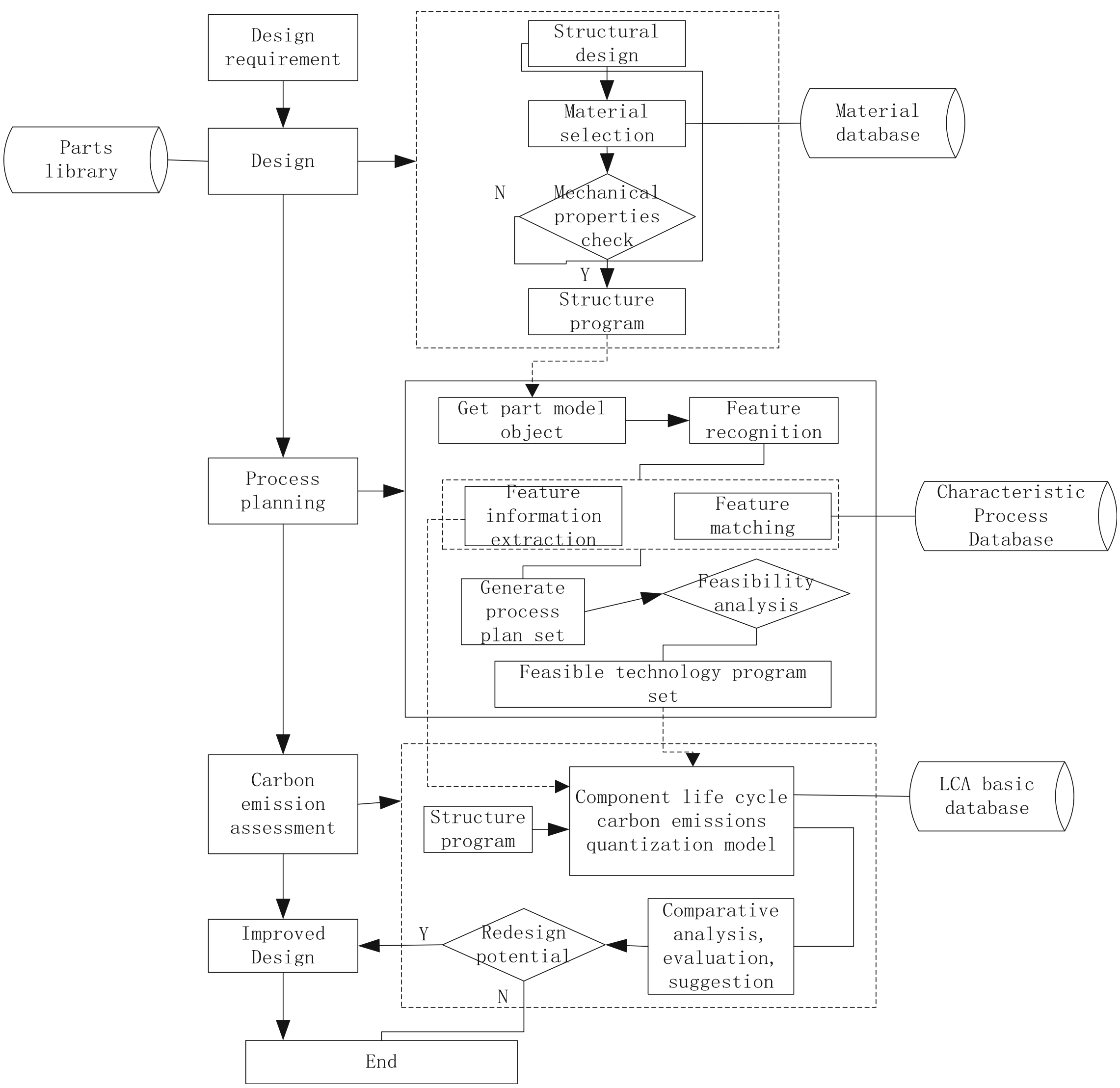


Fig. 7 Product low-carbon design integrated system workflow

disassembly sequence can be optimized or the number of adjacent parts can be reduced during the assembly process.

5 Overview of low-carbon design integration system

In order to evaluate the life cycle carbon emission of parts and give the suggestion of low-carbon design while designing the structure of the part on the 3D design software platform, it is necessary to apply the secondary development technology to integrate LCA with CAD. In the product low-carbon design-integrated system, through the identification and extraction of the feature of the part, combined with the corresponding feature matching algorithm, the process design of the part is completed. Then, based on the carbon emissions quantification model, the component life cycle carbon emissions are assessed according to the acquired component information and process design. Finally, the corresponding low-carbon design suggestions are given for the evaluation results of the feedback, and the corresponding improvement design is completed on the 3D design platform. The workflow is shown in Fig. 7.

5.1 The theoretical realization scheme of integrated system

At present, the product's 3D design tools and the product environment performance evaluation tools are still independent of each other, and the data related to them cannot communicate and integrate with each other. In order to realize the integration of LCA with CAD, it is necessary to solve the communication problem of information data first. Through the integration of secondary development technology, database technology, feature recognition, and matching technology, the data exchange of integrated system is realized theoretically, and the theoretical realization of the program is shown in Fig. 8. First, the feature information model is built based on the feature description of parts. According to the feature information model, database technology is used to build the database of integrated system. By running the corresponding database, it provides data support for the low-carbon design of components. Secondly, on the Creo platform, CAD technology, parametric design, and part model library technology are used to design the parts structure and the 3D model of the parts is built to provide the foundation for the later process design. Then, based on the 3D model, the CAPP technology is applied

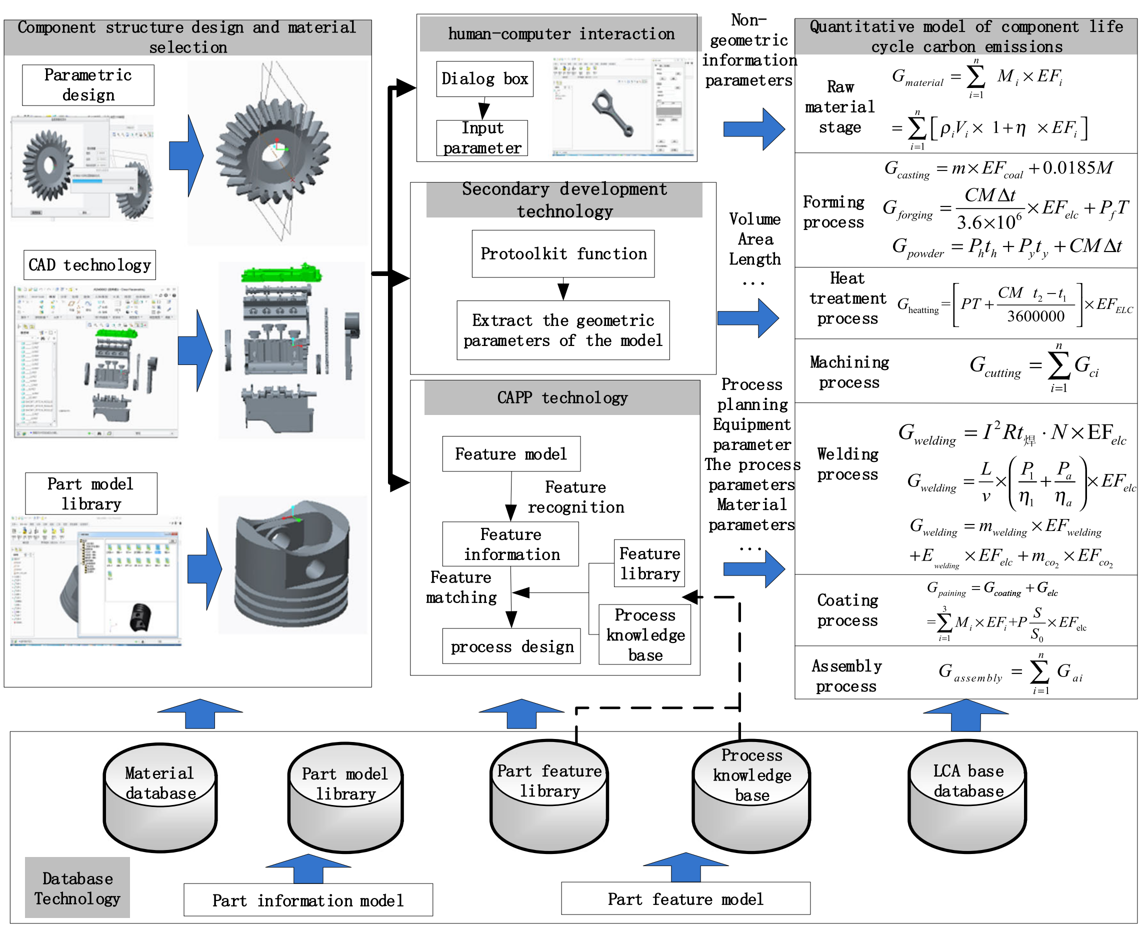


Fig. 8 Data flow diagram of integrated system

to process design of the parts, the corresponding process information is extracted, and then other data information of the parts is extracted through human-machine interaction and the secondary development technology. Finally, the life cycle data of the extracted parts are input into the life cycle quantitative model of the components. Based on the corresponding LCA basic data, the life cycle carbon emissions evaluation of components is carried out, feedback results are evaluated, and design proposals for low-carbon improvement design are generated.

6 Case study

Taking automobile engine as an example, the life cycle carbon emission of the engine is evaluated through a low-carbon design integration system and a low-carbon improvement design proposal is proposed.

Taking the piston of the engine as an example to illustrate the steps of the part design:

1. Part design. According to the design requirements, a similar model is searched in the model library and imported and part performance requirements are chosen. The piston is subjected to high temperature, high-pressure heat load, and mechanical load during operation, and its material requirements are very high. The material can be selected from silicon aluminum alloy, cast steel, cast aluminum, etc. In this paper, according to the structure and mechanical properties of the parts, the silicon aluminum alloy is selected. After selecting material, the mechanical properties are checked to meet the design requirements, and the part design is completed.
2. Technological design. Click on the "production process," based on the structure model supported by the process knowledge base, the system background generates several technological solutions according to the set feature recognition and matching algorithm, and designers choose feasible process scheme. This paper selects process plan 1: casting, rough rabbet, end face, rough boring, coarse to fine pin hole outside the dome surface, ring groove, drill hole, fine car stop opening, finish cutting ring groove to fine car cylindrical pin hole boring to fine roof surface, chamfer, and click on the "options", process design is completed. The machining process information of the piston is shown in Table 6.
3. Carbon emission assessment. Pick up the selected component model, based on the carbon emission quantizing model of the part life cycle, the life cycle carbon emission of the piston is evaluated according to the above structural scheme and the process plan. The piston life cycle carbon emissions are calculated to be 2.03 kg CO_2e through the integrated platform, of which the raw material phase

Table 6 Machining process information for the piston

Step	Step name	Equipment	Machining parameters	Machining allowance (mm)
1	Rough turning seam allowance	CNC lathe	Back engagement 2.5 mm; feed rate 0.5 mm/r; rotation rate 1200 r/min	1.2
2	Rough end face	CNC lathe	Back engagement 2.5 mm; feed rate 0.5 mm/r; rotating speed 1200 r/min	1
3	Coarse boring pin hole	Horizontal boring and milling machine	Cutting speed 50 m/min; feed speed 300 mm/min; rotating speed 600 r/min; feed rate 0.4 mm/r	2.7
4	Rough turning outer circle	CNC lathe	Back engagement 2.5 mm; feed rate 0.5 mm/r; rotating speed 1200 r/min	3.7
5	Rough turning roof surface	CNC lathe	Back engagement 2.5 mm; feed rate 0.5 mm/r; rotating speed 1200 r/min	6.5
6	Rough turning ring groove	CNC lathe	Back engagement 2.5 mm; feed rate 0.5 mm/r; rotating speed 1200 r/min	1.2
7	Drilling hole	Drilling machine	Feed rate 1.5 mm/r; rotating speed 1200 r/min	0.5
8	Fine turning seam allowance	CNC lathe	Back engagement 1 mm; feed rate 0.2 mm/r; rotating speed 1200 r/min	0.3
9	Fine cut ring groove	CNC lathe	Back engagement 1 mm; Feed rate 0.2 mm/r; rotating speed 1200 r/min	0.3
10	Fine turning outer circle	CNC lathe	Back engagement 1 mm; Feed rate 0.2 mm/r; rotating speed 1200 r/min	0.3
11	Coarse boring pin hole	Hydrostatic boring machine	Cutting speed 100 m/min; feed speed 150 mm/min; rotating speed 1000 r/min; feed rate 0.08 mm/r	0.2
12	Fine turning roof surface	CNC lathe	Back engagement 1 mm; feed rate 0.2 mm/r; rotating speed 1200 r/min	0.3
13	Fine turning chamfer	CNC lathe	Back engagement 1.5 mm; feed rate 0.5 mm/r; rotating speed 1200 r/min	0.5

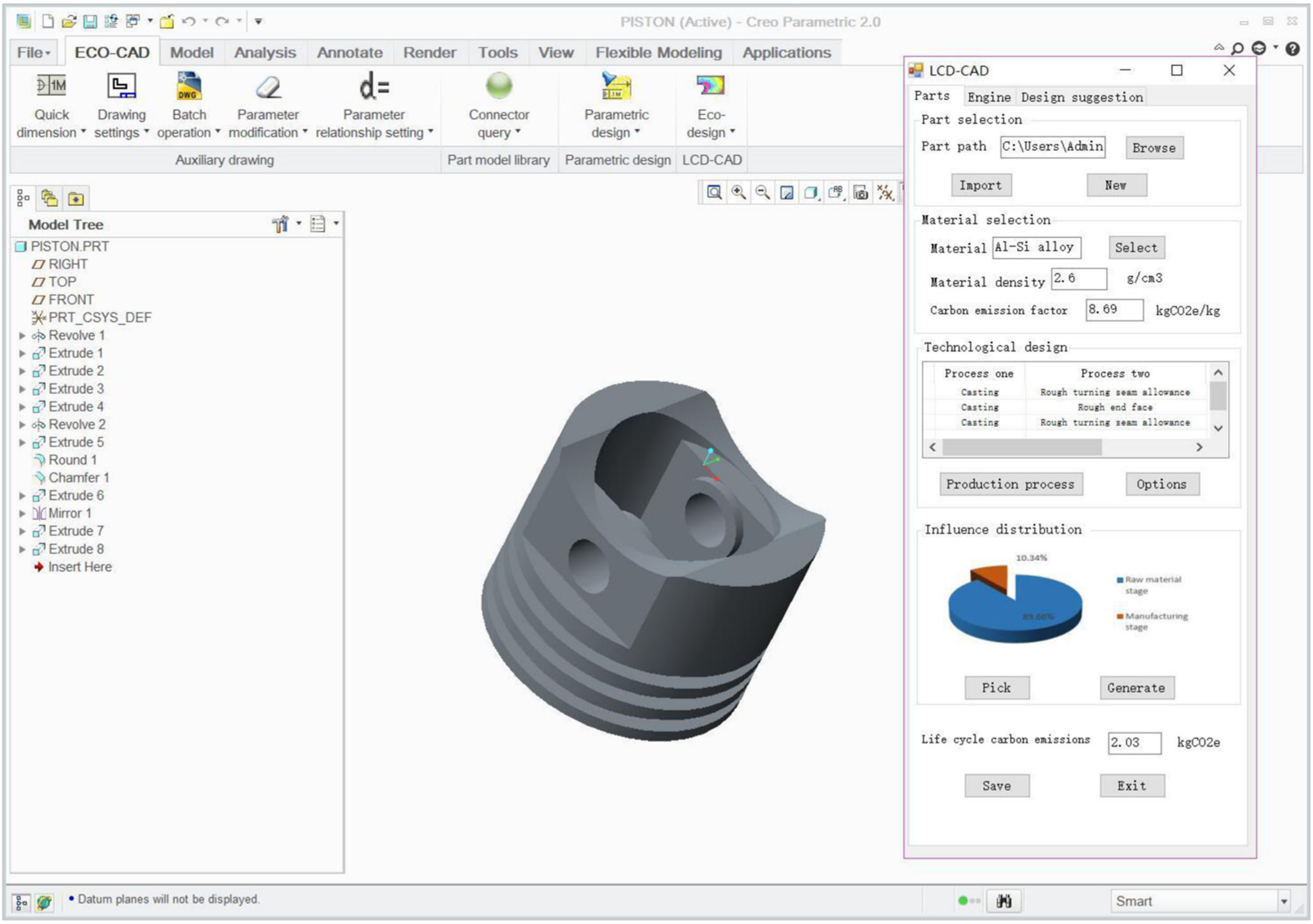


Fig. 9 The carbon emissions assessment of the piston

accounts for 89.66%, the manufacturing phase accounts for 10.34%, and finally click on "save;" the carbon emission assessment of the piston has been completed. Figure 9 shows the carbon emissions assessment of the piston. By comparing and analyzing the life cycle carbon emissions of various schemes under Table 7, the optimum scheme is obtained; the material is silicon aluminum alloy, and the process scheme is scheme 1.

According to the above procedures, the design and evaluation of other engine parts, such as crankshaft, connecting rod, cylinder head, and engine block, are carried out separately. After the part emission evaluation is completed, the parts are assembled according to the connection type and the adjacent relation between parts; after the components are assembled, emission analysis of the whole component is carried out.

Table 7 Evaluation results of piston carbon emissions

Structure scheme	Material selection	Process plan	Life cycle carbon emissions (kg CO_{2e})
	Silicon aluminum alloy	Process plan 1: casting → rough car mouth, end face → rough boring pin hole → rough car outside the roof, ring groove → drilling hole → fine gate → fine cut ring groove → fine wheel → fine boring pin hole → fine car top, chamfer	2.03
	Cast aluminum	Process plan 1: casting → rough car mouth, face → rough boring pin hole → rough car outside the roof, ring groove → drilling hole → fine gate → fine cut ring groove → fine wheel → fine boring pin hole → fine car top, chamfer	2.48
	Silicon aluminum alloy	Process plan 2: casting → rough car roof, ring groove → rough boring pin hole → rough car mouth, face → drilling hole → fine valve mouth → fine wheel → fine cutting ring groove → fine top, chamfering → fine boring pin hole	2.12

4. Component carbon emission assessment. In the assembly environment, with the support of the data analysis of the carbon emission of each component in the previous step, the life cycle carbon emission assessment of the component is carried out by identifying the connection relationship among the parts. Figure 10 shows the carbon emission assessment of the engine components. Figure 11 presents the carbon emission assessment results of the engine components and its recommendations.

As can be seen from Fig. 11, the life cycle carbon emissions of the automobile engine components are 380.63 kg CO_2e, and the carbon emissions of each component and its connection information are shown in Table 8. Automatically generate its low carbon design proposal by selecting the body in Fig. 11; (1) Materials with low carbon emission coefficient; (2) Optimize the structure or select lightweight materials to reduce the quality of the parts; (3) Use the lower level of carbon emission connection. The designer can make an improved design of the camshaft according to the suggestion. In addition, according to the size of the *K* value in the diagram, the components should be optimized. Table 9 shows the results of carbon emissions from engine components.

7 Conclusions

In this paper, based on the issue of carbon emission, the auto parts are taken as the research object, the life cycle evaluation theory is used to analyze the sources of carbon emission at various stages of automobile life cycle, and the quantitative model of carbon emission is constructed. Combining secondary development technology, the product low-carbon design-integrated system is developed for supporting low-carbon design of auto parts. The main research contents are as follows:

1. According to the theory of life cycle analysis, through the analysis of automobile structure and typical manufacturing process, the system boundary of this study is defined, and the life cycle carbon emission characteristics of automobile components are analyzed.

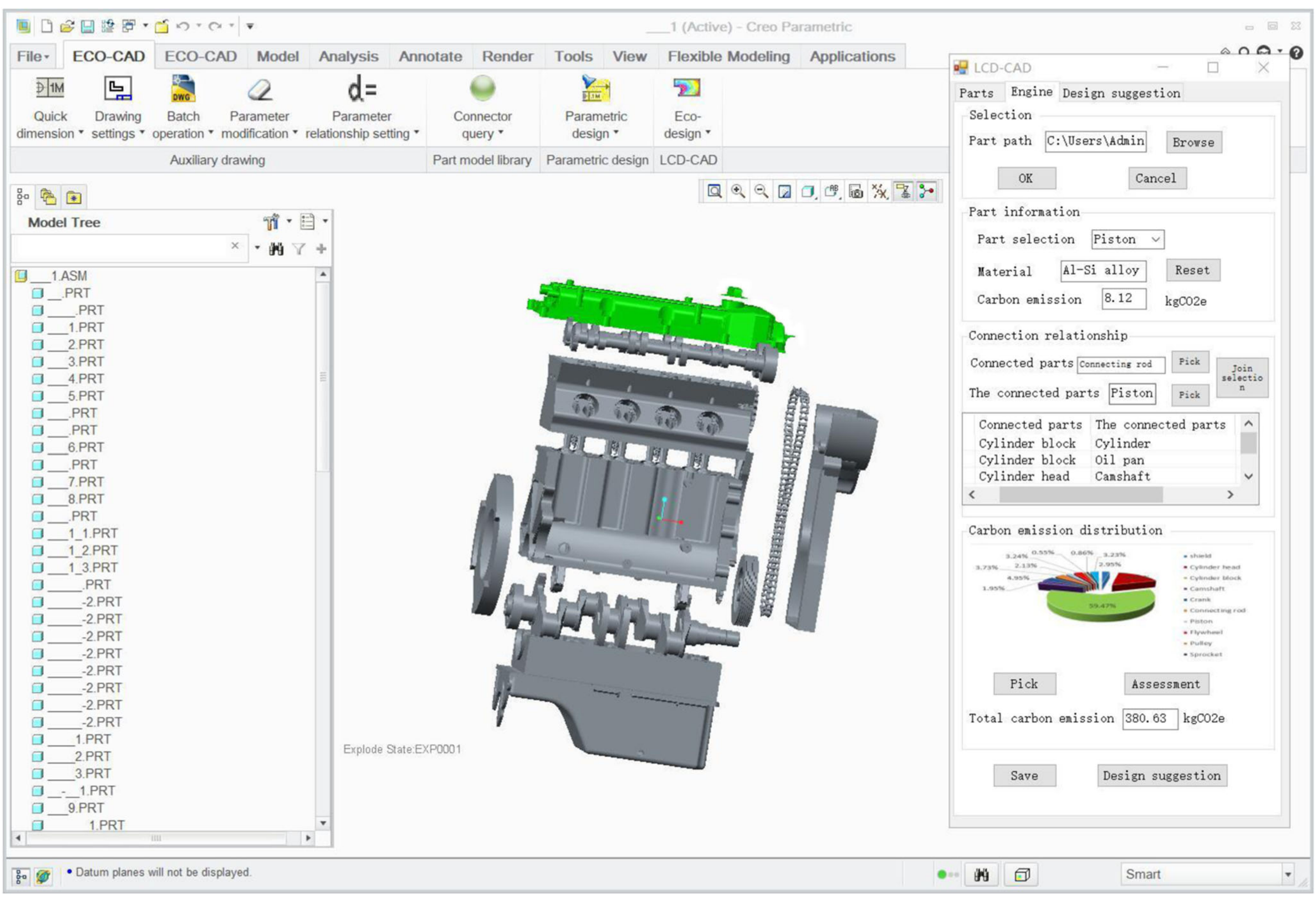


Fig. 10 Carbon emissions assessment of engine components

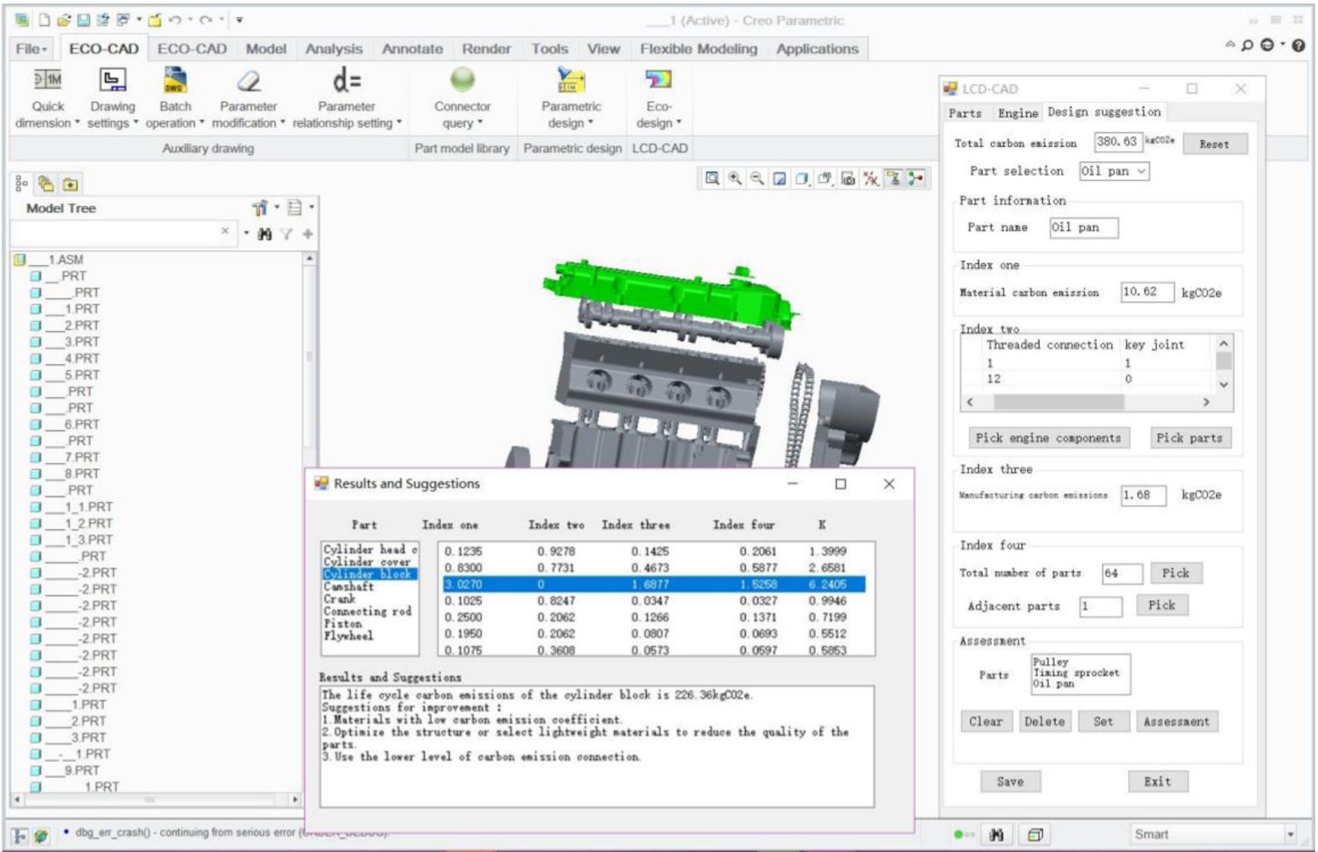


Fig. 11 Carbon emissions from engine components and recommendations

2. According to the life cycle carbon emission characteristics of the typical parts of the automobile, the carbon emission quantification model of its life cycle was constructed. This paper presents a method to identify the potential of carbon

Table 8 Parts information of engine assembly

Component	Raw material emissions	Welding	Riveting	Interference joint	Threaded joint	Keyed joint	Pin joint	Carbon emissions from parts connections	Manufacturing emissions	The number of adjacent parts
		The number of connection types of each part in the component								
Shield	8.35	0	0	0	12	0	0	36	2.89	1
Cylinder head	56.2	0	0	0	10	0	0	30	8.24	15
Cylinder block	204.97	0	0	0	0	0	0	0	21.39	18
Camshaft	6.97	0	0	0	10	0	1	32	0.46	8
Crank	16.93	0	0	2	0	0	0	8	1.92	9
Connecting rod	13.22	0	0	0	2	0	1	8	0.97	2
Piston	7.28	0	0	3	0	0	1	14	0.84	2
Flywheel	9.17	0	0	0	6	0	0	18	3.17	1
Pulley	1.92	0	0	0	1	1	0	6	0.18	4
Sprocket	2.94	0	0	0	1	1	0	6	0.32	3
Oil pan	10.62	0	0	0	12	0	0	36	1.68	1
Total	338.57	0	0	5	54	2	3	194	42.06	64

Table 9 Carbon emission results of engine components

Component	Indicator 1	Indicator 2	Indicator 3	Indicator 4	*K*
Cylinder head cover	0.1235	0.9278	0.1425	0.2061	1.3999
Cylinder cover	0.8300	0.7731	0.4673	0.5877	2.6581
Cylinder block	3.0270	0	1.6877	1.5258	6.2405
Camshaft	0.1025	0.8247	0.0347	0.0327	0.9946
Crank	0.2500	0.2062	0.1266	0.1371	0.7199
Connecting rod	0.1950	0.2062	0.0807	0.0693	0.5512
Piston	0.1075	0.3608	0.0573	0.0597	0.5853
Flywheel	0.1355	0.4639	0.2389	0.2262	1.0645
Pulley	0.0285	0.1546	0.0136	0.0129	0.2096
Timing sprocket	0.0285	0.1546	0.0241	0.0228	0.2450
Oil pan	0.0435	0.9278	0.1266	0.1197	1.3311
Indicator weights	5	3	5	3	–

emission and establishes the feedback mechanism of evaluation result and improvement suggestion.

3. A low-carbon design aided system based on a commercial computer-aided design software was designed and verified by an automobile engine.

There are many issues that need to be considered in ecological design and it is a multi-objective decision-making problem. From the perspective of carbon emissions, the design of products in this paper is not comprehensive enough. Comprehensive consideration of various environmental, economic cost, and parts performance factors are important directions for the future of automotive eco-design.

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