A product carbon footprint model for embodiment design based on macro-micro design features

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Abstract
Greenhouse gas emissions have become one of the most prominent global concerns of sustainable development. To reduce product life cycle carbon footprint, planning should begin at embodiment design phase. The accurate assessment of carbon footprint is the foundation of carbon footprint reduction. However, existing carbon footprint models cannot be applied to embodiment design phase due to incomplete and limited design information. With this in mind, this paper proposes a carbon footprint model for embodiment design based on macro-micro design features. First, a Function-Structure-Feature (FSF) model for embodiment design is established to convey the design information. The concept of design features is introduced (at both macro and micro levels). The macro design feature denotes the different operational states of the product and the constraint relationships between parts. The micro design feature denotes the specific properties of parts. Then, a model of product carbon footprint based on design features is presented through the analysis of the relationships between macro-micro design features and product carbon footprint. The feasibility of the proposed method is demonstrated through a gear hobbing machine. The product carbon footprint model allows quantitative evaluation of product carbon footprint during embodiment design phase, and the amount of carbon footprint from each type of design feature is predicted. Based on evaluation result, the design features can be improved to reduce product carbon footprint. Case study results show that the carbon footprint is decreased by 10.96% after improving design features.

Keywords Embodiment design · Low-carbon design · Carbon footprint · Design feature · Product life cycle

1 Introduction
In recent decades, global warming has attracted wide public concern as one of the most serious challenges of sustainable development. The primary cause of global climate change is the emission of greenhouse gases (GHGs), which could result in potential damages to the ecological environment [1]. Known as the most common GHG, carbon dioxide (CO2) is the reference in measuring the global warming potential of other gases. Statistically, nearly 40% of carbon dioxide emissions worldwide are attributable to industries [2]. Manufactured products, as the final output of industries, account for a significant amount of CO2 emissions throughout its life cycle [3]. Therefore, adopting some measures to reduce the product life cycle GHG emission is crucial to the mitigation of global warming.

Product design plays a very important role in the entire product life cycle. It is noted that approximately 90% of a product’s costs and environmental impacts are committed early in the design phase [4]. Eco-design, which integrates environmental factors into the design process, has been considered an effective way of minimizing the environmental impact of products [5, 6]. In general, product design could be divided into four phases: requirements analysis, conceptual design, embodiment design, and detailed design. The design information increases as the design matures, but the opportunity and
effect of design decisions decline sharply \cite{7}. The opportunity and potential for improvement are great at early design phase. Therefore, many design tools are investigated to implement eco-design in early design phase, such as Quality Function Deployment for Environment (QFDE) \cite{8, 9}, inventive problem-solving (i.e., TRIZ) \cite{10, 11}, and Function Impact Matrix \cite{12}. However, these design tools are only applicable to conceptual design. Furthermore, the decisions made using these design tools, which mainly depend on the experience or knowledge of designers, are largely subjective. The subjectivity can be attributed to the highly subjective design knowledge and the lack in quantitative description during conceptual design phase \cite{3, 7}. Therefore, an objective quantitative and eco-design method of reducing carbon footprint in conceptual design phase is difficult to develop.

Embodiment design phase determines the quality and performance specifications of a product and generates the preliminary design scheme. Once the design scheme is fixed, the shortcomings of a poor design scheme are extremely difficult, costly, time-consuming, or even impossible to remedy in the next design phase, that is, the detailed design phase \cite{7}. Embodiment design phase starts with the concept variants generated from conceptual design phase and aims to develop the overall layout and preliminary design solutions that meet the requirements \cite{13, 14}. After acquiring the preliminary design schemes, evaluation and optimization are performed to seek the optimal design scheme \cite{13}. However, only technical and economic indicators are considered in the decisions made in this phase \cite{14}, where environmental indicators (such as carbon emission) are ignored. Therefore, considering environmental impact of the product life cycle at embodiment design phase is critical and requires further study.

Recently, low-carbon design, as a subset of eco-design, has become a popular research topic, aiming to reduce the carbon emission throughout the product life cycle. Some prominent efforts on reducing carbon emission have been investigated. A multi-objective optimization strategy for low-carbon design to balance the demands of enterprises, the government, and users was undertaken \cite{15}. Wang et al. \cite{16} established an optimization model for remanufactured products family design. Kuo \cite{17} proposed a multi-objective optimal design method for reducing carbon emission and cost. Chiang et al. \cite{18} presented a low-carbon decision-making method under the low-carbon emission constraints. Zeng \cite{19} conducted a sensitivity analysis method to redesign machine tools in order to reduce life cycle carbon emissions. Instead of embodiment design, the focus of the existing research is majorly on the detailed design phase.

Carbon footprint is used to represent the GHG emission in product life cycle \cite{20}. Accurate carbon footprint assessment is the prerequisite of low-carbon design. Many governments, organizations, and enterprises have calculated product carbon footprint to formulate many standards \cite{20–22} and regulations \cite{23–25}. However, no unified method for assessing product carbon footprint has been developed. The existing common methods include input-output analysis (IOA) \cite{26}, life cycle assessment (LCA) \cite{20}, and hybrid LCA \cite{27}. With these methods, many related researches have been carried out. Some researches focused on the development of carbon footprint at one particular stage of product life cycle. At raw materials’ acquisition stage, carbon footprint was combined with unascertained number theory in order to reduce the impact of data uncertainty \cite{28}. The carbon footprint in manufacturing stage was calculated based on carbon coefficients of fossil fuels used for an electrical power grid \cite{25}. The carbon footprint models for supply chains \cite{29} and assembly \cite{30} were also studied. Considering product life cycle, LCA was used to evaluate product carbon footprint and optimize product parameters \cite{31, 32}. In addition, g-BOM, which is an integration of the embedded GHG emissions of parts and the bill of material, was proposed to evaluate product carbon footprint \cite{33}. To simplify carbon footprint calculation, products were divided into different connection units, where the main connection units with high carbon emissions could be identified \cite{34}. For machine tools, the sources of carbon footprint in machining systems were analyzed \cite{35}, and a carbon efficiency approach was put forward to quantitatively characterize the carbon footprint of machine tools \cite{36}.

However, the approaches for carbon footprint mentioned above cannot support product low-carbon embodiment design. Firstly, existing carbon footprint calculations require detailed and accurate life cycle inventory data, and the input and output must be confirmed in the entire life cycle. But only the critical design information could be obtained in embodiment design phase. The product carbon footprint is difficult to evaluate because the design and life cycle information are limited, vague, fuzzy, and incomplete. Secondly, the carbon footprint evaluation results cannot guide the design optimization in embodiment design phase. The correlation between critical design information and carbon footprint is still lacking. The feedback from evaluation results to design information needs to be established. To fill this gap, this work presents a product carbon footprint model for embodiment design based on macro-micro design features. The main contributions of this study can be summarized as follows: (1) product carbon footprint can be evaluated during embodiment design phase, (2) the correlation between design scheme and carbon footprint can be established based on design feature, and (3) the approach can support designers in optimizing design scheme to reduce carbon footprint.

The remaining of this paper is organized as follows. Section 2 describes the feature-based carbon footprint model. A case study on a gear hobbing machine is provided in Section 3. Concluding remarks are covered in Section 4.
2 Methods

2.1 The embodiment design model based on design features

2.1.1 Function-Structure-Feature model for embodiment design

In embodiment design phase, one of the critical tasks is to explore the best solution by evaluating and optimizing different schemes. To evaluate product carbon footprint in this design phase, the first and foremost step is to identify and articulate the carbon footprint information hidden in the design scheme. Feature-based approaches have been widely applied in product design modeling recently [37, 38]. Features play an important role in generation, analysis, and evaluation of a product model [39]. Therefore, design feature is applied to evaluate product carbon footprint in this paper. The concept of design feature will be thoroughly introduced in the next section.

On the basis of design feature, the Function-Structure-Feature (FSF) model for embodiment design is established as shown in Fig 1. The FSF model is a visual representation of the design information related to the product’s carbon footprint and can track and feedback the feature, structure, and function with high carbon footprint. The FSF model is divided into three layers: function layer, structure layer, and feature layer. The function layer shows the purpose of the design object. The structure layer describes the carrier for implementing the corresponding function. The function layer and structure layer could be identified by designer during embodiment design. The feature layer reveals the design information that supports the estimation of product carbon footprint, which is derived from the structure layer and function layer.

2.1.2 The concept of design feature

In this paper, product design feature is defined as the collection of macro design feature (macro-feature for short) and micro design feature (micro-feature for short). Macro-feature and micro-feature describe the design information from product layer and component layer, respectively, which are the carrier of important product design information that determines carbon footprint in product life cycle.

The macro-feature represents the product’s operational state parameters and the constraint relationship between different parts, including relation feature and operational state feature. Relation feature is composed of connection feature and spatial constraint feature. The connection feature shows the connection mode between parts. The connection mode could be divided into physical connection and chemical connection. The physical connection includes bearing, pin, spline, and thread, and the chemical connection contains welding and

![Fig. 1 FSF model for embodiment design](image-url)
gluing. The spatial constraint feature denotes the constraint relationship between parts, which can be expressed by spatial topological relationship. The topological relationship between two parts can be determined by the nine-intersection model based on point-set topology. On the basis of the intersections of boundary, interior, and exterior of two objects, the topological relationship could be classified into eight categories: meet, equal, overlap, disjoint, contains, covers, coveredBy, and inside \[40, 41\]. Considering the physical characteristics of the parts, the topological relationship can be simplified into five categories: meet, disjoint, contains, overlap, and covers. The significant constraint relationship between parts could be described based on graph theory \[42, 43\]. Therefore, the relation feature could be expressed by the liaison graph (Fig. 2). The symbol on connecting lines is the combo of connection relation and spatial constraint relation between two parts, which corresponds to a specific assembly process. As shown in Table 1, the uppercase letter represents the spatial constraint and the lowercase letter shows the connection relation. As listed in Table 2, the operational state feature describes the design parameters of functional systems in different operational states, such as the power of energy-intensive components in standby state of a machine tool.

The micro-feature denotes the specific properties of components, and includes material feature, geometry feature, and surface treatment feature, as shown in Table 3. The material feature shows the variety, weight, and recovery mode about part materials. Geometry feature denotes the geometry shape and size information of parts, including shape feature and size feature. Generally, each part contains one or several geometry features, and each geometry feature corresponds to a series of specific machining processes. Shape feature can be divided into two categories: overall shape feature and local shape feature. The overall shape feature describes the main shape of a part, e.g., cylinder, cone, and cuboid. For complex parts, the main shape may contain multiple shapes, and the symbol “+” is used to represent a combination of these shapes. For example, the main shape of bearing seat is “cylinder + cuboid.” The local shape feature supplements the overall shape feature, describing the subtle shape to be machined, such as hole, slot, and face. Size feature represents the accurate or approximate size information on the shape feature, including length, width, height, radius, angle, and volume. The surface treatment feature shows the technical processing requirements of parts, such as heat treatment, spraying, and phosphatizing.

### 2.2 Product carbon footprint calculation model based on design features

#### 2.2.1 The analysis of product carbon footprint

To calculate the product carbon footprint, the product system boundary should be analyzed and determined first. As shown in Fig. 3, the system boundary contains the entire life cycle of the product. Based upon the concept of product life cycle defined in ISO \[44\], the product carbon footprint could be divided into five stages: extraction of raw materials stage, manufacturing stage, transportation stage, use stage, and recycling stage. In each stage, the direct carbon emissions and indirect carbon emissions should be taken into account. The direct carbon emissions are caused by the activities in producing a product. For example, when the parts are heat-treated in a workshop, the GHGs from this process are the direct carbon emissions. The indirect carbon emissions are generated outside the production. For instance, the consumption of electricity is an indirect carbon emission from the electricity generation process.

The product carbon footprint model is expressed by Eq. (1). The carbon dioxide equivalent (CO₂e) is used to calculate the product carbon footprint and could describe different GHGs in a unified unit.

\[
CF_{total} = CF_e + CF_m + CF_t + CF_u + CF_r
\]

(1)

where \(CF_{total}\) is the product carbon footprint throughout its life cycle, \(CF_e\) is the product carbon footprint at extraction of raw materials stage, \(CF_m\) is the product carbon footprint at manufacturing stage, \(CF_t\) is the product carbon footprint at transportation stage, \(CF_u\) is the product carbon footprint at use stage, and \(CF_r\) is the product carbon footprint at recycle and disposal stage.

#### 2.2.2 The calculation of product carbon footprint

Product life cycle includes various activities, such as assembly activity, processing activity, and recycling activity. Some of the activities will generate carbon emissions and referred to as
carbon footprint activities. The carbon footprint activities are determined by design features. In this study, the operations of design features are proposed to correlate product carbon footprint and design features. The product carbon footprint could be equal to the carbon emissions generated from the process of operating some design features. The operating activities of design features include five categories: establishing some features, recovering some features, transferring some features, removing some features, and maintaining some features. As shown in Fig. 4, the mapping relations are constructed by analyzing the impact of design features on life cycle carbon footprint activities. The carbon footprint activity at each stage of product life cycle could be considered one or many operations of design features. The different design features may affect the same carbon footprint activity. For example, the carbon footprint at the manufacturing stage is determined by establishing geometry feature, technology feature, and relation feature. The same design feature could influence multiple carbon footprint activities. For example, the material feature may affect carbon footprint activities in three stages. The detailed expression of mapping relations can be found in A-E below.

A. Extraction of raw materials stage

The carbon footprint in this stage is generated in the extraction of materials. That is, the carbon emissions generated from the process of establishing material features. The carbon footprint is estimated by the following equation.

\[
CF_e = C_{est}(F_{mate}) = \frac{N_0}{p=1} \left[ C_{est}(F_{mate}) \right]_p = \frac{N_0}{p=1} \sum_{a=1}^{N_1} m_{pa} \cdot f_a (2)
\]

where \(C_{est}(F_{mate})\) denotes the carbon emissions in establishing material features, \(N_0\) is the number of parts, \(\left[ C_{est}(F_{mate}) \right]_p\) is the carbon emission of the \(p\)th part in establishing material features, \(N_1\) is the number of types of material features, \(m_{pa}\) is the material weight of the \(a\)th material feature for the \(p\)th parts, and \(f_a\) is the carbon emission coefficient of the \(a\)th material feature.

B. Manufacturing stage

The manufacturing stage includes production process and assembly process. The product carbon footprint in production process is treated as the carbon emissions caused by establishing geometry features and surface treatment features. The carbon emissions risen from establishing connection features represent the product carbon footprint in assembly process. The calculation of product carbon footprint in manufacturing stage is denoted in Eq. (3).

\[
CF_m = C_{est}(F_{geom}) + C_{est}(F_{surf}) + C_{est}(F_{rela}) (3)
\]

In the equation, \(C_{est}(F_{geom})\) denotes the carbon emissions caused by establishing geometry features, \(C_{est}(F_{surf})\) is the carbon emissions caused by establishing surface treatment features, and \(C_{est}(F_{rela})\) is the carbon emissions aroused from establishing relation features.

During the production process, each geometry feature of parts is created by one or more manufacturing processes (e.g., casting, forging, turning, and milling). Each surface treatment feature corresponds to a particular technical process (e.g., heat treatment, spraying, electroplating). The consumption of energy in these processes generates carbon emissions. During the energy consumption, carbon emissions include direct and indirect carbon emissions. The indirect carbon emissions are produced in energy generation, and the direct carbon emissions are directly generated in the process of energy consumption. The carbon emissions caused by establishing geometry features and surface treatment features can be evaluated as follows.

\[
C_{est}(F_{geom}) + C_{est}(F_{surf}) = \sum_{b=1}^{N_0} \sum_{f=1}^{N_1} E_{be} \cdot (f_e + f_e') + \sum_{d=1}^{N_1} E_{de} \cdot (f_e + f_e') (5)
\]

where \(C_{est}(F_{geom}) + C_{est}(F_{surf})\) is carbon emissions caused by establishing geometry features and surface treatment features.
features for \( p \)th part, \( N_2 \) is the amount of the geometry features, \( N_b \) is the quantity of the manufacturing processes for establishing the \( b \)th geometry feature, \( N_3 \) is the number of types of energy, \( E_{bc} \) is the usage of the \( e \)th energy in the \( c \)th manufacturing process for establishing the \( b \)th geometry feature, \( f_e \) is the carbon emission coefficient of the production process for the \( e \)th energy, \( f_e \) is the carbon emission coefficient of the use process for the \( e \)th energy, \( N_4 \) is the amount of the surface treatment features, and \( E_{de} \) is the consumption of the \( e \)th energy in the technical process for establishing \( d \)th surface treatment feature, which is determined by the selected equipment.

According to the processing mode, \( E_{bc} \) could be acquired in two ways. Specific energy consumption (SEC) is the energy consumption for removing material per unit volume as calculated in Eq. (6) for milling, turning, grinding, drilling, etc. [45]. An empirical model was put forward as shown in Eq. (7) [46], which accuracy to predict energy consumption can reach 90–95% [45]. Embedded energy consumption (EEC) is used to evaluate the energy required for deformation processing [36, 47]. The calculation method is presented in Eq. (8).

\[
E_{bc} = \frac{SEC_{bc} \times V_{bc}}{C_2} \quad (6)
\]

\[
SEC_{bc} = c_1 + \frac{c_2}{MRR_{bc}} \quad (7)
\]

\[
E_{bc} = EEC_{bc} \times M_{bc} \quad (8)
\]

In Eqs. (6) and (7), under the premise of using the \( e \)th energy in the \( c \)th manufacturing process for establishing the \( b \)th geometry feature, \( SEC_{bc} \) is the specific energy consumption of the \( e \)th energy in the \( c \)th manufacturing process for establishing the \( b \)th geometry feature, \( V_{bc} \) is the volume of material removal, \( c_1 \) and \( c_2 \) are specific coefficients of the machine tools, and \( MRR_{bc} \) is the material removal rate per unit time. In Eq. (8), \( EEC_{bc} \) is the embedded energy consumption of the \( e \)th energy in the \( c \)th manufacturing process for establishing the \( b \)th geometry feature, \( M_{bc} \) is the weight of the material.

In assembly process, the main energy consumption is by the machine operations for assembling parts or components. The energy consumption can be evaluated by the connection mode and spatial constraint relations [30]. The carbon

![Fig. 3 System boundary of product carbon footprint](image-url)
emissions generated from establishing relation features can be calculated as Eq. (9).

\[
C_{\text{est}}(F_{\text{rela}}) = \sum_{g=1}^{N_5} \sum_{e=1}^{N_3} E_{ge} \cdot (f_e + f'_e)
\] (9)

where \(N_5\) is the amount of the relation features, and \(E_{ge}\) is energy consumption of the \(e\)th energy to create the \(g\)th relation feature.

C. Transportation stage

The carbon emissions generated from transferring material features are used to represent the carbon footprint in transportation stage. During this stage, the raw materials must be shipped to the factory, and the final product should be transported to customers by airplane, train, or truck. The calculation of carbon footprint in this stage is shown in Eq. (10).

\[
CF_t = C_{\text{tran}}(F_{\text{mater}}) = \sum_{p=1}^{N_6} \left[ C_{\text{tran}}(F_{\text{mater}}) \right]_p
\]

\[
= \sum_{p=1}^{N_6} \sum_{a=1}^{N_7} \sum_{i=1}^{N_7} M_a \cdot L_{ai} \cdot f_i
\] (10)

In the equation, \(C_{\text{tran}}(F_{\text{mater}})\) denotes the carbon emissions generated from transferring material features, \([C_{\text{tran}}(F_{\text{mater}})]_p\) is the carbon emissions of the \(p\)th parts from transferring material, \(N_7\) is the number of transportation styles, \(L_{ai}\) is the distance of the \(i\)th transportation styles for the \(a\)th material feature, and \(f_i\) is the carbon emission coefficient of the \(i\)th transportation styles, which refers to carbon emissions per unit of distance and per unit of material mass.

D. Use stage

The carbon footprint in use stage is regarded as the carbon emissions generated from maintaining operational state features. For mechanical products, use stage is the longest in their life cycle with a large energy consumption. Generally, a product may have several operational states. For example, a machine tool has standby state, unloaded state, and cutting state; the energy demand varies under different operational states. The carbon footprint in this stage can be calculated using Eq. (11).

\[
CF_u = C_{\text{maint}}(F_{\text{opera}}) = \sum_{j=1}^{N_8} \sum_{e=1}^{N_3} E_{je} \cdot (f_e + f'_e)
\] (11)

where \(C_{\text{maint}}(F_{\text{opera}})\) denotes the carbon emissions generated from maintaining operational state features; \(N_8\) is the amount of operational state features; \(E_{je}\) is the usage of the \(e\)th energy in the \(i\)th operational state feature, which is determined by the design parameters in the \(i\)th operational state feature.

E. Recycle and disposal stage

The carbon footprint in recycle and disposal stage is defined as the carbon emission caused by removing and recovering micro-features. At the stage of end of life, some
scraped products still have a substantial recovery value. The recovery methods of components include product/component reuse, material recycling, and remanufacturing. Reuse can lead to less carbon emission. Material recycling recovers resources from the used components. Remanufacturing renews the waste components to meet or exceed the quality of the original components with some advanced restoration technology. In recycling and remanufacturing processes, the carbon emissions mainly come from the usage of energy in operation processes. The recycled parts and materials can be used to produce new products, which will result in negative carbon emissions. However, some waste components cannot be recycled due to low value and severe damage. Therefore, direct disposal (e.g., landfill, burning) is adopted to handle these wastes. The carbon footprint in this stage could be evaluated by Eq. (12).

\[
CF_e = \sum_{e=1}^{N_{e}} \left( C_{rem}(F_{micro}) + C_{rec}(F_{micro}) \right)
\]

\[
+ \sum_{q=1}^{N_{q}} \left( C_{shape}(F_{micro}) \right)
\]

where \( C_{rem}(F_{micro}) \) denotes the carbon emissions from removing micro-features, \( C_{rec}(F_{micro}) \) denotes the carbon emissions generated from recovering micro-features, \( N_{e} \) is the amount of reused micro-features, \( N_{10} \) is the number of remanufactured micro-features, \( E_{fe} \) is the usage of the eth energy for remanufacturing the th micro-feature, \( N_{i} \) is the quantity of material recycled micro-features, \( E_{me} \) is the consumption of the eth energy for recycling the mth micro-feature, \( N_{12} \) is the amount of directly disposed micro-features, and \( E_{ge} \) is the usage of the eth energy for disposing gth micro-feature.

\[\text{(12)}\]

3 Case study

On the basis of macro-feature and micro-feature, the carbon footprint model for embodiment design phase could be established. The carbon footprint model can quantitatively evaluate carbon emission of product life cycle and support designers in making decisions for low-carbon design. A case study of a gear hobbing machine is used to validate the proposed approach. The gear hobbing machine is widely used for gear cutting, such as straight teeth and oblique teeth.

3.1 Product life cycle conditions

To calculate the carbon footprint of the gear hobbing machine, the following conditions are considered:

(A) The carbon emission coefficients of raw material and energy are derived from IPCC [48] and GB/T 2589-2008 [49]. Table 4 presents some carbon emission coefficients in this case study. It is noted that the coefficients of fuels are the indirect carbon emission coefficients. The direct carbon emission coefficient could be obtained by the chemical formula of fuel burning.

(B) At manufacturing stage, the equipment for every manufacturing process is fixed in this company, and the SEC or EEC of each equipment could be determined by experiment; some of the equipment used in this study are exhibited in Table 5.

(C) The raw material supplier is a company in Chongqing, which is approximately 200 km away from Chongqing Machine Tool Group Co. The produced gear hobbing machine is sold to a company in Zhejiang. The transportation distance between companies is 2000 km. The transportation modes in this case study are by truck. The carbon emission coefficient of truck is 0.188 kg CO2e/km [50].

(D) The service life of the gear hobbing machine is 10 years. According to the customer’s actual demand, the working time per year is 300 days, and the operational time of the machine is 12 h per day. The operational time ratio in the unload, standby, and cutting states is set to 1:3:6; this ratio comes from the statistical analysis of the production orders of the enterprise and actual survey data. The time in standby state is reduced by 50% with the automatic load-unload device. The cutting efficiency of dry cutting is increased by 20%. According to the requirements of consumer, the gear hobbing machine is used to machine a specific product, and the related parameters of this product are given in Table 6.

(E) At the product’s end of life stage, the recycling processes are assumed in ideal conditions. Approximately 80% of the parts could be remanufactured to meet the function of a new one. The material recycling rate is 100%. No component requires direct dispose.

3.2 The carbon footprint of gear hobbing machine

The design schemes of a gear hobbing machine are obtained from Chongqing Machine Tool Group Co. in China. The company is planning to design a high-speed dry-cutting gear hobbing machine. The overall technical specification parameters are shown in Table 7. The gear hobbing machine is designed to have six main functions: structural support function, main drive function, feed function, workpiece rotation function, auxiliary function, and numerical control function, as shown in Table 8.
The original design scheme (Scheme 1) is determined by designer, and the details are described as follows.

**Scheme 1** “Cast iron machine body” + “Coolant and lubricant oil” + “Geared transmission spindle” + “Motor direct-drive feed” + “Manual load-unload” + “FANUC NC device”

The main corresponding structure of Scheme 1 is obtained by analyzing the function-structure mapping. The details of the functions and the corresponding components are described in Table 9.

Based on the FSF model, the design feature can be derived. The macro-feature is shown in Table 10 and Fig. 5. Table 10 elaborates the operational state feature of Scheme 1. The power in standby state and unloaded state are the design power. In cutting state, the cutting power can be estimated by cutting force and cutting speed [51, 52]. Fig. 5 shows the relation feature of Scheme 1. The micro design features of bearing seat (CN7) and workbench table (CN17) are given as examples in Table 11 and the micro design feature of the other components could be expressed similarly.

According to the Eq. (1)–Eq. (14) in Section 2, the carbon footprints of Scheme 1 is calculated based on the micro-feature and macro-feature. The calculation of bearing seat (CN7) in Scheme 1 is given as an example; the details are shown in Appendix.

As shown in Table 12, the carbon emissions from establishing material features are 19451 kg CO₂e. The carbon emissions generated from establishing geometry features, relation features, and surface treatment features are 7586 kg CO₂e, 1812 kg CO₂e, and 3099 kg CO₂e, respectively. The carbon emissions aroused by transferring material features are 4963 kg CO₂e. The carbon emissions in maintaining operational features are 235224 kg CO₂e. The carbon emissions generated from removing and recovering micro-features are −17368 kg CO₂e. The total carbon footprint of Scheme 1 is 254767 kg CO₂e.

### 3.2.1 Optimization analysis of Scheme 1

According to the carbon footprint results in Table 12, within these operating activities, the maintaining operational features in use stage has the largest amount (more than 90%) of total carbon footprint. Establishing and transferring material feature also contribute greatly to carbon footprint, accounting for 9.58%. The other activities contribute little to the total carbon footprint. Therefore, some adjustments should be made to the operational feature and material feature.

Fig 6 shows the carbon footprint distribution of operational feature. The proportions of standby state feature, unloaded state feature and cutting state feature are 18%, 9% and 73%, respectively. Cutting state feature and standby state feature are identified as the design feature with high carbon footprint. The decomposition of material feature carbon footprint is shown in Fig. 7. It can be found that material feature of CN1 accounts for the largest carbon footprint among all material features. Therefore, the material feature of CN1 is selected as another design feature with high carbon footprint.

Some feasible optimization measures are adopted to improve the selected design feature, as listed in Table 13.

The improved design scheme (Scheme 2) is formed based on the above optimization measures. The details of Scheme 2 are described as follows.

| Equipment type       | SEC (KJ/cm³)       |
|----------------------|--------------------|
| Colchester Tornado A50 | 1.494+2.191/MRR   |
| IKEGAI AX20          | 2.093+4.415/MRR   |
| Mori Seiki SL-15     | 2.378+2.273/MRR   |
| Mori Seiki Dura Vertical 5100 | 2.830+1.344/MRR |
| DMU60P               | 2.411+5.863/MRR   |
| Fadal VMC 4020       | 2.845+1.330/MRR   |
| Nakamura TMC-15      | 3.730+2.349/MRR   |

### Table 6 The parameters of processed product

| Part name   | Teeth number | Modulus (mm) | Tooth width (mm) | Gear material |
|-------------|--------------|--------------|------------------|--------------|
| Gear        | 30           | 2.5          | 20               | 45#steel     |
Table 7 The overall technical specification parameters of the gear hobbing machine

| Parameter type                              | Dimension          |
|---------------------------------------------|--------------------|
| Maximum processing diameter                | 210mm              |
| Maximum processing module                  | 4mm                |
| Maximum rotational speed of workbench      | 300r/min           |
| Rotational speed range of hob              | 600–3000r/min      |
| Overall dimension (length × width × height)| 3010mm × 3200mm × 2900mm |
| Machining accuracy grade                   | 7                  |

Scheme 2 “Mineral casted machine body” + “Dry cutting” + “Motorized spindle” + “Motor direct drive feed” + “Automatic load-unload” + “SIEMENS NC device”

The main corresponding structure can be obtained by analyzing the function-structure mapping. The details of the functions and the corresponding components are described in Table 14.

Based on the FSF model, the design feature is secured. The macro-feature is shown in Table 14 and Fig. 6. Table 15 elaborates the operational state feature of Scheme 2. Fig. 8 shows the relation feature of Scheme 2. The micro design feature of bearing seat (CN7) and workbench table (CN17) are given as examples in Table 16, and the micro design feature of the other components could be expressed similarly.

According to the Eq. (1)–Eq. (14) in Section 2, the product carbon footprints of Scheme 2 is calculated based on the micro-feature and macro-feature.

As shown in Table 17, the carbon emissions in establishing material features are 17228 kg CO2e. The carbon emissions generated from establishing geometry features, relation

Table 8 The main function of the gear hobbing machine

| Function no. | Main function                     | Description                                                                 |
|--------------|-----------------------------------|-----------------------------------------------------------------------------|
| FN1          | Structural support function       | The basic module to connect other parts and provide support                  |
| FN2          | Main drive function               | Provide and transmit powers for rotating hob                                |
| FN3          | Feed function                     | Provide and transmit powers for axial and radial feed motion                |
| FN4          | Workpiece rotation function       | Fix and rotate the workpiece                                                |
| FN5          | Auxiliary function                | Protection, cooling, dusting, etc.                                         |
| FN6          | Numerical control function        | Control machine tool by the coded programmed instruction                   |

Table 9 The main function and corresponding components of Scheme 1

| Function no. | Components no. | Components name               | Function no. | Components no. | Components name               |
|--------------|----------------|-------------------------------|--------------|----------------|-------------------------------|
| FN1          | CN1            | Machine body                  | FN4          | CN18           | Workbench shell               |
|              | CN2            | Stand column                  |              | CN19           | Workbench shaft               |
| FN2          | CN3            | Hob shaft                     | CN4          | CN20           | Workbench table               |
|              | CN4            | Slide base                    |              | CN21           | Workbench shaft motor         |
|              | CN5            | Hob Shaft motor               | CN6          | CN22           | Latter stand column           |
|              | CN6            | Hob holder                    |              | CN23           | Slider                        |
|              | CN7            | Bearing seat                  |              | CN24           | Bearing seat                  |
|              | CN8            | Transmission box 1            | FN5          | CN25           | Ball screw                    |
|              | CN9            | Transmission box 2            |              | CN26           | Full-enclosed guards          |
| FN3          | CN10           | Radial feed planker           |              | CN27           | Lubricating device            |
|              | CN11           | Worm wheel                    |              | CN28           | Dry separator                 |
|              | CN12           | Worm screw                    | FN6          | CN29           | FANUC NC device               |
|              | CN13           | Axial feed slider             |              |                |                               |
|              | CN14           | Supporting base               |              |                |                               |
|              | CN15           | Servo motor                   |              |                |                               |
|              | CN16           | Connecting base               |              |                |                               |
|              | CN17           | Servo motor                   |              |                |                               |

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features, and surface treatment features are 6759 kg CO$_2$e, 1752 kg CO$_2$e, and 2965 kg CO$_2$e, respectively. The carbon emissions aroused by transferring material features are 4728 kg CO$_2$e. The carbon emissions in maintaining operational features are 208672 kg CO$_2$e. The carbon emissions generated from removing and recovering micro-features are $-15256$ kg CO$_2$e. The total carbon footprint of the gear hobbing machine is 226848 kg CO$_2$e.

4 Results and discussions

The carbon footprints of the two design schemes are calculated in Section 3.2. Then, the validity of the proposed model is verified by the comparison of these two design schemes. The carbon footprint comparison of the two schemes is shown in Fig. 9. After improving design features, the carbon footprint of Scheme 2 decreased by 10.96% compared to that of Scheme 1. That is, for a company with 100 gear hobbing machines, the carbon footprint reduction will be 2790 tons. Therefore, the optimum adjustment of design feature in Scheme 2 could effectively reduce product lifecycle carbon footprint.

The carbon footprint in different life cycle stage is analyzed and exhibited in Fig. 10. Among the five lifecycle stages, the carbon footprint in use phase contributes the most to the total carbon footprint in both design schemes. This is caused by a large amount of energy consumption due to the long service time. The carbon footprint during the transportation stage is

| Operational state feature | Description                                           | Power (KW) |
|--------------------------|-------------------------------------------------------|------------|
| Standby state            | Only the basic auxiliary equipment is activated, such as computer panel, cooling | $P=4$      |
| Unloaded state           | The main drive system and feed system begin to run; the tool does not touch the workpiece | $P=6$      |
| Cutting state            | The tool touching the workpiece and removing materials | $P=8$      |
the lowest, which is mainly determined by the mode of transport and location of customer. At the end of life, the results indicate that the reduced carbon footprints of the two schemes after recycling are 17368 kg CO2e and 15256 kg CO2e, respectively. Therefore, effective recycling methods could significantly reduce the potential carbon footprint generated in material extraction stage and manufacturing stage.

Fig. 11 shows the carbon footprint comparison in use stage of the two schemes. The carbon footprint of Scheme 2 in use phase has decreased by 11.28% (26.54 t CO2e), which is a considerable reduction. This result could be attributed to the reduction of carbon emission generated from standby feature and cutting feature. Although the total power in Scheme 2 is higher than that in Scheme 1 after the optimization of standby feature and cutting feature, the use of an automatic load-unload device and dry cutting will significantly improve processing efficiency and reduce standby time. Consequently, the proper adjustment of operational feature could bring potential benefits in reducing carbon footprint.

The carbon footprint in material extraction and manufacturing stage has decreased by 9.97% (3.184 t CO2e) from Scheme 1 to Scheme 2, as shown in Fig. 12. It is noted that material extraction stage is the main contributor to this reduction. The reason is that the employment of a mineral casted machine body can lead to the reduction of carbon footprint in material extraction stage. The lightweight technology for improving material feature is an effective method to decrease carbon footprint. In addition, geometry feature is more carbon-intensive in manufacturing stage. Thus, it can

Fig. 6 Carbon footprint distribution of operational feature
conclude that optimizing part geometry feature may be a feasible approach to reduce the carbon footprint in this stage. The smallest amount of carbon footprint is generated by the establishment of relation feature, in which the assembly process is dominated by manpower with low energy consumption.

Reducing product life cycle carbon footprint in embodiment design stage through this method has significant use. The carbon footprint model can be used to evaluate the carbon footprint of design schemes, enabling the identification of the design feature with high carbon footprint. The proper improvement of these design features is a promising method that could support designers in optimizing design scheme.

Compared with the prior researches, the approach proposed in this paper has two advantages: (1) this model achieves an accurate carbon footprint assessment in embodiment design phase and (2) the design scheme can be optimized to reduce life cycle carbon footprint. This approach is a promising method to help enterprise achieve the goal of energy saving and emission reduction.

5 Conclusion and future work

Product embodiment design phase has a significant effect on carbon footprint throughout its life cycle. However, the existing carbon footprint model is unsuitable for embodiment design stage and cannot guide design scheme optimization for reducing life cycle carbon footprint. This paper evaluates product carbon footprint in embodiment design phase. A Function-Structure-Feature model is presented to convey the

### Table 13 The optimization measures for design features with high carbon footprint

| Design features               | Optimization measures       |
|------------------------------|------------------------------|
| Standby state feature        | Automatic load-unload device |
| Cutting state feature        | Dry cutting                 |
| Material feature of CN1      | Mineral casted machine body |

### Table 14 The main function and corresponding components of Scheme 2

| Function no. | Components no. | Components name            | Function no. | Components no. | Components name             |
|--------------|----------------|-----------------------------|--------------|----------------|-------------------------------|
| FN1          | CN1            | Machine body                | FN4          | CN16           | Workbench shell              |
|              | CN2            | Stand column                |              | CN17           | Workbench shaft              |
| FN2          | CN3            | Hob shaft                   |              | CN18           | Workbench table              |
|              | CN4            | Slide base                  |              | CN19           | Workbench shaft motor        |
|              | CN5            | Hob Shaft motor             |              | CN20           | Latter stand column          |
|              | CN6            | Hob holder                  |              | CN21           | Slider                       |
|              | CN7            | Bearing seat                |              | CN22           | Bearing seat                 |
| FN3          | CN8            | Radial feed planker         | FN5          | CN23           | Ball screw                   |
|              | CN9            | Worm wheel                  |              | CN24           | Full-enclosed guards         |
|              | CN10           | Worm screw                  |              | CN25           | Lubricating device           |
|              | CN11           | Axial feed slider           |              | CN26           | Dry separator                |
|              | CN12           | Supporting base             |              | CN27           | Automatic load-unload device |
|              | CN13           | Servo motor                 | FN6          | CN28           | SIEMENS NC device            |
|              | CN14           | Connecting base             |              |                |                               |
|              | CN15           | Servo motor                 |              |                |                               |
embodiment design scheme. The design feature is defined as a collection of macro-feature and micro-feature, which are the carrier of design information related to carbon emission activities during product life cycle. The macro-feature denotes the different operational states of the product and the constraint relationships between parts. The micro-design feature denotes specific properties of parts. In addition, the correlation between product carbon footprint and design feature is analyzed, and then the product carbon footprint model is established based on design feature. The design feature could be optimized to reduce life cycle carbon footprint by implementing this approach. Finally, a gear hobbing machine is evaluated and optimized to validate the proposed method. Compared with the original scheme, the scheme with improved design features significantly reduces the carbon footprint. The results show that this method can be used to evaluate carbon footprint and guide designer in optimizing design schemes in embodiment design phase.

The proposed carbon footprint model can be used to evaluate product footprint in embodiment design phase. However, this study has several limitations. First, the uncertainties in the product life cycle are ignored, which may affect the accuracy of the evaluation results. A systematic analysis approach will be conducted to reduce the impact of uncertainties. Second, the optimization of the design scheme only considers life cycle carbon footprint, and other indicators, such as cost and reliability, are not taken into account. A multi-objective optimization design based on design features is deserved to study. Third, in case study, the use stage of the gear hobbing machine is in an ideal state, and the production plan is fixed. Therefore, the carbon footprint computation in use stage is imprecise and needs further improve. Fourth, the improvements of design

| Operational state feature | Description | Power (KW) |
|---------------------------|-------------|------------|
| Standby state             | Only the basic auxiliary equipment are activated, such as computer panel, cooling, load-unload, etc. | P≈4.5 |
| Unloaded state            | The main drive system and feed system begin to run; the tool does not touch the workpiece | P≈6.2 |
| Cutting state             | The tool touching the workpiece and removing materials | P≈9.5 |

Fig. 8 The relation feature of Scheme 2
Table 16  The micro-feature of bearing seat (CN7) in Scheme 2 and the micro-feature of workbench table (CN18) in Scheme 2

| Components | Material feature | Geometry feature | Surface treatment feature |
|------------|------------------|------------------|--------------------------|
|            |                  |                  |                          |
| Shape feature | Size feature   |                  |                          |
| CN7        | Types HT300      | Overall shape feature Cylinder+ Cuboid | 2.1×10^6 mm^3 | Annealing |
| Weight     | 15kg             | Local shape feature Face               | 240mm×135mm     |          |
| Property   | Forging          | Face×2            | 50mm×135mm               |          |
| Recovery mode | Remanufacturing | Hole              | Ø110mm×H135mm            |          |
|            |                  | Hole              | Ø16mm×H25mm              |          |
|            |                  | Hole              | Ø24mm×H35mm              |          |
|            |                  | Hole              | Ø120mm×H55mm             |          |
| CN18       | Types 40Cr       | Overall shape feature Cylinder           | Ø180mm×H50mm    | Annealing |
| Weight     | 17.3kg           | Local shape feature Hole×6               | Ø12mm×H20mm     |          |
| Property   | Forging          | Hole              | Ø75mm×H6mm               |          |
| Recovery mode | Remanufacturing | Hole              | Ø24mm×H40mm              |          |
|            |                  | Face              | Ø180mm                   |          |

Table 17  The carbon footprint of Scheme 2

| Life cycle stage                  | Operating activities                              | Scheme 1     | Proportion (%) |
|-----------------------------------|---------------------------------------------------|--------------|----------------|
| Material extraction stage         | Establishing material features                     | 17228kg CO2e | 7.59           |
| Manufacturing stage               | Establishing geometry features                     | 6759kg CO2e  | 2.98           |
|                                   | Establishing relation features                     | 1752kg CO2e  | 0.77           |
|                                   | Establishing surface treatment features            | 2965kg CO2e  | 1.31           |
| Transportation stage              | Transferring material features                     | 4728kg CO2e  | 2.08           |
| Use stage                         | Maintaining operational features                   | 208672kg CO2e| 91.99          |
| Recycle and disposal stage        | Removing and recovering micro-features             | −15256kg CO2e| −6.72          |
| Total carbon footprint            |                                                   | 226848kg CO2e| 100            |

Fig. 9  Total carbon footprint of two schemes
Fig. 10 Carbon footprint of two schemes in different lifecycle stage.

Fig. 11 Carbon footprint of two schemes in use stage.

Fig. 12 Carbon footprint of two schemes in material extraction and manufacturing stage.
feature mainly depend on the user’s knowledge. The future work will focus on how to construct improvement rules of design feature for practical application.

Appendix

According to the micro-feature of CN7 in Table 11, the carbon footprint of CN7 could be calculated as follow.

1) Carbon footprint in extraction of raw material stage.

\[
CF_e = C_{ext}(F_{matter}) = 15 \times 1.51 = 22.65 \text{ (kgCO}_2\text{e)}
\]

2) Carbon footprint in manufacturing stage.

The machining process and related information are shown in Table 18. For a component, the carbon footprint in assembly process is not taken into account.

The failure mode of bearing seat is abrasion; plating process is selected to remanufacture it.

\[
CF_r = C_{rem}(F_{micro}) = 6.72−22.65−13.55 = −29.48 \text{ (kgCO}_2\text{e)}
\]

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Code availability Not applicable.

| Process No. | Process name  | Equipment                | Parameters                          |
|-------------|---------------|--------------------------|-------------------------------------|
| P1          | Casting       | precision forging machine | $EEC=2453\text{KJ/kg}$            |
| P2          | Heat treatment| Annealing equipment      |                                     |
| P3          | Milling       | Horizontal miller        | $SEC=11.03\text{KJ/cm}^3$; allowance=3mm |
| P4          | Milling       | Horizontal miller        | $SEC=11.03\text{KJ/cm}^3$; allowance=2mm |
| P5          | Boring        | Vertical Lathe           | $SEC=8.53\text{KJ/cm}^3$; allowance=3mm |
| P6          | Boring        | Vertical Lathe           | $SEC=6.41\text{KJ/cm}^3$; allowance=10mm |
| P7          | Drilling      | Driller                  | $SEC=13.02\text{KJ/cm}^3$; allowance=25mm |
| P8          | Boring        | Vertical machine center  | $SEC=10.33\text{KJ/cm}^3$; allowance=35mm |

Table 18 The machining processing information of CN7

The carbon footprint in use stage is calculated at product level; therefore, the carbon footprint of CN7 in use stage is not taken into account.

5) Carbon footprint in recycle and disposal stage.

\[
CF_r = C_{rem}(F_{micro}) = 6.72−22.65−13.55 = −29.48 \text{ (kgCO}_2\text{e)}
\]
Declarations

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Consent to participate Not applicable.

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Competing interest All authors declare no competing interests.

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