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ORIGINAL ARTICLE

Low-carbon conceptual design based on product life cycle assessment

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Abstract Greenhouse gas emission becomes a recent global concern for manufacturing. As product design has a profound effect on a product's carbon footprint in its life cycle, recent research efforts of low-carbon design provided valuable insights and contributions. Yet, most of the research is about detailed design instead of the conceptual stage. Conceptual design of a product determines over 70 % of its life cycle costs. The decisions made during the conceptual design also have extensive impacts on the environment. Therefore, it is important to estimate the carbon footprint of a product at its conceptual design stage. In this paper, we present a carbon footprint model and a low-carbon conceptual design framework where the environmental impacts throughout the life cycle of a product can be assessed. In the carbon footprint model, the amount of carbon emission is estimated at the five stages of the entire product life cycle. The carbon footprint analysis is based on product life cycle assessment. Sensitivity analysis for design parameters is also performed to measure the effects of design parameters on the estimation of product carbon footprint quantitatively. The conceptual design of a cold heading machine is used to demonstrate the proposed methodology.

Keywords Carbon footprint · Product life cycle assessment · Low carbon · Carbon emission · Conceptual design · Green manufacturing · Low-carbon manufacturing

1 Introduction

Greenhouse gas (GHG) emission becomes a recent global concern for manufacturing. The emission of GHGs, such as carbon dioxide, is believed to be the main contributor of the so-called global climate change, which could potentially break the ecological balance [1, 2]. About 84 % of energy-related carbon dioxide emissions and 90 % of the energy consumption can be attributed to a variety of manufactured products [3]. Therefore, the Kyoto Protocol and the Copenhagen Accord stipulate that products must follow the principle of reducing GHG emissions [4]. The Intergovernmental Panel on Climate Change (IPCC) [1] defines low-carbon technology as the one that results in a lower level of carbon emission than the regular ones for the entire life cycle of products.

The terms carbon emission and carbon footprint are widely used as an indicator of environmental performance, which were derived from ecological footprint coined by Wackernagel and Rees [5]. With different objectives and granularities, several indicators such as product carbon footprint and organization carbon footprint are used [6]. Particularly, product carbon footprint refers to the emission of a variety of GHGs in product life cycle. Carbon footprint is typically calculated by considering carbon emission factors and activity data [7], which could be evaluated by life cycle assessment (LCA). LCA is based on life cycle inventory (LCI), which is a repository that includes the data of resource and energy consumptions, and emissions to the environment throughout the entire product life cycle. In addition, the consideration of uncertainty associated with all phases in the LCI is important to make LCA-based decisions justifiable [8]. For production systems, based on the input/output data in LCI, the possible environmental impacts can be assessed. Umeda et al. [9] provided a systematic framework and methodology for life cycle development and proposed the concept of life cycle planning.

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Kellens et al. [10] proposed a life cycle analysis methodology for inventory analysis of manufacturing unit processes providing unit process datasets to be used in LCI databases.

LCA is a widely used approach to assess the actual environmental impact of a product caused by its production and use. The standards to evaluate the product carbon footprint in the life cycle are mainly PAS 2050 [7] and ISO/TS 14067 [11]. The life cycle is defined as a series of consecutive stages of a product by ISO 14040 [12], including acquisition of raw materials, manufacturing, transportation, usage, and recycle and disposal. The LCA framework includes the determination of the objective and scope of the evaluation, inventory analysis, life cycle impact assessment, and life cycle interpretation [12]. PAS 2050 uses the LCA framework to evaluate GHG emissions from products, either business-to-consumer or business-to-business, to find ways to minimize carbon footprint. The potential environmental impacts of a production system, either for the entire life cycle of the product or a specific stage, could be effectively assessed through the LCA of the product.

As design has a profound effect on product carbon footprint, recent research efforts of low-carbon design provided valuable insights and contributions. Two general approaches targeted at carbon footprint for sustainable design have been developed [13, 14]. One is design methods to reduce carbon footprint, and the other is carbon footprint modeling.

For design methods to reduce carbon footprint, existing research focused on the development of methods that integrate product carbon footprint assessment tools. For example, Song et al. [15] proposed a low-carbon product design system based on the bill of materials (BOM) using the embedded GHG emissions data of the parts. Kuo [16] constructed a collaborative design framework to help enterprises collect products' carbon footprints and use a computer-aided tool to integrate enterprise's internal systems with the life cycle inventory database. Jeswiet et al. [17] proposed ecodesign rules to reduce GHG emissions and environmental impacts. Alsaffar et al. [18] provided a method for reducing carbon footprint through simultaneous consideration of manufacturing processes and supply chain activities. Devanathan et al. [19] developed a semi-quantitative ecodesign methodology that is a combination of environmental life cycle assessment and visualization tools. Li et al. [20] proposed a quantitative approach to analyze carbon footprint of machining systems.

For carbon footprint modeling, existing research focused on the construction of product carbon footprint models based on design rules. For example, Jiao et al. [21] proposed an affective design framework to facilitate decision making in designing customized product ecosystems and applied association rule mining techniques to construct an analytical model. Elhedhli et al. [22] proposed a model to minimize the carbon footprint for the supply chain based on Lagrangian relaxation. Giurco et al. [23] developed an approach to design preferred features for the life cycle of metal using dynamic material flow models. Ball et al. [24] developed a model to represent material, energy, and waste flows to support manufacturing facility design. He et al. [25] combined carbon footprint model with the consideration of data imprecision in product life cycle, which could model carbon footprint of design solutions in conceptual design.

The above approaches for carbon footprint calculations are mainly based on one or several carbon footprint influence factors to construct the evaluation tools. The carbon footprint analysis is focused on one particular stage of production. They do not provide the analysis for the entire life cycle of products. In addition, existing carbon footprint calculation methods are too complex and time consuming for the purpose of product design. As conceptual design largely depends on the knowledge of designer [26, 27], providing carbon footprint information with the right format is important to low-carbon conceptual design. In this paper, a new carbon footprint calculation approach is proposed to quantify the carbon footprint for all stages of production. The low-carbon conceptual design includes two steps. One is the routine conceptual design, and the other is redesign. The general low-carbon design process includes (1) routine conceptual design, (2) initial subsequent embodiment and detail design, (3) redesign in conceptual design, and (4) final subsequent embodiment and detail design. After the initial principle solution is developed in the routine conceptual design process, sensitivity analysis is applied to quantitatively determine the impacts of design parameters on the carbon footprint of the system. With this information, carbon footprint could be reduced effectively through the adjustment of the most influential design parameters. After the design concept meets the requirements, the conceptual design process will end, and the final low-carbon design concept is transferred to the subsequent design process.

In the remainder of the paper, the proposed model is first described in Section 2. A cold heading machine then is used to demonstrate our approach in Section 3. Section 4 concludes this paper.

2 Modeling product carbon footprint

2.1 Calculation process of product carbon footprint

The calculation of product carbon footprint includes four steps: selection of functional units, determining the system boundary, collecting data, and calculating carbon footprint. The detailed calculation procedure of carbon footprint is shown in Fig. 1 and described as follows.

(1) Select functional unit

In the LCA of a product, the functional unit needs to be identified for analysis and calculation. The functional unit used for an analysis should remain as the same for a

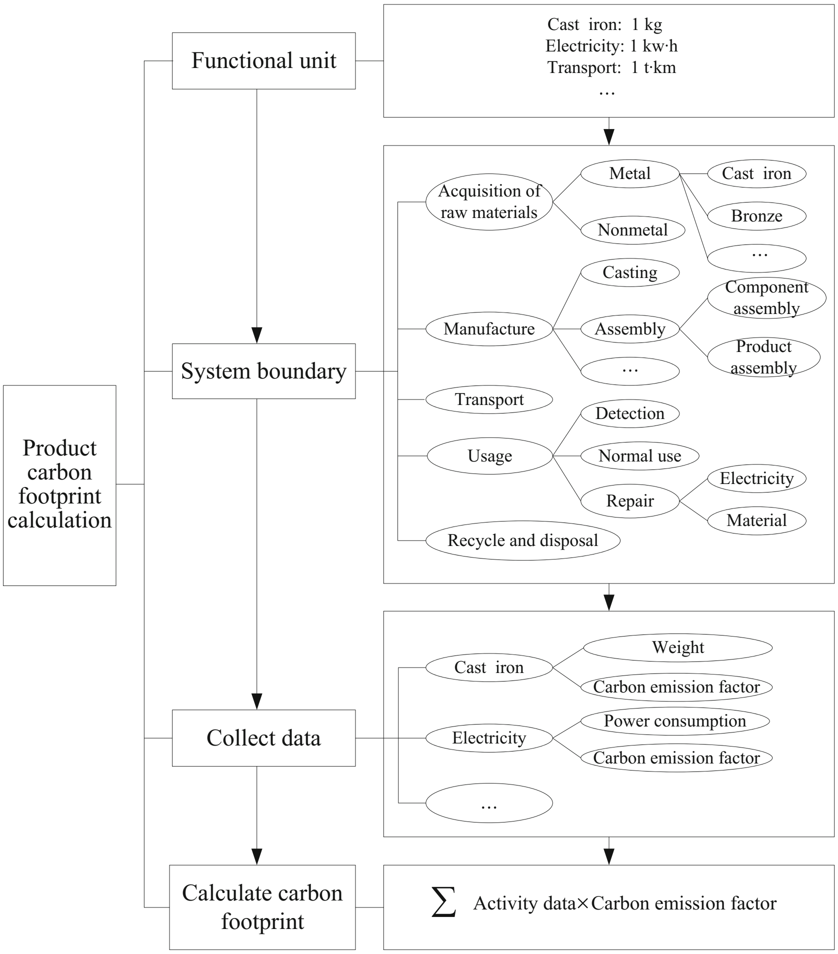


Fig. 1 The calculation procedure of product carbon footprint

particular stage of life cycle. The functional unit provides a unified reference to measure the input and output of resource consumption. The convenience of data collection and calculation needs to be considered when the functional unit is selected. The functional unit may vary at different stages of its life cycle. For instance, during the production of a gear box, 1 kg material is the functional unit during the production of cast iron, steel, and other raw materials. At the manufacturing stage of components, such as transmission shafts and gears, the main carbon footprint is caused by the electricity consumption. Thus, 1 kWh can be selected as a functional unit for this stage.

(2) Determine the system boundary

The system boundary should be defined so that it indicates the calculation scope for carbon footprint, including the inputs and outputs of materials, energy, and other resources involved in LCA. The input of human and animal power and carbon footprint that do not exceed 1 % of the expected total emissions in the product life cycle could be excluded from the system boundary. The system boundary should include energy inputs and GHG emissions at all stages of the life cycle. The material and energy flows for each stage also need to be identified. For example, at the manufacturing stage, energy flow mainly includes casting, assembly, and other processes of energy consumption. And the material flow in the assembly process contains parts assembly and product assembly, and materials of various parts that the assembly requires are provided from the acquisition of raw materials stage.

(3) Collect data

Data that need to be collected to calculate carbon footprint include activity data and carbon emission factors in the product life cycle. The accuracy and completeness of data collection affect directly the feasibility of the carbon footprint calculation and the reliability of the calculation results. Unfortunately, there are some limitations in the available LCA databases. For instance, they only provide average values of emissions and energy consumption over a range of different machines that are used in manufacturing industry. This could cause inaccurate predictions because some specific machines could dramatically increase energy consumption [28, 29]. Furthermore, only limited information is available for products at the early design stage, which is a major uncertain factor in assessing a product's carbon footprint at its conceptual design stage. The major task of LCA is to build the inventory of the energy consumption for each activity for the whole life cycle [30]. The collected data could come from primary or secondary sources [7]. Primary data refer to direct measurements made internally or by someone else in the supply chain about a specific product's life cycle [7], such as the quantity of cast iron as raw material and the power consumption in the production process. Secondary data refer to external measurements that are not specific to a product, but rather an average or generic estimate of similar processes or materials [7], such as the global warming potential (GWP) of GHGs, which could be obtained from the evaluation report issued by the IPCC [1]. Activity data and emission factors could come from either primary or secondary sources.

(4) Calculate carbon footprint

Product carbon footprint is a term used to describe the amount of greenhouse gas (GHG) emissions caused by a particular activity or entity across the product life cycle. It is a way for organizations and individuals to assess their contribution to climate change [7]. The carbon footprint is the accumulated result of all materials, energy, and wastes for all activities throughout the life cycle of a product and its corresponding emission factors. Carbon footprint calculation is determined by the system boundaries that meet the needs of applications and collected data. An operational carbon footprint model should have good efficiency for calculating product carbon footprint. All input and output of materials and energy consumptions should be taken into considerations in the calculation to estimate the true balance of the system.

2.2 Product carbon footprint calculation model for entire product life cycle

According to the definition of product life cycle and the analysis of product carbon footprint [7], the contribution of carbon footprint is divided into five stages for the entire product life cycle: acquisition of raw materials, manufacturing, transportation, usage, and recycle and disposal. The carbon footprint model of the product life cycle is defined as

$$E = \sum_{i=a}^{r} E_i \tag{1}$$

where E is carbon footprint in the product life cycle, E_i is the ith stage of product life cycle, for example, i=a, m, t, u, and r are for the acquisition of raw materials, manufacturing, transportation, usage, and recycle and disposal stage, respectively.

Carbon footprint of product at the ith stage is calculated as

$$E_i = \sum_{j=1}^{M_i} M_{ij}\cdot C_{ij} + \sum_{k=1}^{G_i} G_{ik}\cdot \mathrm{GWP}_{ik} \tag{2}$$

In the calculation of carbon footprint at the acquisition of raw material stage, M_a is the number of raw material types consumed at the acquisition of raw material stage, G_a is the number of direct GHG emissions types at the acquisition of raw materials stage, M_{aj} is the consumption of the jth raw material, C_{aj} is the carbon emission factor of the jth raw material, G_{ak} is the emission of the kth type GHG at the acquisition of raw materials stage, and GWP_{ak} is the global warming potential of the kth type GHG.

In the calculation of carbon footprint at the manufacturing stage, M_m is the number of manufacturing and assembly activity processes, G_m is the number of direct GHG emission types at the manufacturing stage, M_{mj} is the consumed energy in the jth manufacturing and assembly activity processes, C_{mj} is the carbon emission factors of the energy consumed in manufacturing process and assembly process, G_{mk} is the emissions of the kth type GHG at the manufacturing stage, and GWP_{mk} is the global warming potential of the kth type GHG.

In the calculation of carbon footprint at the transportation stage, M_t is the number of transportation stages, including highway, railway, waterway, etc.; G_t is the number of direct GHG emission types at the transportation stage, the item $T_{tj}\cdot L_{tj}\cdot \mathrm{EI}_{tj}$ is activity data at the transportation stage; T_{tj} is the quantities of transportation objects (including materials, parts, products, waste, etc.) in the jth transportation stage; L_{tj} is the transportation distance in the jth transportation; EI_{tj} is the energy intensity of the jth transportation mode, i.e., the energy consumption per unit of energy quantity and per unit of distance in the jth transportation mode; C_{tj} is the carbon emission factor of energy consumption in the jth transportation mode; and G_{tk} is the emission of the kth type GHG at the transportation stage.

Carbon footprint of product at the usage stage is calculated as

$$E_u = \sum_{i=1}^{N_4} U_i\cdot C_{ui} + \sum_{j=1}^{S_2}\left(M_j\cdot C_{mj} + F_j\cdot C_{fj}\right)\cdot \frac{L}{L_j} + \sum_{k=1}^{D_4} G_{uk}\cdot \mathrm{GWP}_k \tag{3}$$

where N_4 is the total types of the energy consumed in normal use and detection, S_2 is the number of parts in the repair process, D_4 is the number of direct GHG emission types at the usage stage, U_i is the mount of consumed ith type energy in normal use and detection, C_{ui} is the carbon emission factor of the ith type energy, M_j is the energy consumption in the ith manufacturing process, F_j is the energy consumption in the jth assembly activity, C_{mj} is the carbon emission factors of the material to the jth part in the repair process, C_{fj} is the carbon emission factors of the energy consumed to the jth part in the repair process, L is the service life of the product, L_j is the service life of the jth part, and G_{uk} is the emission of the kth the GHG at the usage stage.

Carbon footprint at the recycle and disposal stage is calculated as

$$E_r = \sum_{i=1}^{N_5} Q_i \cdot C_{qi} + \sum_{j=1}^{S_3} \left(R_j \cdot C_{rj} - G_j\right) + \sum_{k=1}^{D_5} G_{rk} \cdot \mathrm{GWP}_k \tag{4}$$

where N_5 is the total types of the consumed energy in product disassembly and waste disposal; S_3 is the number of parts and materials in the reuse process of parts; D_5 is the number of direct GHG emission types at the recycle and disposal stage; Q_i is the ith consumed energy in the product disassembly and waste disposal; C_{qi} is the carbon emission factor of the ith type energy; R_j is the quantities of energy consumed in the process of reusing the jth part or material; C_{rj} is the carbon emission factors of energy consumed in the process of reusing the jth part or material; G_j is the carbon emission reduced in the process of reusing the jth part or material, which could be estimated with the ratio between the recycling materials and the original materials; and G_{rk} is the emission of the kth type GHGs at the recycle and disposal stage.

2.3 Low-carbon product conceptual design process

The low-carbon conceptual design process is a process with the consideration of carbon footprint throughout the entire product life cycle. The proposed low-carbon conceptual design process is based on the integrated carbon footprint method, as shown in Fig. 2 and described as follows.

The classical conceptual design is the early stage of the design process with the results of principle solutions, including identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles, and combining these into a working structure [31]. After completing the task clarification phase, the principle solution is determined at the conceptual design phase. The conceptual design process includes two steps, routine conceptual design and redesign.

The routine conceptual design is a general conceptual design process to identify the essential requirements, establish functional structures, search for working principles and working structures, and consolidate concept variants. Various design methodologies [31–33] are available. The purpose of routine conceptual design is to develop an initial principle solution. However, an initial principle solution cannot be assessed until it is transformed into the subsequent embodiment and detail design, which is involved in selecting materials, producing preliminary dimensions, and evaluating technology feasibilities. With these details, it is then possible to evaluate the essential aspects of carbon footprint of the principle solution as well as the design objectives and constraints.

After the initial embodiment and detail design are finished, the redesign of the initial principle solution to reduce the carbon footprint is taken. In this process, design requirements regarding carbon footprint are revisited. The initial product structure tree from BOM is established. The use of the proposed carbon footprint method during the conceptual design allows for a quick calculation of the carbon footprint of a product. Hence, a designer can quickly evaluate alternative design concepts. Design parameters with high carbon footprint are identified through sensitivity analysis. New concepts are generated to improve the design. If several variants look equally promising, then the final decision can be postponed to a more concrete level of design, because the same concept may result in various forms of design. Based on this evaluation, the best concept is selected. After the low-carbon design concept meets the design requirements, the conceptual design process ends and the final low-carbon design concept is carried over to the final subsequent embodiment and detail design. The design process continues on a more concrete level. The embodiment design process is to realize the low-carbon product concepts by incorporating the specific working environment and produce the final documentation of the complete product.

Sensitivity analysis (SA) in product conceptual design is to measure the effect of changing a given input variable or design parameter on a given output of product carbon footprint quantitatively. SA study thus can assess and quantify the uncertainty in the product carbon footprint and determine the impacts of design parameters on carbon footprint in a system [34]. Carbon footprint could be reduced effectively by revising those most influential design parameters. In our model, the sensitivity S_i of carbon footprint E_i with respect to the ith low-carbon design parameter p_i is calculated as

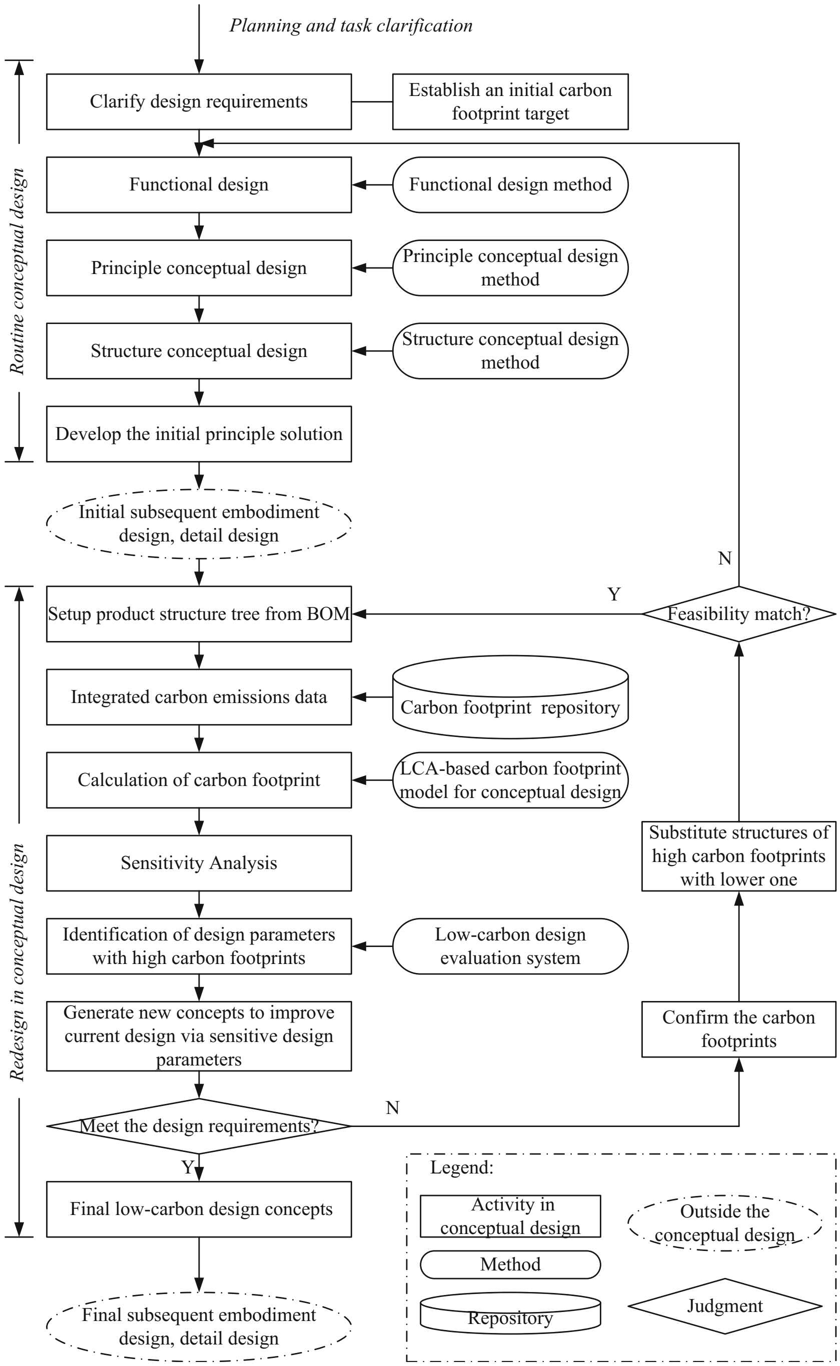
$$S_i = \frac{\partial E_i}{\partial p_i} = \frac{\partial f_{E_i}(p_1, p_2, p_3, \ldots, p_n)}{\partial p_i} \tag{5}$$

where $E_i = f_{Ei}(p_1, p_2, p_3, \ldots, p_n)$ is a function that represents the mapping relationship between design parameters and carbon footprint of a system.

3 Low-carbon conceptual design of a cold heading machine

Cold heading is a manufacturing process in which the coiled wire is fed into a cold heading machine, automatically cut to a

Fig. 2 Low-carbon product conceptual design process based on life cycle assessment



pre-determined length, and inserted into a die to form the pre-determined features, such as a bolt. It is an efficient process with little waste and low costs. However, the cold heading machine consumes a large amount of energy and resources, and at the same time, emits GHGs into the environment. As a case study, the carbon footprint of a cold heading machine is calculated, and the result is analyzed to verify the feasibility of the proposed carbon footprint model. The method described in Section 2 is applied to calculate carbon footprints of the cold heading machine, which also shows the significance of carbon footprint that heavy machinery industry has.

3.1 Analysis of carbon footprint of a cold heading machine

The GHG emissions of the cold heading machine mainly include the acquisition of raw materials, component fabrication from raw materials, subassemblies and final assembly, the transportation of the machine from manufacturer to user, normal use and repair, and recycle and disposal at the end of its life cycle. The system boundary of the cold heading machine is shown in Fig. 3. Not only the direct carbon footprints such as carbon dioxide, methane, and nitrous oxide need to be considered, but also the indirect carbon footprints at each stage of the life cycle should be included in the calculation.

For the raw material acquisition stage, the indirect carbon footprints of cast iron, steel, aluminum, and other raw materials, and the direct carbon footprints of GHGs are both taken into account. The weights of the raw materials inquired from the BOM are shown in Table 1, and the corresponding parts with part numbers are shown in the conceptual model of the machine in Fig. 4.

Carbon footprint factors of all materials are determined according to 2006 IPCC Guidelines for National Greenhouse Gas Inventories [35]. Many carbon footprint factors are listed in the IPCC Guidelines for National Greenhouse Gas Inventories [35]. Some of the carbon footprint factors for the materials and energy used in this case are shown in Table 2.

At the manufacturing stage, the energy consumption involved in the manufacturing processes include the fabrication of various components, such as sliding table, machine bed, and crankshaft, as well as the assembly processes, such as mandrel and cam subassemblies and the final assembly of the cold heading machine. The direct carbon footprints of GHGs are included in the calculation.

Energy consumption at the manufacturing stage is mainly composed of electricity consumption, which was obtained from the statistics of the production workshop. The carbon emission factor of electricity was collected from the Baseline Emission Factors for Regional Power Grids in China issued by the National Development and Reform Commission (NDRC) [36]. In this paper, the 0.81 kg/kWh was selected as the average of electricity emission factors of East of China regional grid between year 2009 and year 2011.

At the transportation stage, the activities that should be considered include the transportation of purchased parts from the manufacturer of the machine to the user, and of the waste and recyclable parts at the end of product life cycle to the disposal and recycling plants. The process of transporting the cold heading machine from the manufacturer to the user is the main consideration at this transportation stage. The machine is transported through highway from Ningbo to Shanghai, which has a distance of 366 km. A diesel truck was used in the highway transportation. The energy intensity of the diesel engine is 0.0650 L/t·km [37]. The determination of diesel emission factor is the same as the raw materials, which was based on the Guidelines for National Greenhouse Gas Inventories issued by the IPCC in 2006 [35].

At the usage stage, carbon footprints include the indirect carbon footprints of installation, detection, normal use and repair for the cold heading machine, and the direct carbon footprints of GHGs. The electricity consumption includes the machine installation and inspection processes. The material consumption and service life in the process of replacing parts need to be collected to calculate carbon footprint. The service life of cold heading machine is set as 15 years, and the working time is

Fig. 3 System boundary of the cold heading machine

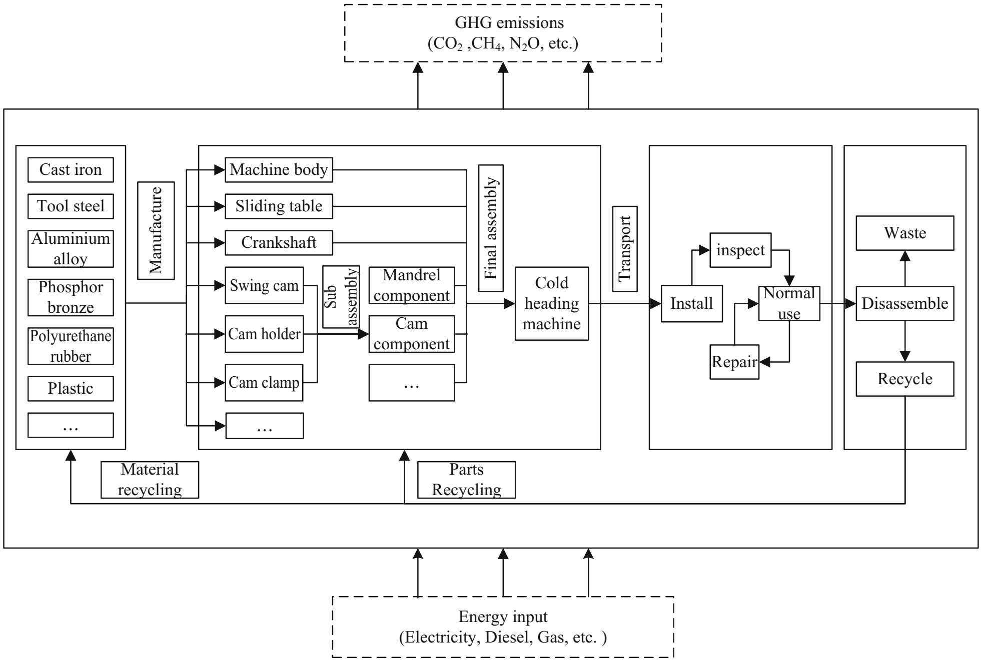


Table 1 The BOM of the main parts of the cold heading machine

Machine system	Number	Part name	Material	Quantity	Weight (kg)
Heading system	1	Machine body	Cast iron HT250	1	2133.0
	2	Sliding table	Cast iron QT500	1	158.0
	19	Static mold base	42CrMo	1	42.5
	20	Moving mold base	Cast steel ZG45	1	36.0
	21	Rocker component	Cast iron QT450	1	32.2
Transmission system	3	Crankshaft	45CrMo	1	230.4
	4	Transmission gear	Cast iron Z45	1	106.8
	5	Transmission spur gear	Cast iron Z45	1	76.1
	6	Transmission shaft	42CrMo	1	48.6
	22	Flywheel	Cast iron HT250	1	617.0
	23	Motor	Cast iron	1	340.0
Feeding system	7	Feeding connecting rod	Cast iron Z45	1	21.0
	10	Feeding rocker	Cast iron QT450	1	46.4
	11	Feeding base	Cast iron HT250	1	156.2
Shearing system	8	Shearing connecting rod	Cast iron Z45	1	11.4
	9	Shearing base	Cast iron HT250	1	151.4
Clamping system	16	Clamping table	Cast iron QT450	1	70.5
	17	Clamping base	Aluminum alloy	1	3.0
	18	Clamping shaft	42CrMo	1	75.8
Ejector system	12	Ejector rocker	Cast iron QT450	4	14.1
	13	Cam component	Cast iron QT450	1	73.4
	14	Mandrel	Tool steel SKD-11	4	5.5
	15	Ejector connecting rod	Cast iron QT450	1	28.4

300 days per year. The effective running time of the cold heading machine is 12 h per day. The operating power of the machine is 15 kW.

At the recycle and disposal stage, the indirect carbon footprints include electricity consumptions in the disassembly process, recycling of materials, and disposal of waste. The direct carbon footprints of GHGs should also be taken into account. Different from the previous four stages of the product life cycle, the recycle and disposal stages have the recycling process that can reduce carbon footprint. The reduction calculation of carbon footprint is based on the recycling rates of materials and components.

3.2 Results and analysis

The carbon footprint calculation is based on the BOM at the stages of material acquisition and manufacturing. Based on the BOM of the cold heading machine and the collected activity data and carbon emission factors, the total amount of carbon footprint of the machine during the entire product life cycle is 673,144 kg CO_2 equivalent (CO_2e) using the carbon footprint model in Section 2.2. Out of the total amount of carbon footprint, the amount of carbon footprint at the raw material acquisition stage is 12,957 kg CO_2e, the amount at the manufacturing stage is 7290 kg CO_2e, the amount at the transportation stage is 810 kg CO_2e, the amount at the usage stage is 659,805 kg CO_2e, and the amount at the recycle and disposal stages is −7718 kg CO_2e. Carbon footprints for each stage are shown in Table 3.

Among the five stages of the life cycle, the largest amount of carbon footprint is produced at the usage stage, accounting for 98.02 % of the total carbon footprint, and the smallest amount is produced at the transportation stage, accounting for 0.12 %. The reason for this ratio distribution is that the usage stage has the longest time period in the life cycle, and the machine requires a large amount of power to operate, and the use of daily maintenance and surrounding safety equipment also increases the carbon footprint.

For the transportation stage, the selections of transportation tools and locations have a great impact on carbon footprint. At the end of the life cycle, recycle of parts not only reduces the carbon footprint of products but also improves the production efficiency of the cold heading machine with the reused parts. In addition, the lightweight design of large-sized parts at the manufacturing stage can reduce the operating power of the

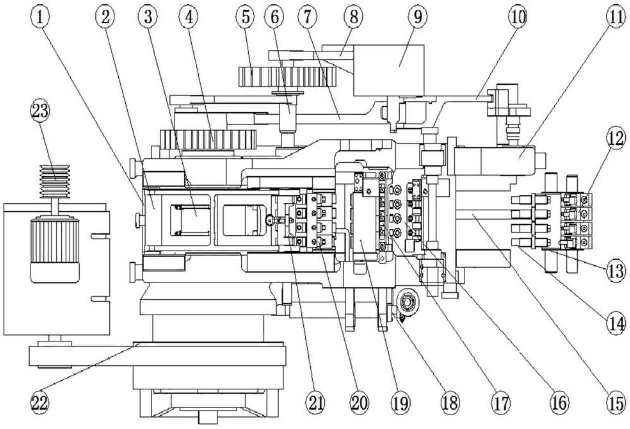


Fig. 4 The conceptual model of the cold heading machine

control system on the machine, which will reduce the total amount of carbon footprint.

3.3 Sensitivity analysis of design parameters

In the process of using the machine, the main energy consumption is to form fasteners such as the bolts and screws. Here, heading a hex bolt M6×75 in the heading system is taken as an example of sensitivity analysis. An improved method is further used to realize the sensitivity analysis of design parameters and help to reduce carbon footprint of analysis object.

At the usage stage, the energy consumption of the cold heading machine is primarily the work during the heading process of bolts. The energy is solely supplied by electrical power, which means that the energy consumption of the heading process is approximately equal to the consumption of electrical power. Therefore, the indirect carbon emission E_h caused by the energy consumption of heading system at the usage stage could be represented by the indirect carbon emission of power. The work of cold heading process is the product of the heading force and the heading distance. The heading force P could be obtained empirically by [38]

$$P = Z \cdot N \cdot \delta \left(1 + \alpha \mu \frac{D}{4H} \right) S \tag{6}$$

Table 2 Carbon emission factors of common materials and energy

Materials or energy	Emission factor
Iron and steel production	1.72 kg CO_{2e}/kg
Zinc production	3.66 kg CO_{2e}/kg
Magnesium production	2.83 kg CO_{2e}/kg
Aluminum production	1.80 kg CO_{2e}/kg
Ferroalloy production	3.60 kg CO_{2e}/kg
Lubricating oil	0.20 fraction
Diesel fuel	2.73 kg CO_{2e}/L
Electricity	0.81 kg CO_{2e}/kWh

where Z is the deformation coefficient of the heading workpiece, N is the shape coefficient of the die, δ is the tensile strength of the heading materials, α is the shape factor of cold heading section, μ is the friction coefficient, D is the head diameter of the workpiece, H is the head height of the workpiece, and S is the projection area of the contact head of tool.

The energy consumption of heading system at the usage stage is mainly the work during the process of heading the bolt and the source of the energy is completely provided by electricity. The functional relationship between indirect carbon footprint generated by the energy consumption of heading system and various design parameters is

$$E_h \approx Z \cdot N \cdot \delta \cdot \left(1 + \alpha \cdot \mu \frac{D}{4H} \right) S \cdot d \cdot C_{\mathrm{e}} \cdot \frac{T}{t} \tag{7}$$

where Z is the deformation coefficient of the heading workpiece, N is the shape coefficient of the die, δ is the tensile strength of the heading materials, α is the shape factor of cold heading section, μ is the friction coefficient, D is the head diameter of the workpiece, H is the head height of the workpiece, S is the area of the workpiece head projecting in the die contact surface, d is the heading distance, C_{e} is the electricity emission factor, t is the time of every heading, and T is the running time of cold heading machine. In these design parameters, some parameters are decided by the bolt shape and actual production needs of cold heading machine.

As a demonstration, three design parameters are chosen to illustrate the sensitivity analysis, including the tensile strength of the heading materials δ, the shape coefficient of the die N, and the friction coefficient μ. They are selected with consideration of the effectiveness of reducing the influence of the carbon footprint at other stages. The sensitivities of all the parameters in Eq. (7), except for d, C_{e}, and t, are listed as

$$\frac{\partial E_h}{\partial Z} = \delta \cdot N \cdot \left(1 + \alpha \cdot \mu \frac{D}{4H} \right) \cdot S \cdot d \cdot C_{\mathrm{e}} \cdot \frac{T}{t} \tag{8}$$

$$\frac{\partial E_h}{\partial \delta} = Z \cdot N \cdot \left(1 + \alpha \cdot \mu \frac{D}{4H} \right) \cdot S \cdot d \cdot C_{\mathrm{e}} \cdot \frac{T}{t} \tag{9}$$

Table 3 Each stage carbon footprint of the life cycle of cold heading machine

Life cycle stages	Carbon footprint (kg CO_2e)	Proportion (%)
Acquisition of raw materials stage	12,957	1.93
Manufacturing stage	7290	1.08
Transportation stage	810	0.12
Usage stage	659,805	98.02
Recycle and disposal stage	−7718	−1.15
Total	673,144	100.00

Table 4 The sensitivity of design parameters of the heading system at the usage stage

Design parameters	Rate of change of design parameter (%)	E_h (kg CO_{2e})	Proportion (‰) of reduction of carbon footprint
δ	−10	−15.5	0.02
N	−10	−5747.8	8.50
μ	−10	−9579.7	14.00
Z	−10	−7983.1	12.00
α	−10	−1437.0	2.10
D	−10	−287.4	0.43
H	+10	−479.0	0.73
S	−10	−183.1	0.27
T	−10	−328.5	0.49

$$\frac{\partial E_h}{\partial N} = Z\cdot\delta\cdot\left(1+\alpha\cdot\mu\frac{D}{4H}\right)\cdot S\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{10}$$

$$\frac{\partial E_h}{\partial \mu} = Z\cdot N\cdot\delta\cdot\alpha\cdot\frac{D}{4H}\cdot S\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{11}$$

$$\frac{\partial E_h}{\partial \alpha} = Z\cdot\delta\cdot N\cdot D\cdot\frac{\mu}{4H}\cdot S\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{12}$$

$$\frac{\partial E_h}{\partial D} = Z\cdot\delta\cdot N\cdot\alpha\cdot\frac{\mu}{4H}\cdot S\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{13}$$

$$\frac{\partial E_h}{\partial H} = -Z\cdot N\cdot\delta\cdot\alpha\cdot\mu\cdot\frac{D}{4H^2}\cdot S\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{14}$$

$$\frac{\partial E_h}{\partial S} = Z\cdot\delta\cdot N\cdot\left(1+\alpha\cdot\mu\frac{D}{4H}\right)\cdot d\cdot C_{\mathrm{e}}\cdot\frac{T}{t} \tag{15}$$

$$\frac{\partial E_h}{\partial T} = Z\cdot\delta\cdot N\cdot\left(1+\alpha\cdot\mu\frac{D}{4H}\right)\cdot S\cdot d\cdot\frac{C_{\mathrm{e}}}{t} \tag{16}$$

The sensitivities of indirect carbon footprint E_h with respect to the design parameters are calculated by reducing 10 % of the respective values while keeping other parameters unchanged. The sensitivities are listed in Table 4. It is shown that the friction coefficient μ has the largest sensitivity. A 10 % reduction can lead to a reduction of carbon footprint by 9579.7 kg CO_2e.

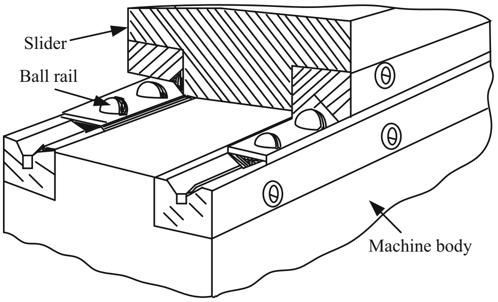


Fig. 5 The sliding table of cold heading machine with ball rail

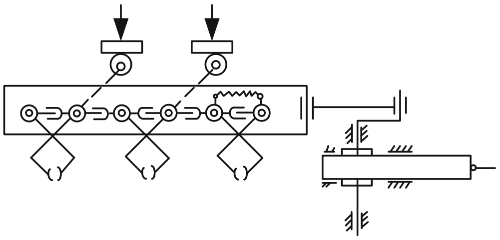


Fig. 6 Sketch of the novel mechanism

The improvement of the friction coefficient will reduce the carbon footprint at the usage stage. Reducing the speed of the machine and improving the forming settings could achieve the goal of reducing the friction coefficient. However, it is also possible that the change may not meet the production condition and also increase production costs. The feasible solutions of reducing the friction coefficient between the die and the heading workpiece include the following four ways:

1. Solution 1. Using lubricant to maintain the die regularly. For example, graphite lubricant is used to reduce the friction resistance, slow down wear, improve the performance of the machine, and reduce energy consumption. The carbon footprint of solution 1 is calculated as 666, 412 kg CO_2e.
2. Solution 2. Reducing the surface roughness of the die during the manufacturing process. The key procedure is to finish, polish, or smooth the die surface that is in contact with the heading workpiece to reduce the roughness. The carbon footprint of solution 2 is calculated as 652, 949 kg CO_2e.
3. Solution 3. Instead of linear rail, the sliding table of cold heading machine used ball rail to reducing the coefficient of friction, as shown in Fig. 5. The carbon footprint of solution 3 is calculated as 639,486 kg CO_2e.
4. Solution 4. The use of novel mechanism. The retooling system in the automatic multi-station cold heading machine consists of a combination of the clamp mechanism and transfer mechanism. In this case, a novel mechanism

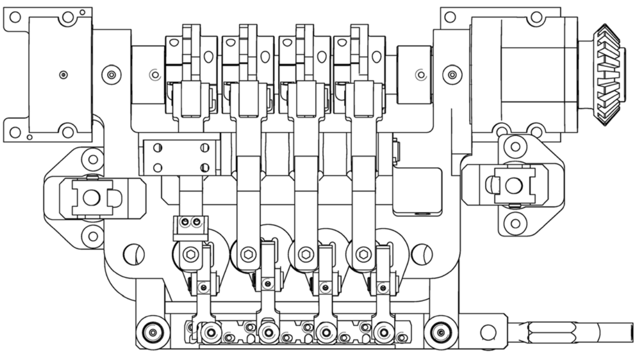


Fig. 7 Structure of the novel solution

of clamping and transferring the semifinished product simultaneously is developed as shown in Fig. 6. With this concept, a structure is developed as shown in Fig. 7. The carbon footprint of solution 4 is calculated as 617,946 kg CO_2e.

The carbon footprint of the original solution is 673,144 kg CO_2e, which is taken as a benchmark. The percentages of relative reduction from solution 1 to solution 4 are 1.0, 3.0, 5.0, and 8.2 %, respectively. In these four solutions, the lowest carbon footprint is from solution 4 with the value of 617, 946 kg CO_2e. Solution 1 of using lubricants to maintain the die regularly is the simplest one, but the main reduction of carbon footprint lies in the reduction of energy consumption through the reduction of friction resistance. Thus, the reduction result of solution 1 is limited. Solution 2 of improving the surface roughness of the die during the manufacturing process is a more effective approach than solution 1, because the reduction of the surface roughness could not only reduce the friction resistance but also improve the efficiency. Solution 3 of using ball rail to reduce the coefficient of friction is a more efficient way to reduce carbon footprint, as the rail carries several components, including slipway, transmission gear and transmission spur gear, flywheel, etc. Solution 4 allows for clamping and transferring the semifinished product simultaneously, which can significantly reduce the energy consumption.

4 Conclusions

In this paper, a general carbon footprint model based on product life cycle assessment is presented. Product carbon footprint was divided into five stages covering the entire product life cycle. A cold heading machine is used as an example to demonstrate the carbon footprint calculation model and low-carbon conceptual design process. The results of carbon footprint at each stage of the cold heading machine show that the carbon footprint could be calculated efficiently. Among the five stages of the cold heading machine, the largest amount of carbon footprint was produced at the usage stage, and the smallest amount was produced during the transportation. Sensitivity analysis of the carbon footprint model can help identify the influential factors and devise low-carbon conceptual design strategies.

Several extensions are needed in the future work. As GHGs are not the only factors that have impacts on the environment, further development of new systematic methodologies for sustainable design is needed to predict product environmental footprints. Both product- and activity-oriented metrics are needed to quantify the environmental impacts. For instance, product environmental footprint (PEF) was recently proposed by the European Commission, which is a multi-criteria measure of the environmental performance of a product throughout its life cycle.

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