Carbon Footprint Assessment during the Manufacturing Phase of Mechanical Products Oriented towards Schematic Design Phase

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Abstract-To reduce the carbon footprint during the manufacturing phase of mechanical products and provide a more accurate method for carbon footprint accounting, this paper proposes a carbon footprint assessment method for the manufacturing process of mechanical products based on design features. This method is mainly aimed at the schematic design phase, utilizing feature modeling theory to define product system features and entity features, thereby elaborating on the constraint relationships among product components in depth. On this basis, a product design scheme expression model based on design features is formed, and an in-depth analysis of the intrinsic connection between the manufacturing process carbon footprint and product design features is conducted, further constructing a carbon footprint quantification model. To test the practicality of the proposed method, a detailed calculation and analysis of the carbon footprint during the manufacturing phase of laminated composite circular saw blades is performed.

Keywords-scheme design; design feature; carbon footprint; saw blade

1. Introduction

With increasing global attention to climate change, the manufacturing industry, as one of the main sources of carbon emissions, urgently needs to adopt measures for low-carbon development[1-3]. In China, the issue of carbon emissions during the manufacturing phase of mechanical products is particularly severe[4-5]. This issue is not only related to the technical level of enterprises and the management of the manufacturing process but is also closely related to the product design scheme. The development process of mechanical products can be divided into four phases: scheme design, technical design, process design, and prototype testing[6-7]. Preliminary modeling and assessment of the carbon footprint of the product manufacturing process during the scheme design phase can not only provide a basis and guidance for optimizing the design scheme but can also find more opportunities for carbon emission reduction from the early stages of design[8-10]. However, current research still lacks comprehensive modeling and analysis of the association between overall product design information and the carbon footprint during the manufacturing phase. This paper introduces feature modeling theory to express mechanical product scheme design information, analyzes the relationship between design features and carbon emission activities during the product

IDEE 2023, November 24-26, Zhengzhou, People's Republic of China

DOI 10.4108/eai.24-11-2023.2343355

manufacturing phase, and constructs a carbon footprint quantification model based on design features. Using a certain saw blade as an example, the proposed model and method are validated. This model can predict and evaluate the carbon footprint of the manufacturing phase during the scheme design phase, providing decision support and guidance for the low-carbon transition and sustainable development of the manufacturing industry.

2. The Product Scheme Design Information Expression Model Based on Design Features

To ensure that the product scheme expression model can both encompass design points to the greatest extent and cover the entire manufacturing phase, feature modeling needs to screen, extract, and aggregate information from both the overall system and part entity levels. This article defines the design features of the product as system feature and individual feature. The product scheme design information modeling based on design features is shown in Figure 1.

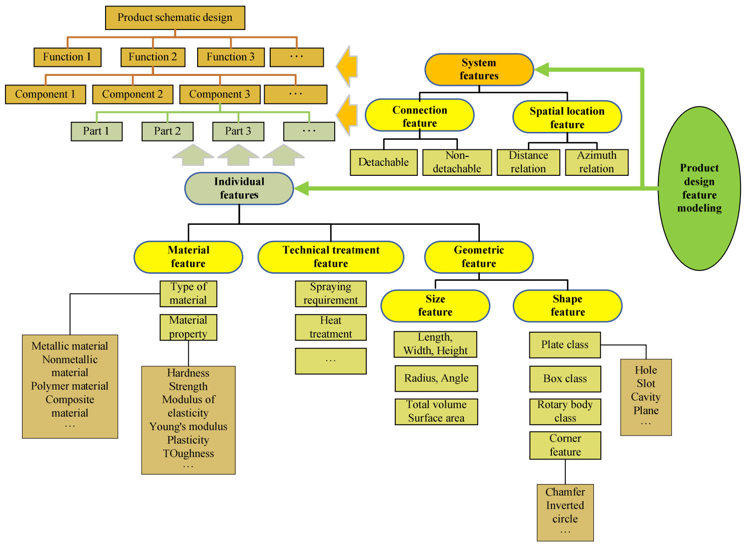

Fig.1 Information Modelling for Product Scheme Design Based on Design Features

System features refer to the expression of the connection methods and spatial constraint relationships among components from the overall product perspective, including connection features and spatial position features. Connection features describe the connection forms between parts, which are divided into detachable and non-detachable. Spatial position features describe the spatial geometric relationships between components, including positional relationships, distance relationships, and topological relationships.

Individual features refer to the physical properties of parts, including geometric features, technological processing features, and material features. Geometric features include shape features and size features. Shape features are composed of a set of geometric elements used to describe the physical shape of an object and should be achievable through existing manufacturing technologies. Size features cover all the geometric elements of machine tool parts, such as length, width, height, diameter, angle, etc., and also include the overall size, total volume, and total surface area of the machine tool parts. Technological processing features describe the technical requirements for heat treatment, spraying, surface quality, and precision after the machining of machine tool parts. Material features include the performance and types of materials.

3. Carbon Footprint Assessment Model in the Manufacturing Phase Based on Design Features

3.1 The Association between Design Features and Carbon Footprint in the Manufacturing Phase

The manufacturing process involves transforming raw materials into the final product, which primarily encompasses the production of raw materials, blank manufacturing, part machining, and component assembly. This paper categorizes various carbon emission scenarios during the manufacturing phase into five "feature-associated activities" oriented towards design features, thereby establishing a linkage between the design information model and carbon emission behaviors. The association between product design features and the carbon footprint in the manufacturing phase is illustrated in Figure 2.

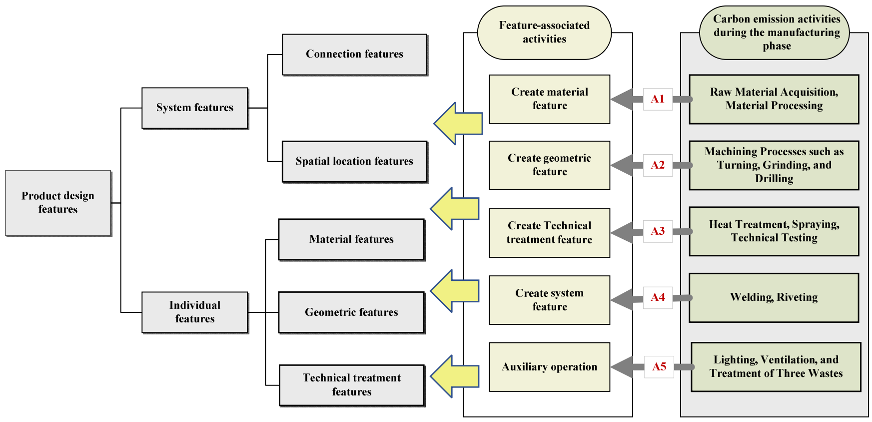

Fig.2 Association between Design Features and Carbon Emissions during the Manufacturing Phase

3.2 Carbon Footprint Quantification Method Based on Design Features

Using the "feature-associated activities" in Figure 2 as the basic analytical unit and the "carbon emission intensity coefficient of feature-associated activities" and the "volume of feature-associated activities" as coefficients, we propose a modeling approach for assessing the carbon footprint of mechanical products during the manufacturing phase.

$$Carbon_{total} = \sum_{i=1}^{5} Carbon_{Ai} = \sum_{i=1}^{5} factor_{Ai} \times Amount_{Ai} \quad (1)$$

In the equation, $Carbon_{total}$ represents the total carbon footprint during the manufacturing phase, $Carbon_{Ai}$ denotes the carbon footprint induced by the feature-associated activity Ai, $factor_{Ai}$ signifies the carbon emission intensity coefficient of the feature-associated activity Ai, and

$Amount_{Ai}$ represents the volume of the feature-associated activity Ai.

Utilizing the product design feature model, a detailed breakdown of the summation terms in the carbon footprint assessment model can be conducted, enabling the calculation of the carbon footprint assessment for the manufacturing process. The following provides a detailed explanation.

a) Carbon emissions from creating material feature (A1)

Assuming there are n types of materials used in the product, the carbon emissions generated by creating material features can be expressed as:

$$Carbon_{1\text{-}mater} = \sum_{i=1}^{n} \left(mater_i \times G_{mater\text{-}i} \right) \tag{2}$$

In this equation, $mater_i$ represents the carbon emissions per unit mass of the i-th type of material during extraction and production. $G_{mater\text{-}i}$ is the mass of the product that uses the i-th type of material.

b) Carbon emissions from creating geometric feature (A2)

The carbon emissions resulting from the creation of geometric feature are calculated in Eq. (3).

$$Carbon_{1\text{-}geometric} = \sum_{i=1}^{n} \sum_{j=1}^{m} geometric_{ij} \times T_{geometric\text{-}ij} \tag{3}$$

Where $geometric_{ij}$ denotes the carbon emissions per unit time generated when the jth manufacturing process is used to create the ith geometric feature of a part of a product, $T_{geometric\text{-}ij}$ denotes the time consumed to create the ith geometric feature of a part using the jth manufacturing process.

c) Carbon emissions from creating technical treatment feature (A3)

The carbon emissions from creating technical treatment feature are calculated in Eq. (4).

$$Carbon_{1\text{-}tech} = \sum_{i=1}^{n} \left(tech_i \times T_{tech\text{-}i} \right) \tag{4}$$

Where $tech_i$ indicates the carbon emissions per unit time generated when the part is treated with the ith treatment technique (e.g. quenching) to achieve a certain technical requirement (e.g. hardness requirement). Where $T_{tech\text{-}i}$ indicates the treatment time during the manufacturing process of the part with the ith treatment technique (e.g. quenching time). It can be calculated by Eq. (5).

$$T_{tech\text{-}i} = V_{tech\text{-}i} / R_{tech\text{-}i} \tag{5}$$

Where $V_{tech\text{-}i}$ is the total volume to be treated with the ith technique, $R_{tech\text{-}i}$ indicates the treatment rate of the ith technique.

d) Carbon emissions from creating system treatment feature (A4)

The carbon emissions resulting from the creation of system feature are calculated in Eq. (6).

$$Carbon_{1\text{-}system} = \sum_{i=1}^{n} \sum_{j=1}^{m} connect_{ij} \times T_{connect\text{-}ij} \tag{6}$$

Where $connect_{ij}$ represents the carbon emissions per unit time when the jth connection method is used to create the ith spatial position relationship between parts under fixed assembly conditions. $T_{connect-ij}$ represents the time required to form the ith spatial position relationship between two parts using the jth connection method.

e) Carbon footprint generated by auxiliary activities(A5)

Various auxiliary activities primarily consume electrical energy.

$$A6_{carbon} = \sum_{1}^{i}(auxiliary_i \times Time_{auxiliary-i}) \tag{7}$$

In the equation, $auxiliary_i$ represents the carbon emissions produced per unit of time when using the ith auxiliary equipment. $Time_{auxiliary-i}$ represents the time spent using the ith auxiliary equipment.

4. Application of model

In this section, based on the design feature establishment method outlined in Section 2, a modeling of the design information for the sandwich composite circular saw blade substrate is conducted. The structural schematic diagram for the design of the sandwich composite circular saw blade substrate is illustrated in Figure 3.

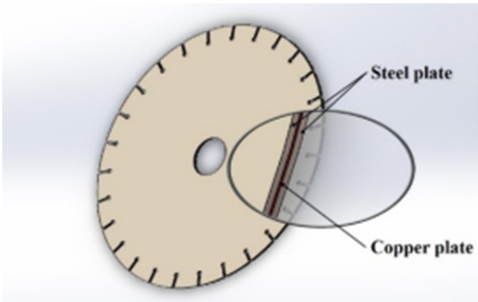

Fig.3 Model for the Design of Sandwich Composite Circular Saw Blade Substrate

The design features of the sandwich composite circular saw blade substrate are as shown in Table 1.

Table 1 Design Features of the Sandwich Composite Circular Saw Blade Substrate

Structure	Material feature	Geometric feature		Technical treatment feature	System feature
		Shape feature	Size feature		
Steel plate	Material: 30CrMo Weight: 0.739kg Recyclable	Overall shape: Cylinder $9.42\times10^4 mm^3$ Local shape: Face ×2 Φ350mm Hole Φ50×H1mm Groove×27 L18×W3×H1mm		Annealing	The upper and lower layers are made of steel plates, while the middle layer is made of copper plate. The steel plates are spot-welded to the copper plate with a total of 68 weld points, which are non-removable.
Copper plate	Material: Brass Weight: 0.084kg Recyclable	Overall shape: Cylinder $9.42\times10^3 mm^3$ Local shape: Face ×2 Φ350mm Hole Φ50×H1mm Groove×27 L18×W3×H1mm		Annealing	

According to equations (2) to (7), the carbon footprint calculation results for the manufacturing stage of the sandwich composite circular saw blade are shown in Table 2.

Table 2 Carbon footprint of the Sandwich Composite Circular Saw Blade Substrate

Features-associated Activities	A1	A2	A3	A4	A5	Total
Carbon footprint/kgCO_{2e}	1.50	5.23	1.41	0.02	0	8.16

5. Conclusion

This paper proposes a design-oriented mechanical product manufacturing phase carbon footprint correlation model and quantification method based on design features in the schematic design stage. This method assists designers in assessing the carbon footprint of the manufacturing phase during the schematic design stage, promoting design optimization. Using a sandwich composite saw blade as a case study, the effectiveness of this model and method was validated. The results show that the carbon footprint induced by geometric features (A2) has the highest proportion in the manufacturing phase carbon footprint. This helps designers identify high carbon footprint processes that need optimization in the design, which is crucial for improvement. However, the model still has limitations, such as not fully considering uncertainties in the manufacturing phase and relying too much on the subjective experience of designers, which may affect the accuracy of the assessment results. With the rapid development of industrial informatization and intelligence, theoretical methods for achieving green manufacturing will need to be integrated into computer-aided design (CAD) software platforms. Therefore, future research should focus on developing an efficient and feasible computer-aided green manufacturing integration platform to achieve seamless information transfer with existing CAD software, thereby improving the efficiency and accuracy of green manufacturing.

Acknowledgments: The research is supported by Entrusted project of Hein (Shandong) Superhard Tools MFG. Co., Ltd: “Development and process research of green and efficient heat treatment production line for saw blade substrate (RH210000206)” and National Natural Science Foundation of China (52105554), and Natural Science Foundation of Shandong Province (ZR2020QE016).

References

[1] Wang, S., Wang, X., Tang, Y., 2019. Drivers of carbon emission transfer in China—An analysis of international trade from 2004 to 2011. Sci of The Total Environment. 709:135924.

[2] IEA (International Energy Agency), 2020. Energy Technology Perspectives 2020: Scenarios and Strategies to 2050.

[3] Gui, F., Ren, S., Zhao, Y., Zhou, J., Xie, Z., Xu, C., 2019. Activity-based allocation and optimization for carbon footprint and cost in product lifecycle. Journal of Cleaner Production. 236(C).

[4] He, B., Pan, Q., Deng, Z., 2018. Product carbon footprint for product life cycle under uncertainty. Journal of Cleaner Production. 187(JUN.20):459-472.

[5] Andrews-Speed, P., 2009. China's ongoing energy benefit drive: Origins, progress and prospects. Energy Policy. 37(4):1331-1344.

[6] Ishak, N.M., Mansor, M.R., Ghani, A., 2021. Conceptual design development and selection of green product.

[7] Jun, M., Geo, K., 2016. A sustainable modular product design approach with key components and uncertain end-of-life strategy consideration. International Journal of Advanced Manufacturing Technology 2016,85(1-4): 741-763.

[8] Wang, L., Shen, W., Xie, H., 2002. Collaborative conceptual design - state of the art and future trends. CAD Comput Aided Des. 34:981–996.

[9] Gaha, R., Benamara, A., Yannou, B., 2013. Eco-designing with CAD features: Analysis and proposals. Advances in Mechanical Engineering.

[10] Wen, X., Cao, H., Hon, B., Chen, E., Li, H., 2021. Energy value mapping: A novel lean method to integrate energy benefit into production management. Energy.