A customization-oriented carbon footprint service for mechanical products

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Abstract. As the growing concerns of global warming, carbon footprint of a product becomes an important designing criterion. In recent years, the issue of product carbon emission has been extensively studied and most research focus on the computing method, life cycle assessment and optimized design of single category product. However, a lack of versatility in these existing research programs make them difficult to be applied in other product. Furthermore, in many cases, target customers are not concerned about carbon emissions throughout the life cycle of the product and full-cycle calculations of carbon emissions make no sense. To fill this gap, a service mode to provide quantification of carbon footprint for mechanical products is presented in this work. The multi-scale and full-direction system, which is based on process chain employing multiple scale task model is proposed to meet the different carbon footprint requirements, and then encapsulate it as a service to the user.

1. Introduction

With the issue of atmospheric warming becomes increasingly intensified, concerns about climate change rose sharply[1]. The climatic change brings threaten to the human survival and development. Sustainability, especially environmental sustainability, has emerged as a crucial issue amongst states, policymakers, researchers, and the public[2]. Manufacturing industry plays an important role all over the world and it is the key industry in every modern market economy[3]. However, converting materials into industrial parts causes a large amount of energy consumption and carbon emissions[4]. Several reports reveals that, products are responsible for about 84 % of energy-related greenhouse gases (GHGs) emissions and 90 % of the energy consumption in the industrial sector[5]. Carbon emission has become an important topic in the industry, especially in the manufacturing industry. It is critical to quantify product carbon footprints so that appropriate reduction actions can be taken[6].

Over the past two decades, many scholars and researchers have devoted to the studies on the calculation and optimization of carbon footprint, the carbon footprint of products has become an important design criterion[7]. As a result, many companies are focusing on a servitization pattern towards calculating carbon emission[8]. Those companies calculate the carbon footprint of the product during the life cycle, and the results are encapsulated into services available to the users. The service
can be recognized as a new kind of environment friendly service, which can effectively reduce greenhouse gas and provide strong support for the realization of green manufacturing[9]. However, the service of calculating carbon emission provided by many companies are still in the primary level and unable to support the diverse requirements of users[10].

In modern industry, the production process is regarded as a chain of processes. Normally, a process chain is a set of independent production processes made up of various processing equipments, raw material and operators[11]. However, the existing services of carbon emission rarely take the process chain as the unit of calculation, which leads to the problem that the accuracy of the calculation results is often hard to control, and cannot provide users with diversified services according to their requirements. Sometimes, the target customers are not focusing on the carbon emission throughout the life cycle of the product. Another remarkable problem is that the optimization of manufacturing process on low-carbon is often considered inadequate[12]. Currently, carbon services are limited to the calculation, but the ultimate goal is reducing carbon emission not calculating. It is worth to investigate how to combine optimization with services.

To solve the problem mentioned above, this paper proposes a closed-loop scheme of carbon footprint service based on the process chain. According to the user requirements, it would provide multidimensional dynamic and customized carbon footprint service.

2. Methodology

The general framework of the proposed method is depicted in figure 1. There are three keys related to the carbon service, namely, user requirements analysis, the establishment of task set, and carbon footprint service results. User submit information related with mechanical product to the system, and the information includes designing information, manufacturing information and the requirements of carbon service. The related production process chain is added to the system according to the requirement analysis, and the execution task set is automatically generated by semantic matching. The results of calculation and optimization are combined as decision schemes which are finally delivered to the user of the carbon service.

![Figure 1. General methodological framework.](image1)

![Figure 2. The ontology model of carbon footprint variables.](image2)

2.1. Requirements analysis

First, users submit the product related information to the system to request the corresponding carbon footprint service, and the information submitted includes the designing information, the manufacturing information and the requirements for carbon service. The processing of the product is the process that makes rough pieces with certain geometric shape to meet certain mechanical properties[13]. It is made up of a series of independent machining steps. Each
step has its unique properties, so considering resource consumption and carbon emission from the viewpoint of process are more reliable than traditional methods[14]. The process-cycle is a dispersed manufacturing system with multiple-input multi-output. The status of the workpiece, processing requirements, equipment and personnel will all influence the output of the carbon emissions. Therefore, the carbon emission of the product is a dynamic process based on the process chain.

In this paper, the process chain is used as the reference template to integrate the related information of the product. It also divides the factors that influence carbon footprint into three kinds of variables: state variables (Xj), environmental variables (Ej) and requirement variables (Rj). Then, the related information are reorganized by ontology model as shown in figure 2. Ontology is an explicit formal specification of shared conceptual model[15]. It greatly improve the efficiency of the search, accumulation, and sharing of information. Finally, user requirement is transformed into a set of ontology model based on process chain, which would provide support for generation of task sets.

In this paper, the variables that affect carbon footprint are classified into three categories. The state variable describes the related variables in the process of changing the current state of the workpiece into the target state. It includes the serial number of the step (SequenceNum), the type of the step (NodeType), the size of the operation (OperationSize), etc. The environment variable describes the external variables in the process, including device (Device), humanlabor (HumanLabor), material (Material), etc. Requirement variables vary dynamically according to user requirements, which consisted of accuracy, quality and even alternative working steps can be selected. The ontology class diagram shown in Figure 2 is incomplete, but based on the characteristics of ontology, the model does not need too much modification can support the evolution of ontology. It can be quickly extended according to real-time requirements.

2.2. The task model of user requirement

The demands of carbon services are diverse and the target customer sometimes is not focusing on carbon emissions throughout the life cycle of the product. For example, designers are concerned about the carbon emissions of product features, manufacturers pay more attention to the carbon emissions generated during the manufacturing process, while different technologists care more about different machining steps. The demand for carbon footprint service is not the same even in the same company at different department. Plainly, the life cycle method could no longer satisfy the diversified requirements of users.

A task set model is proposed in this paper, which contains a series of independent tasks which are corresponding to the machining steps in the ontology model. As the basic unit of manufacturing processing, it can reflect the carbon emission at each stage. And it also can be further combined and subdivided.

The description of the task node of mechanical products or components is given by equation (1).

\[ et^i = \{PF^i, A\}, \quad A = \{Query, Calculation, Visible, Decision, \ldots\} \]  

(1)

Where et^i is the ith task in the whole task set. PF^i is corresponding to geometric structure, material, and other information of the working step, which is obtained by matching with the process chain model introduced in the section 2.1. A is the target of the service request, which includes query, calculation, data visualization, service decision, etc.

All carbon service tasks are arranged in order, the set of service tasks can be formed as equation (2).

\[ ET = \{et^1, et^2, et^3, \ldots, et^n\} \]  

(2)

Where n represents the total number of tasks containing user requirements.

When users input their carbon service requirements, the system automatically assigns an empty set of service tasks. By matching the corresponding process chain resources in the database, the task set obtains the carbon knowledge which is used for the carbon footprint calculation of the process. The length of service task set is not fixed, it can be adjusted automatically according to the user requirements, and the corresponding link is automatically locked according to the matching algorithm.
2.3. The calculation model of carbon footprint

Carbon emissions reflect the impact the manufacturing process of products on the natural environment. With the increasing problem of global warming, low carbon manufacturing has become the common goal of global manufacturing. It is one of the main purposes of this paper to study the carbon footprint of the product through the process chain and refine the carbon footprint of every node in the manufacturing process. In this paper, the process chain is matched with the task model, and the carbon emissions of single node is calculated by task unit. In the calculation process, three main aspects are considered, there are device, materials, transportation, etc. In terms of device, this paper mainly considers the power consumption, machine wear, the use of cooling fluid and lubricating fluid, etc. in the manufacturing process. The material mainly refers to the carbon emissions from the part of the waste that is not converted into the product during the process. The transportation of raw materials is an essential link between working steps. Many literatures have pointed out that the carbon footprint of transportation process is an important component of product carbon footprint, so this is a problem that cannot be ignored. Other factors include manpower, substandard products, and other uncertainties. In general, these parts account for a relatively small proportion. So, these parts are considered by making a reasonable small scale amplification of the total carbon footprint in the foregoing aspects.

The carbon emission of single task $C_{eti}$ is constructed as equation (3):

$$C_{eti} = \left\{ \sum_{r=1}^{n} D_{ir} \cdot \left( t_{load}^{ir} F_{load}^{ir} dt + t_{no-load}^{ir} P_{no-load}^{ir} dt \right) \cdot CE_{f}^{ir} \right\} + \sum_{r=1}^{n} T_{ir} \cdot t_{transport}^{ir} \cdot CE_{f}^{tool} + \sum_{r=1}^{n} F_{ir} \cdot m_{fluid}^{ir} \cdot CE_{f}^{fluid} + \sum_{r=1}^{n} M_{ir} \cdot m_{material}^{ir} \cdot CE_{f}^{material} + \sum_{r=1}^{n} T_{ir} \cdot t_{ir}^{transport} \cdot CE_{f}^{transport} \cdot \mu_{i}$$

Where $D_{ir}$, $F_{ir}$, $M_{ir}$ and $T_{ir}$ are the types of device, fluid, material and transport involved in ith task, respectively. $t_{load}^{ir}$, $t_{no-load}^{ir}$ and $P_{load}^{ir}$ are the time and power when device is under load or no load running. $t_{transport}^{ir}$ is the total time of the device working in this task. $T_{ir}$ is defined as the total service time of this device. $m_{fluid}^{ir}$ is the mass of fluid consumed in ith task, $m_{material}^{ir}$ is the mass of the material that fails to be converted into the product in the process of processing. $t_{transport}^{ir}$ is the time that spent in material transportation. If it is the transportation between two nodes, half of the process is calculated. $CE_{f}^{x}$ is the carbon emission factor of class x. Finally, $\mu_{i}$ is the factor that adjusts the overall carbon emissions according to other factors.

2.4. The optimization model of carbon footprint

Carbon footprint optimization is the ultimate goal of this research. At present, the related research is mainly concentrated in three aspects: equipment level, product level, manufacturing system level. The optimization results mainly include simplification of manufacturing process and resource conversion. But these methods are lack of guiding significance in real life, and cannot be effectively realized in daily production. This paper proposes a model similar to the RFM model in customer relationship management, which evaluates the carbon footprint of each manufacturing node, and realizes the classification of carbon footprint. Low carbon manufacturing can be achieved by adopting targeted methods for different types of nodes.

Similar to the RFM model, three key parameters are proposed for each node in this paper: carbon emissions, values, and interchangeability. The carbon emissions of nodes have been discussed in detail in section 2.3. Node value refers to the contribution of the node to the whole product value in the manufacturing process. Due to the limited space, the specific methods are not repeated here. Interested readers are encouraged to read Song et al[8]. In his paper, the concept of node value is described in detail. Node interchangeability refers to whether the process of the node can be replaced by other process, and the feasibility of the implementation is also considered. Then, the scores of three parameters are obtained through expert evaluating method and further divided into high or low parts. Finally, the types of nodes are divided into 8 categories and table 1 shows several typical categories. Different measures can be taken for different types of carbon emissions to achieve green production.
3. Conclusion
There are many factors affecting the carbon emission in the process of production, and the diversity of user needs also makes the traditional life cycle based evaluation method no longer feasible. In order to meet the demands of different users for carbon emissions at different stages of production, a multi scale task model of carbon footprint based on process chain is proposed in this paper and encapsulated as service for the user. This fine-grained carbon footprint assessment method would help users have a deeper cognition of carbon emissions in the production process, and also makes the proposed process optimization plan more practical.

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Table 1. Several typical categories.

| Node type                             | Carbon emission | Values | Interchangeability | Scene corresponding to machining process                                                                 |
|---------------------------------------|-----------------|--------|--------------------|---------------------------------------------------------------------------------------------------------|
| High value replacement node           | ↓               | ↑      | ↑                  | The node can be replaced by other low carbon process.                                                   |
| High value maintenance node           | ↑               | ↑      | ↓                  | The node is low carbon and high value, but the interchangeability is not high, and it is an important maintenance node. |
| Removable node                        | ↓               | ↓      | ↓                  | The three parameter are low and this node can be removed.                                              |
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