Diagnosis and application of carbon footprint for machining workshop on energy saving and emission reduction

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Received 26 October 2014, www.cmnt.lv

Abstract

This paper takes carbon footprint of the machining workshop as the research object, and carbon footprint connotations of energy, material, and environment were defined, and then standard carbon emission formula of workstation was made with the thought of industrial engineering and the practical production requirement of workshop. We took standard carbon emission as comparison object and constructed uncertain measure model of carbon emission in workshop to describe the control level of workshop carbon footprints quantitatively under uncertainty. A diagnosis method of the station carbon footprints was proposed. The application of this method in a machining workshop demonstrated its effectiveness and feasibility. This diagnosis method on energy saving and emission reduction can provide instruction for optimal control and management of workshop carbon footprint and provide the solution for low carbon production mode. It is an innovative application of industry engineering basic theory in carbon footprint control and management under uncertainty, so it can provide theory and technology support for energy saving and emission reduction, cost saving and production safety.

Keywords: machining workshop, carbon footprint, optimization decision, energy saving and emission reduction

1 Introduction

With the global industrialization process accelerating, resource crisis and greenhouse effect have become a difficulty for governments, and controlling the emission of greenhouse gases has attracted much attention all over the world. As the biggest emission of artificial greenhouse gases, industrial department is drawing more and more attention. A lot of energy and raw materials are consumed in the industrial production process, which is the main source of artificial greenhouse gas emission. According to the IPCC statistics, global industry has contributed more than 66% of greenhouse gas emission [1]. Reduction of carbon emission in the industry field is the key to the control of climate change. Production mechanical workshop is the main body of the carbon emissions in the industrial field. So carbon footprint optimal control of production workshop is the primary object of energy saving and emission reduction in industry.

Control of the carbon footprints in the production workshop is one of the main measures to save energy and reduce emission. On the other hand, it can also prevent accidents to ensure safe production of enterprises. Scholars have researched product carbon footprint in the production process. For example, on the aspect of product design, BAO Hong and LIU Guangfu proposed the multi-hierarchy carbon footprint analysis method to support product low-carbon design. And Song J S and Lee K M proposed a low-carbon product design system based on BOM using the embedded GHG emission's data of the parts [3]. On the hand of product life cycle, Lauren analysed the relationship between carbon footprint and toxicity of human body and other environmental impact indicators, and discussed the possibility of the carbon footprints as an overall indicator of the environmental performance [4]. According to the analysis of product structure and life cycle characteristics of machine tools, a method for assessing the carbon emissions of machine tools life cycle was introduced by CAO based on the principles of Life Cycle Assessment (LCA) [5]. Yin analysed the dynamic characteristics of carbon flow in mechanical manufacturing system and proposed a dynamic model based on extended first-order hybrid Petri nets [6]. Sun analysed carbon emission links in manufacturing process for complex equipment, and proposed a method to describe the carbon emissions to support low-carbon design of complex equipment [7]. In the aspect of production process, Burnham [8], Cagiaoa [9], Zhai Pei and Williams [10] studied the carbon footprint of coal and oil industry, cement industry and polycrystalline silicon photovoltaic power generation system. Haapala studied the prediction of manufacturing waste and energy for sustainable product development via WE-Fab software [11]. Li studied the NC turning parameters optimization problem for high efficiency and low carbon to realize the low carbon of the NC machining [12], and so on.

Existing research mainly focus on carbon footprint evaluation in product life cycle and carbon footprint model of product process, while the diagnosis and application of carbon footprint for machining workshop under uncertain is very few [13-16].

Based on the above research, this paper takes diagnosis and application of carbon footprint for machining workshop as the research target, and the carbon footprint connotations of energy, material, and environment are defined. Then it

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makes the standard carbon flow of workshop, and constructs uncertain measure model of carbon flow in the workshop. A control and diagnosis method of carbon footprint in machining workshop is also proposed, which provides decision support for energy saving and emission reduction of the enterprise production process.

2 The carbon emission model of workshop

2.1 CARBON FOOTPRINT CONNOTATION OF MACHINING WORKSHOP

In this paper, machining workshop refers to the production workshop using lathe machine, milling machine, drilling machine, grinding machine, punching machine, broaching machine and other special equipment that makes parts to change dimension or the performance of the work pieces.

The material consumption and energy consumption are the main source of carbon emissions of the machining workshop. Material consumption includes the consumption of raw materials and auxiliary materials in the process. The consumption of raw materials mainly depends on its design and properties, and has nothing to do with the process. So carbon emissions of auxiliary materials (such as cutting oil) consumption in the process were mainly considered. Energy consumption includes the consumption of electric energy and others (such as coal, natural gas, gasoline, compressed gas), and electric energy was given priority. Carbon emissions in the machining workshop mainly include direct or indirect carbon emissions of energy and materials, such as equipment energy consumption, raw material's consumption, auxiliary materials consumption and other energy and materials consumption for supporting production.

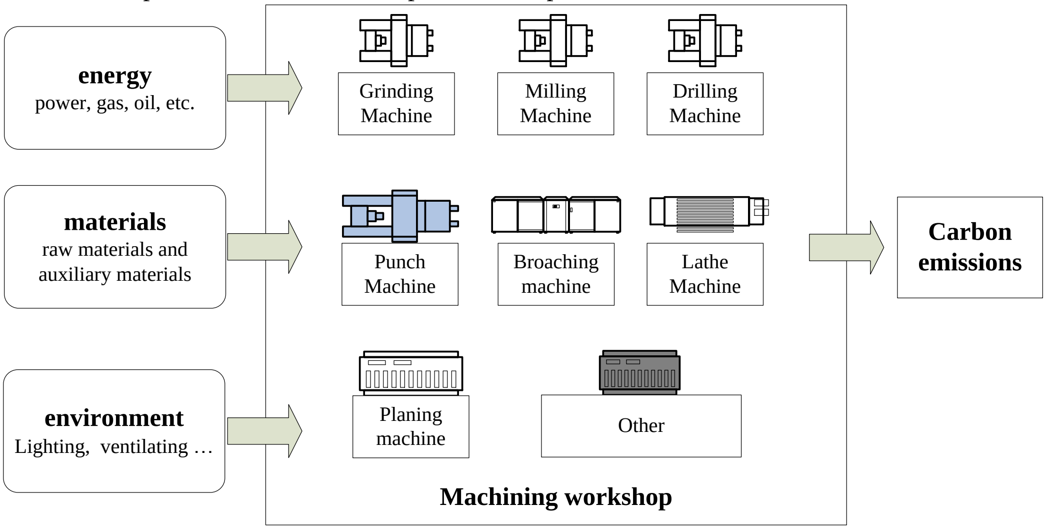

FIGURE 1 Carbon footprint schematic diagram of machining workshop

The first difficulty of this paper is how to define various carbon emission factors, and measure its value. The solution is that carbon footprints emission factors of the workshop are divided into energy, materials, environment and others (mainly waste and its disposal) based on the carbon footprint characteristics of machining workshop. Energy is calculated according to power consumption of various machines, measuring instruments, and forklift equipment, etc.

Material was calculated input and output of the workshop station as a unit. Environment is mainly power consumption of ventilation, lighting and temperature control. Others are mainly the waste and its disposal costs. Carbon emission of every factor in the workshop was calculated referring to the international general carbon emission calculation factor (as shown in Table 1).

TABLE 1 part of carbon emission calculation factor

names	Emission factor of CO2
Diesel oil	2.778Kg CO2/L
petrol	2.361 Kg CO2/L
power	0.882 Kg CO2/Kw•h
steel	1.991 Kg CO2/kg
Cu	6.830 Kg CO2/kg
Al	7.089 Kg CO2/kg
aluminum alloy	Kg CO2/kg

2.2 STANDARD CARBON EMISSION OF WORKSTATION

In order to accurately describe carbon footprint of machining workshop, as well as locate the management level of carbon emissions fast and accurately, according to the practical situation of machining workshop and standard production rhythm method in industrial engineering, this paper defines standard carbon emissions of machining workshop are as follows:

(1) There is only one machine in every processing workstation of machining workshop, and there are N processing stations. A machine produces only one part every time.

(2) Production rhythm is t_0 second per piece, and working time of every batch is T.

(3) During T time range, the uncertainty of equipment, technology, management and environment (The carbon emission of people is little relative to the energy, materials and environment, so this paper does not consider) causes that energy, material, environment is different processing the same type of mechanical parts in every workstation.

(4) There is no abnormal accident in the process of production.

Therefore, the calculation formula of the carbon emissions in the i_{th} workstation is as follow:

$$S_i = E_i + W_i + H_i + A_i = \sum_{p=1}^{P} c_{ep}E_p + \sum_{q=1}^{Q} c_{wq}W_q + \sum_{s=1}^{S} c_{hs}H_s + \sum_{t=1}^{T} c_{at}A_t , \quad (1)$$

where, S_i denotes workshop carbon emissions of i_{th} workstation. E_i, W_i, H_i, A_i respectively denote carbon emissions of energy, material, environment and others. E_p, W_q, H_r, A_s respectively denote different species. p, q, s, t respectively denote total number of species. $c_{ep}, c_{wq}, c_{hs}, c_{at}$ respectively denote carbon emissions calculation factor of corresponding species.

This paper defines the unit carbon emissions:

$$s_i = S_i / N , \quad (2)$$

Where, $N = T/t_0$ denotes the number of the batch parts.

Similarly, e_i, w_i, h_i, a_i respectively denote the unit carbon emissions corresponding to energy, materials, environment and others in workshop.

(5) It is assumed that the carbon emissions of each sub-factors of the same part of *J* batches are as follows.

Unit carbon emissions of every batch of workshop energy $E(J)$:

$$E(J) = \begin{bmatrix} e_{11} & e_{12} & e_{13} & \dots & e_{1j} & \dots & e_{1J} \\ e_{21} & e_{22} & e_{23} & \dots & e_{2j} & \dots & e_{2J} \\ e_{31} & e_{32} & e_{33} & \dots & e_{3j} & \dots & e_{3J} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ e_{N1} & e_{N2} & e_{N3} & \dots & e_{Nj} & \dots & e_{NJ} \end{bmatrix} . \quad (3)$$

Unit carbon emissions of every batch of workshop material $W(J)$:

$$W(J) = \begin{bmatrix} w_{11} & w_{12} & w_{13} & \dots & w_{1j} & \dots & w_{1J} \\ w_{21} & w_{22} & w_{23} & \dots & w_{2j} & \dots & w_{2J} \\ w_{31} & w_{32} & w_{33} & \dots & w_{3j} & \dots & w_{3J} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ w_{N1} & w_{N2} & w_{N3} & \dots & w_{Nj} & \dots & w_{NJ} \end{bmatrix} . \quad (4)$$

Unit carbon emissions of every batch of workshop environment $H(J)$:

$$H(J) = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \dots & h_{1j} & \dots & h_{1J} \\ h_{21} & h_{22} & h_{23} & \dots & h_{2j} & \dots & h_{2J} \\ h_{31} & h_{32} & h_{33} & \dots & h_{3j} & \dots & h_{3J} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ h_{N1} & h_{N2} & h_{N3} & \dots & h_{Nj} & \dots & h_{NJ} \end{bmatrix} . \quad (5)$$

Unit carbon emissions of every batch of others in workshop $A(J)$:

$$A(J) = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1j} & \dots & a_{1J} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2j} & \dots & a_{2J} \\ a_{31} & a_{32} & a_{33} & \dots & a_{3j} & \dots & a_{3J} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ a_{N1} & a_{N2} & a_{N3} & \dots & a_{Nj} & \dots & a_{NJ} \end{bmatrix} . \quad (6)$$

To compare and measure carbon emissions uncertainty of each workstation, we refer to the above formulas and make standard carbon emissions of the type parts in every workstation of machining workshop.

We define the minimum energy carbon emission of the i_{th} workstation in these J batches is the standard energy carbon emission. That is:

$$e_{i0} = \min\{e_{i1}, e_{i2}, e_{i3}, \dots\dots, e_{ij}, \dots\dots, e_{iJ}\} . \quad (7)$$

Likewise, material, environment, and other standard carbon emission of the i_{th} workstation in these *J* batches are defined as follows:

$$w_{i0} = \min\{w_{i1}, w_{i2}, w_{i3}, \dots\dots, w_{ij}, \dots\dots, w_{iJ}\}$$

$$h_{i0} = \min\{h_{i1}, h_{i2}, h_{i3}, \dots\dots, h_{ij}, \dots\dots, h_{iJ}\}$$

$$a_{i0} = \min\{a_{i1}, a_{i2}, a_{i3}, \dots\dots, a_{ij}, \dots\dots, a_{iJ}\} . \quad (8)$$

So, the standard carbon emission of the i_{th} workstation is:

$$s_i = e_{i0} + w_{i0} + h_{i0} + a_{i0} . \quad (9)$$

The standard carbon emission of each workstation in workshop is:

$$S = \{s_1, s_2, s_3, \dots\dots, s_i, \dots\dots, s_N\} . \quad (10)$$

The formula (8) expresses the sum of minimum unit carbon emissions of energy, materials, environmental and others in J batch's production process, which is standard carbon emission of the type parts in the machining workshop.

Due to carbon footprint would change with the difference of equipment, personnel, time, mission and management in the machining workshop, setting up standard carbon emission is to make a unified standard in many uncertain factors, and be gradually updated with the improvement of the carbon footprints' optimal control. At the same time, the workshop standard carbon emission is also an important index compared with similar products of other enterprises.

3 Uncertainty measure of workshop carbon emission

Carbon emission's uncertainty of the machining workshop is carbon emissions variation size generated by each assembling resource (personnel, material, equipment, environment, information system, process, etc.) in the random machining process.

Uncertainty measure model of the workshop carbon footprints is based on the theory of gravitational potential energy of physics, using the standard carbon emissions for comparison, and then discrete degree between multi batch carbon emission's random variables and standard carbon emissions for the same type parts under the same conditions were calculated, which is the uncertainty degree of the workstation carbon footprints. Its value reflects the size of the carbon emission's fluctuations, and this value is inversely proportional to the management level of workshop carbon footprints.

Base on the above research, this paper constructs the uncertainty measurement model of workstation carbon emissions is:

$$h_i = \{\sum_{j=1}^{J}(e_{ij}-e_{i0})^2 / J + \sum_{j=1}^{J}(w_{ij}-w_{i0})^2 / J + \sum_{j=1}^{J}(h_{ij}-h_{i0})^2 / J + \sum_{j=1}^{J}(a_{ij}-a_{i0})^2 / J\}. \quad (11)$$

By (11), we can diagnosis carbon emission of each workstation, the workstation whose uncertainty degree is the highest will be the important object of carbon emission control.

$$h_{max} = \max\{h_1, h_2, h_3, ..., h_i, ..., h_N\}. \quad (12)$$

We can get the following enlightenments:

(1) The model can quantitatively measure carbon emission uncertainty of each workstation in the machining workshop, providing the basis for enterprise production and management;

(2) By decomposing and processing the formula (11) and (12), carbon footprint optimized object of the machining workshop can be analysed and diagnosed.

(3) The uncertainty measurement model can quickly and efficiently determine the uncertainty optimization object of workshop carbon footprint, and timely process it and effectively improve carbon footprint management level of machining workshop.

4 Control methods and diagnosis of carbon footprint in machining workshop

The formula (11) can describe quantitatively the carbon emission uncertainty of each workstation in machining workshop, and also provide reference for optimization control of workshop carbon footprints. First, we will permute the uncertainty degree of each carbon emission factor of workshop in decreasing order: $\{h_{max}, \ldots, h_{ij}, \ldots, h_{min}\}$.

According to the carbon footprint uncertainty measurement model of each workstation, the uncertainty degree of each carbon emission factor is sorted. The highest is the object being controlled and diagnosed. Then according to the actual situation of the factor analysis, we further study carbon emission elements of the factor and make the optimization scheme, and improve it. In the same way, we gradually improve carbon emission factor uncertainty, and thus reduce carbon emission uncertainty of machining workshop, and improve the management level of workshop carbon footprints. In view of the above research, this paper formulates the following control methods and diagnosis process networks of carbon footprint in machining workshop:

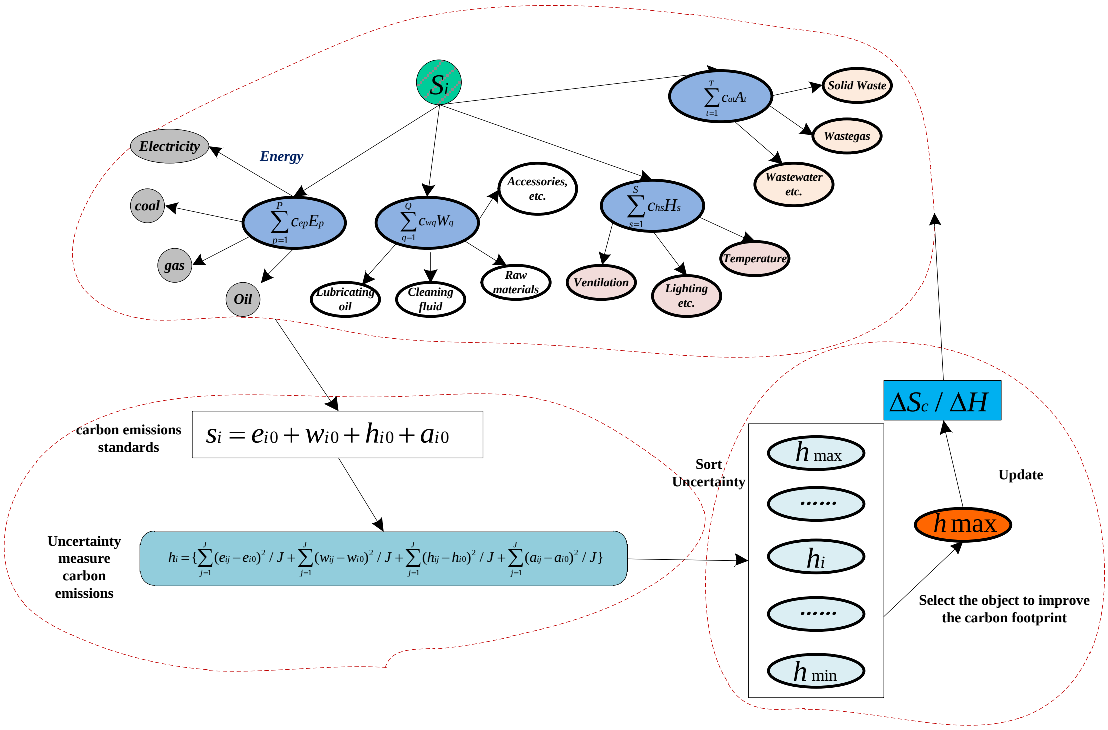

FIGURE 2 Control and diagnosis network of carbon footprint in machining workshop

Through figure 2 we can know, the control and diagnosis method of the carbon footprints for machining workshop on energy-saving and emission reduction is a continuous optimization and update dynamic closed-loop control mode. It can realize monitoring, analysis, extraction, processing, diagnosis and optimization of workshop carbon footprints, and it is also an adaptive optimizing process of collection, processing, organizing, mining, renewing and innovation for enterprise carbon footprint management knowledge. It can provide strong support for energy-saving and emission reduction, reducing costs, ensuring production safety and reducing production accidents of enterprises.

5 Application examples

The control and diagnosis method of the carbon footprints for machining workshop on energy-saving and emission reduction was applied to a connecting rod machining workshop of a manufacturing enterprise, whose main customers are Shanghai Volkswagen, Beiqi Foton, Changan Ford and other famous Chinese joint venture automobile enterprises. Its annual production capacity is 500000 pieces. The workshop has 34 equipment, using advanced connecting rod fracture splitting technology, and its materials are high carbon micro-alloying steel C70S6, which is high-strength and very sensitive to stress concentration.

The equipment energy of the connecting rod fracture cracking processing workshop is mainly electricity, materials are lubricating oil, cutting fluid, machine oil and cutting tool, environment includes ventilation, lighting and temperature control, and others are waste water, waste gas, waste residue and its processing.

On the basis of long-term investigation on a workshop of this enterprise, under the domination of IE (Industrial Engineer) engineering department, quality engineering department and the office of energy-saving and emission reduction, we take the 1.5GT223 type of engine connecting rod as the study object with the largest production volume. With the active cooperation and help from the workshop staff, we obtained the carbon footprint data of this type part manufacturing processes, and the data of some key workstations are described in the following table 2.

TABLE 2 The carbon footprint data of some key workstations in connecting rod workshop

sequence number	workstation	energy carbon emission		unit material		unit environment carbon emission		Unit other carbon emission	
		power	*lubricating oil \ cutting fluid*	*cleaning liquid*	*water*	*high power fan*	*lighting*	*temperature control*	*Wastes and treatment of workshop*
1	Grinding both ends	654.25	0.35	23.56	0.54	91.85	87.25	125.54	203.59
2	Boring and drilling big end hole	642.56	0.34	24.57	0.62	89.24	86.14	142.63	218.38
3	Chamfer / boring small end hole	466.24	0.55	25.34	0.68	92.64	83.95	145.56	198.24
4	Bolted joints	453.53	0.27	24.27	0.64	93.24	86.43	145.54	208.96
5	thread Machining	678.64	0.16	26.97	0.58	97.48	81.27	143.92	210.47
6	The assembly bushing	765.27	0.06	27.64	0.54	84.27	68.57	139.65	213.55
7	Processing fracture splitting notches	651.27	0.84	25.67	0.62	83.19	79.51	138.76	207.95
8	Cracking	1209.57	1.35	24.68	0.57	92.64	83.29	140.28	209.34
9	Assembly bolt	789.57	0.05	28.64	0.61	95.21	84.56	148.32	216.24
10	Fine grinding both ends	962.16	2.54	26.37	0.57	96.91	83.57	150.05	218.57
11	Processing step/ wedge	867.53	0.44	25.5	0.56	84.76	87.61	148.24	219.85
12	Fine boring small end hole	653.27	0.33	24.15	0.67	90.27	86.18	147.88	205.61

Note: in order to protect corporate interests, the above data is processed

In order to determine the optimization object of carbon emissions in machining workshop under uncertainty environment, the project team uses the mechanical processing procedure as the unit. With the support of these data and the formula (11) and (12), the uncertainty of each carbon emission factor in machining workshop is sorted. So we get the conclusion that the two highest uncertainties are rough boring big end hole and fine grinding face. After the analysis and research of its reason, the reasons are as follows.

TABLE 3 The carbon footprint control and diagnosis effect of workshop station

Order	station	Diagnostic object	encoding	uncertainty	reason analysis	solutions	result
1	Drill head boring	Rough boring head hole boring machine	T670-12	38.32	Lathe generator coil aging	Replace the generator coil	Uncertainty decline, and the lathe consumption fell by 8.2%
2	Fine grinding	cleanout fluid	W-Qy-150	28.46	Cleaning fluid wasted, there is no uniform standard cleaning	Developed using standard cleaning solution	Cleaning fluid consumption decreased by 24.3%

Through the above example, we can draw the conclusion that the control and diagnosis method of the carbon footprints for machining workshop on energy-saving and emission reduction has the following advantages:

(1) It can describe each element state and behavior of workshop carbon emissions after feature extraction and model matching for scattered, isolated, and incomplete carbon emission's data of machining workshop, and quantitatively describe workshop carbon emissions.

(2) It can monitor, analyze and extract carbon emission's information from the workshop through uncertainty measure of workshop carbon emissions, and quantitatively measure carbon emission uncertainty of each element, then diagnose carbon emission element of workshop station to determine the improve sequence of the carbon footprints.

(3) Through making diagnosis and control method of carbon footprints for machining workshop on energy-saving and emission reduction and using PDCA (Deming Cycle, initials of Plan, Do, Check and Act) cycle mode at the same time, the diagnose, optimal decision, organization, innovation and evolution can be realized.

(4) On the one hand, the control and diagnosis method of the carbon footprints can achieve energy-saving and emission reduction, reduce costs for enterprises, on the other hand, it can ensure product security and reduce production accidents.

6 Conclusions

In this paper, the main innovations are as follows:

(1) Based on defining carbon footprint connotations of energy, materials, environmental in machining workshop, we made standard carbon flow of the workshop, comprehensively considering production practice.

(2) We take standard carbon emission as contrast object, establish the uncertain measure model of workshop carbon emission, and quantitatively describe the control level of the workshop carbon footprints under uncertainty environment.

(3) This paper puts forward a control and diagnosis method of the carbon footprints for machining workshop on energy-saving and emission reduction, and illustrates its effectiveness and feasibility through the case.

The control and diagnosis method of the carbon footprints for machining workshop on energy-saving and emission reduction can provide theory and method support for energy-saving, emission reduction, cost saving and safety production of enterprises.

Acknowledgments

This research is supported by Colleges and universities in Anhui provincial young talents Fund Project (2013SQRL084ZD), and Suzhou University General research Project (2013yyb01).

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