A METHOD OF CARBON FOOTPRINT CALCULATION FOR THE PRODUCT LIFE CYCLE

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ABSTRACT: This paper proposes a concept model for product life cycle to present the characteristics of material flow, energy flow and waste flow in a manufacture system. Furthermore, two energy consumption calculation methods are provided according to the different components of the manufacture system, one is e-p method based on the processes of the system, and the other is e-f/s method based on the functions and statuses of the system. Then a carbon footprint calculation method is proposed on the basis of the characteristics of material flow, energy flow and waste flow in a manufacture system, and the energy consumption calculation above. Input-output analysis is carried out to establish the carbon emission calculation information table.

KEY WORDS: Carbon footprint, Emissions, Energy, Material, Input-output analysis.

1 INTRODUCTION

With rapid development of world economics and population explosion, carbon emissions make huge impact on global environment. The deterioration of climate seriously harms humans' health and safety. Low carbon emissions, green and sustainable development has become a global consensus, an industrial revolution which the low carbon emissions economy as its core has appeared gradually, various kinds of low carbon emission technologies arise [1].

The Carbon Footprint of Product (Carbon Footprint) measures the total emission of CO2 that a product emits in its lifecycle and the CO2 equivalent which other greenhouse gases converted. However, calculating the total carbon footprint is impossible due to the large amount of data required and the fact that carbon dioxide can be produced by natural occurrences [2]. It is for this reason that the researchers gave the more practicable calculation model. Simon Petty integrated renewables into the energy source mix and consequently reduce the carbon footprint of these locally integrated energy sectors [3]. Christopher L .Weber analyzed American household carbon footprint and its environmental impact, using consumer expenditure surveys and multi-country lifecycle assessment techniques [4]. Gaurav Ameta focused on machining operations, specifically turning and milling, for computing carbon footprint and applied mechanical tolerance principles for computing worst case and statistical case of a product carbon footprint [5].

This paper focuses on the description and calculation of material flow and energy, and the impact on carbon footprint.

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2 THE PRODUCT LIFECYCLE MODEL OF MATERIAL FLOW, ENERGY FLOW AND WASTE FLOW

The carbon footprint of manufacturing system is related to the material flow, energy flow and waste flow of product lifecycle, so establishing three flow model of product lifecycle is the foundation to do the carbon footprint analysis.

This paper establishes the three flows model as showed in Fig.1, which combines with the characteristics of material energy and waste during each stage in manufacturing system lifecycle. The material flow in Fig.1 is the principle (material includes raw material, intermediate products, products and working medium), while the energy as driving force which transmits the material, changes the form or property of material and does the service behavior. Each activity of lifecycle is involved with input and output of material and energy, after carrying out the recycle and remanufacture, some material and energy has been recycled, the other has to be discharged to the external environment which called carbon emission.

In Fig.1, the box represents the activity in manufacturing system lifecycle, including blank manufacturing, processing, assembling, servicing, maintaining, remanufacturing, disassembling and recycling etc. The line in the figure represents direction of the material flow and the material amount, the material amount is related to thickness of the line, each activity must follow the Law of conservation of Mass.

$$\sum Q_{mi} = \sum Q_{mo} + \sum Q_w \qquad (1)$$

In the formula1, $\sum Q_{mi}$ represents the mass of input, $\sum Q_{mo}$ represents the mass of output, and $\sum Q_w$ represents the mass of recycling or waste.

By analyzing the material flow, energy flow and waste flow model of manufacturing system full lifecycle, the corresponding strategy which can raise energy and material efficiency is proposed.

(1) The main strategy for improving the energy efficiency is involved with energy saving and recycling, showed in figure ① and ②.

(2) The strategy to improve material utilizing efficiency includes recycling material, overdue using and repairing products, upgrading products performance, modular replacement and remanufactures, recycling remanufacturing parts, reducing the utilization of metal parts and improving the comprehensive utilization rate of material, showed in ②-⑦.

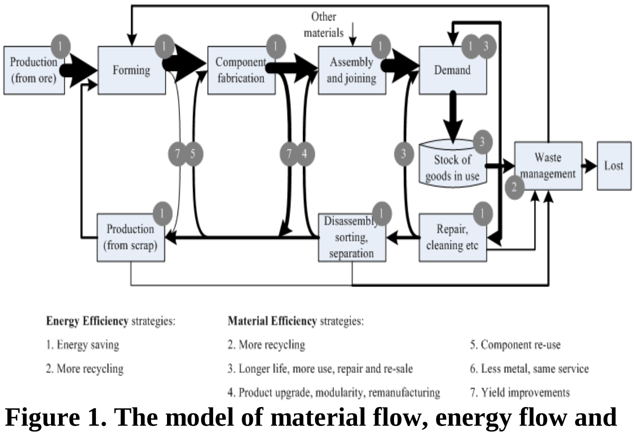

Figure 1. The model of material flow, energy flow and waste flow in manufacturing system

3 THE COORDINATION MODEL OF MATERIAL FLOW AND ENERGY FLOW OF MANUFACTURING SYSTEM

During the whole lifecycle of manufacturing system, material, energy and information are exchanging constantly, researching on the material flow and energy flow is very important. But the material flow and energy flow are not isolated. The mutual effect between them makes the functions or activities working. So focusing on the relation between material flow and energy flow is significant for tracing carbon footprint and carbon emission characteristics.

3.1 The basic characteristics of energy flow and material flow

Flow is the object which has certain functions and targets and structural, it also has the characteristics of flow and transmission. It is generated among the components and connects the components together.

Combining with the characteristics of flow, the input and output information of each single active component in manufacturing system can be expressed as the model showed in Fig.2.

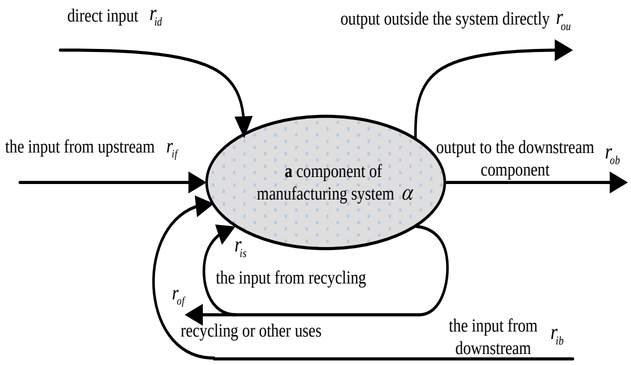

Figure 2. The input and output model of a component in manufacturing system

The input information is mainly derived from 4 parts:

① Direct input r_{id}, such as the direct input of the activities of raw materials and electric energy;

② The input from upstream r_{if}, such as the output of prior component as the input of next component, the input information is intermediate products or the energy transmitted.

③ The input from downstream r_{ib}, normally the lifecycle of products is not to be absolute straight line, during the manufacturing process, series of improving links are involved.

④ The input from recycling r_{is}, recycling is one of the main approaches for saving energy and material during manufacturing process.

The output information mainly includes:

① Output outside the system directly r_{ou}, including as the form of products needed energy also as the form of waste which output to the external environment.

② Output to the downstream component r_{ob}.

③ Recycling or other uses r_{of}.

3.2 The coordinating structure of material flow, energy flow and information flow of manufacturing system

During the transfer, conversion and consumption of energy and materials in the manufacturing system, at the same time, it along with the flow of information input and output. Information is the identification of matter, energy and process, it is vital for effective organization and management of material and energy, therefore, the model as shown in Fig.3 set up the relationship between among material flow, energy flow and information flow.

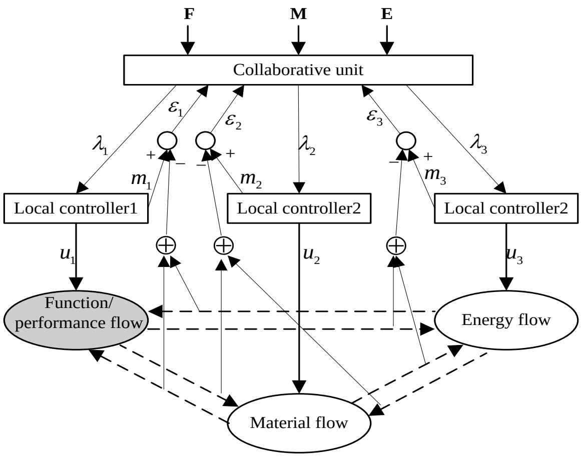

Figure 3. The coordinating structure of material flow, energy flow and information flow

The material flow, energy flow and information flow are treated as the three subsystems of a large system respectively, by coordinating among them; the subsystems can coordinate, cooperate, restrict and promote each other. Thus, the task and target of each subsystem can be fulfilled and the total target of the entire system also can be completed which is to implement the most optimal structure. The system coordinating structure adopts hierarchical control structure, showed in the figure below. In the Fig.3, F is the total function need, M is the total matter need, E is the total energy need. λ_1, λ_2, and λ_3 are the coordinating variables. μ_1, μ_2, and μ_3 are the controlling variables. m_1, m_2, and m_3 are the hypothetical variables. ε_1, ε_2, and ε_3 are the coordinating offsets. The connections between energy flow, material flow and performance flow are expressed in dotted line.

The coordinating structure of performance flow, material flow and energy flow is divided into two levels, the upper level is coordinating element, which controls the flows synergistically, the lower level are three partial control elements, which make each layer of the subsystems works synergistically.

4 THE DESCRIPTION AND CALCULATION OF THE FEATURES OF MATERIAL, ENERGY, WASTE, AND THE CARBON EMISSION

For calculating the carbon emission of each manufacturing system component, firstly, the corresponding matter and energy consumption, recycling and waste emission has to be calculated. So this paper focuses on the description and calculation of material, the description and calculation of energy and the relational impact of material flow, energy flow and waste flow on the carbon footprint.

4.1 The description matrix of material flow

According to the characteristics of flow, the material and energy are both divided into two parts, input and output. The output part can be divided into the following types: put directly outside the system r_{ou}, including not only the product, the form of energy needed, but also the energy and material as waste put into the environment; Output to the downstream process r_{ob}, recycling for own use or used by others.

In order to further describe material's effects on manufacturing system, based on whether input material is part of the product, input material is divided into Primary input (Primary input) and auxiliary input (Ancillary input).

Yield ratio which measures the proportion of product input material takes has significant meanings on analyzing material utilization. Assume Q_i represents total input material, Q_{pi} represents the input material which is part of the product, and Yield radio $\gamma \in [0,1]$ can be described as:

$$r = Q_{pi} / Q_i \quad (2)$$

We can know, if some $input_j$ as primary input, then exists $0 < r_j \leqslant 1$. If some $input_j$ as ancillary input, then $r_j=0$.

Corresponding to yield radio, yield of finished products loss of input material （yield loss） τ can be calculated, as: $\tau = 1 - r$.

The involved materials in manufacturing system not only include raw materials S_R, but also the intermediate products (including recycling materials) S_M and products S_P etc. In order to describe the relationship between different types of materials, the material flow of manufacturing system or manufacturing unit can be described as flowing matrix:

$$\begin{pmatrix} \tilde{A}_{PP} & \tilde{A}_{PM} & \tilde{A}_{PR} \\ \tilde{A}_{MP} & \tilde{A}_{MM} & \tilde{A}_{MR} \\ \tilde{A}_{RP} & \tilde{A}_{RM} & \tilde{A}_{RR} \end{pmatrix} \quad (3)$$

Among this, $\tilde{A}_{RM}$ represents the mapping relation between S_R and S_M , $\tilde{A}_{RM}$ represents the input of S_R as S_M , $\tilde{A}_{RM}$ represents the input of S_M as S_R during resource recycling process. Similarly, $\tilde{A}_{RP}$ and $\tilde{A}_{PR}$ represents the mapping relation between S_R and S_P . $\tilde{A}_{MP}$ and $\tilde{A}_{PM}$ represents the mapping relation between S_M and S_P . $\tilde{A}_{RR}$, $\tilde{A}_{MM}$ and $\tilde{A}_{PP}$ represent the transition among same type of materials.

In the traditional manufacturing process, it is considered that from S_R and S_M to S_P has specific directivity, S_M is derived from S_R , S_P is derived from S_R and S_M . In the traditional way, $\tilde{A}_{iR} = O, i \in \{P, M, R\}$, $\tilde{A}_{iM} = O, i \in \{P, M\}$, then the material flow can be expressed as：

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & O & O \\ \tilde{A}_{MP} & O & O \\ O & \tilde{A}_{RM} & O \end{pmatrix} \quad (4)$$

It can be found through analysis in chapter 1 that recycling and remanufacturing is the main approach to improve the efficiency of material. Therefore, considering resource recycling and remanufacturing, $\tilde{A}_{iR} \neq O, i \in \{P, M, R\}$, and $\tilde{A}_{iM} \neq O, i \in \{P, M\}$ can be achieved. The material flow matrix which considering waste recycling can be described as:

$$\tilde{A}_1 = \begin{pmatrix} \tilde{A}_{11} \\ \tilde{A}_{w1} \end{pmatrix} = \begin{pmatrix} \tilde{A}_{PP} & \tilde{A}_{PM} & \tilde{A}_{PR} \\ \tilde{A}_{MP} & \tilde{A}_{MM} & \tilde{A}_{MR} \\ \tilde{A}_{RP} & \tilde{A}_{RM} & \tilde{A}_{RR} \\ \tilde{A}_{WP} & \tilde{A}_{WM} & \tilde{A}_{WR} \end{pmatrix} \quad (5)$$

Among this, S_P represents information of waste, $\tilde{A}_{iW}, i \in \{W, R, M, P\}$ indicates the transition relationship of materials during the process of waste producing. $\tilde{A}_{Wi}, i \in \{W, R, M, P\}$ represents the transition relationship of materials during the process of waste recycling.

4.2 The consuming characteristic of the intermediate materials

During the transmission and transform of matter, there are a series of intermediate matter form, for example, when manufacturing a precision machining center, processing workbench often is involved with several processes such as casting, rough machining and finish machining, The product which produced by rough machining is the base of the finish machining, so-called intermediate product. And the product from finish machining is the intermediate product of assembling. So when establishing matter flow model for product lifecycle, a certain type of matter in certain manufacturing unit needs to be understood.

For describing the relations between products and intermediate products, the consumption model of intermediate materials is established in Fig.4.

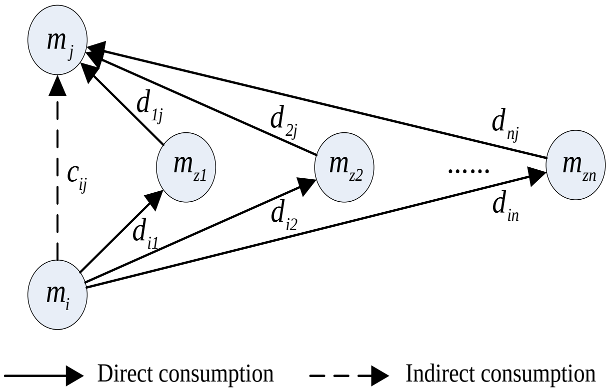

Figure 4. The consuming characteristic of the intermediate materials

The variable m_i is the initial matter for one manufacturing unit. m_j is the product output (this product can be the intermediate product of other units), $\{m_{z1}, m_{z2}, ..., m_{zn}\}$ is the intermediate matter, c_{ij} is the indirect consumption between m_j and m_i, $\{d_{i1}, d_{i2}, \cdots, d_{in}\}$ is the consumption from the corresponding variables $\{m_{z1}, m_{z2}, \cdots, m_{zn}\}$, There are relations between c_{ij} , $\{d_{i1}, d_{i2}, \cdots, d_{in}\}$ and $\{d_{1j}, d_{2j}, \cdots, d_{nj}\}$ is showed below:

$$c_{ij} = \sum_{k=1}^{n} d_{ik} d_{kj} \quad (6)$$

4.3 Description and Calculation of energy consumption in manufacturing systems

Considering the characteristics of machinery equipment' energy consumption such as machine tools and engineering machinery in each phase of product lifecycle, two energy consumption calculation methods is raised: energy consumption calculation method (e-p method) based on process, energy consumption calculation method (e-f/s method) based on system function and status.

4.3.1 E-p method

The major energy consumption point of machinery equipment includes manufacturing phase and operating phase, manufacturing phase is the process of producing machinery equipment, the e-p method is suitable for calculating the energy consumption. The energy consumption calculation formula of the process is as follows:

$$E = \sum_i e_i = \sum_i (e_i^x - e_i^h) \tag{7}$$

In the formula, is the corresponding energy consumption amount of the process , is the corresponding direct energy consumption amount, and is the recycling amount of remaining heat and energy.

It can be found from the formula that there are several ways to improve energy efficiency during manufacturing phase: Reducing direct energy consumption in each process; Increasing recycling amount of remaining heat and energy.

In order to analyze energy's effects in manufacturing phase in detail, so as to further improve the foundation of energy efficiency establishment, we set up a composition diagram of energy consumption in manufacturing process as shown in Fig.5. Energy can be divided into Direct Energy (Direct) Energy and Indirect Energy (Indirect Energy) depending on the energy function in the manufacturing process. Direct Energy is the energy consumed by manufacturing products such as casting, machining and assembling, while indirect energy is the energy consumption associated with manufacturing process indirectly, such as workshop lighting, temperature control etc.

Direct Energy can be further divided into theoretical Energy and auxiliary Energy. Theoretical Energy refers to the energy demand corresponding to the process' core functions, such as the consumed energy during the cutting process at CNC machining center, this part of energy can be calculated based on basic manufacturing theories and mechanical equipment movement principle, so it is often called ideal energy consumption; while auxiliary energy refers to the energy consumption which is related to manufacturing process auxiliary behavior, such as the energy consumption of fast forward, push broach, cooling and chip removal during the mechanical machining process, auxiliary energy can be obtained through actual measurement or system specifications.

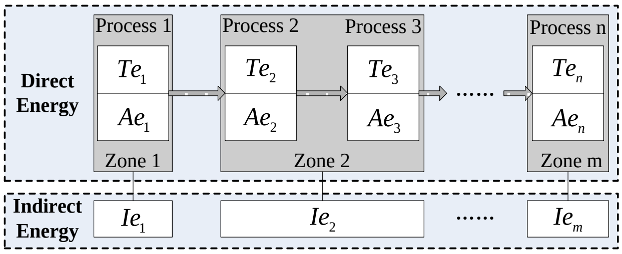

Figure 5. The composition of energy consumption in manufacturing process

During the manufacturing process, direct energy consumption is often directly related to process and workstation etc. While indirect energy is usually associated with manufacturing environment. Such as lighting and cooling is directly associated with manufacturing environment, the manufacturing environment involves several processes and workstations. So when calculating the indirect energy consumption, a series of work ranges must be divided according to the manufacturing environment, indirect energy consumption of every product's manufacturing process is obtained after the distribution of processes and workstations.

By allocating the process and workstation reasonably in work space, it can help to reduce indirect energy consumption. Theoretical energy of direct energy is idealized energy demand, without changing the condition of processes, it is difficult to reduce. Thus, reducing auxiliary energy is the key to achieve more efficient manufacturing and machining.

4.3.2 Energy consumption calculation method (e-f/s method) based on system function and status

There is a big difference in energy consumption between the distribution and use of product and the manufacturing process, so energy consumption calculation method (e-f/s method) based on system functions and status is raised. For the distribution process, the energy consumption is calculated mainly based on distribution method and materials' spatial location; during the product serving period, energy consumption is calculated based on product functions and working condition.

The corresponding energy consumption formula is as follows:

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l}\int_{ts_{ij}}^{te_{ij}} p_{ijk}\,dt \tag{8}$$

In the formula 8， i is corresponding to system functions; j is corresponding to functional status; k represents source of energy; p_{ijk} is the power information of every energy source for ensuring functional status.

The function connotation of typical mechanical system is shown in Fig.6.

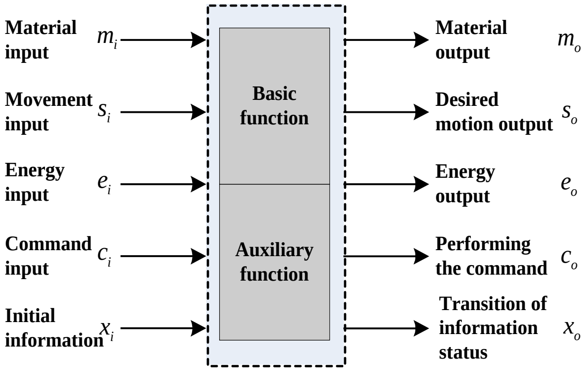

Figure 6. The function connotation of typical mechanical system

The functions mainly represent movement, force transfer and transition; Material, input and output of energy is the foundation of implementing the functions, the process of implementing functions is often accompanied with the information generation and status transition. In addition, command signal has great significance on effectively controlling the implementation of functions. Therefore, typical input involved with basic mechanical functional unit $Function_i$ includes material input m_i, movement input s_i, energy input e_i, command input c_i and initial information x_i. Typical output includes material output m_o, required movements s_o, energy output e_o, feedback of work command c_o and transition of information status x_o.

According to the meaning of the functions, the functions' units can be divided into two types of functions: the major function(basic function) and auxiliary function, the major function is for converting the state of geometry, the state of physics, the chemical composition, physiological function of the machining objects(processed item, objects or materials) or transmitting and processing information; Auxiliary function can complete the auxiliary works which the major function needed, such as: transporting, assembling and fixing of the machining objects(processed item, objects or materials); controlling the emitting and executing of command signal; collecting and testing of working information and system controlling.

Assume p_{ij} is the consumed power for implementing function unit f_{ij}, then：

$$p_{ij} = mp_{ij} + ap_{ij} \tag{9}$$

In the formula， mp_{ij} represents the power consumed for implementing the major function, ap_{ij} represents the power consumed for implementing the auxiliary function.

4.4 Description and Calculation of energy consumption in manufacturing systems

4.4.1 The calculation model of mechanical products carbon footprint

Considering the carbon footprints of mechanical products in the whole lifecycle is mainly related to the energy consumption, material consumption and waste, and then the carbon footprint formula of mechanical products in the whole lifecycle is as follows:

$$\begin{aligned} C_i &= C_{im} + C_{ie} + C_{is} - C_{ir} \\ &= \sum_{j=1}^{n} \{m_j * (1-b_j) * f_{mj}\} \\ &+ \sum_{l=1}^{m} \{e_l * f_{el}\} \\ &+ \sum_{k=1}^{p} \{s_k * f_{sk}\} \\ &- \sum_{g=1}^{q} \{r_g * f_{rg}\} \end{aligned} \tag{10}$$

In the formula, C_i is the corresponding carbon footprint of activity i , C_{im}, C_{ie} and C_{is} are the carbon footprints which related to material, energy and waste respectively, C_{ir} is the recycling carbon footprint; m_j, e_l and s_k are material consumption ,energy consumption and waste amount respectively; f_{mj}, f_{el} and f_{sk} are the emission factors of material, energy and waste respectively. r_g is the recycling amount of material or energy, f_{rg} is the corresponding emission factor.

4.4.2 Calculating information table of Carbon emissions based on the IOA

For simple equations in the text always use superscript and subscript (select Font in the Format menu). Do not use the equation editor in text on same line.

Combining with the research results of the mentioned material flow and energy flow, and the relation model between material, energy and carbon emissions, the technology based on IOA designs the carbon emission information table of manufacturing system as showed in Table 1.

Left side of the table represents the input information of manufacturing system or manufacturing system unit. Top of the table represents output information. Among this, the input includes intermediate products, recycling resources (including material and energy) and outsourcing resources, intermediate products refers to the obtained materials which go through a series of processing and manufacturing; Output includes products and intermediate products, recycling resources (including material and energy) and waste which are the material and energy emit to the environment and have impact on local environment. In the table, *p* is the input material amount; *q* is the output material amount; *k* is the carbon emission factor of different material, it is derived from the carbon emission factors of the intermediate resources and recycling resources. Namely, the units of carbon dioxide generated during one unit of the material produced. It can be got from the carbon footprint calculation formula that the main focus of calculating carbon footprint is the material and energy which have impact on environment, while the existence of intermediate products and recycling resources makes it more difficult to calculate carbon footprint.

Carbon emission is calculated based on the pollutants, the pollutants refer to the materials which emit to natural environment and damage the environment. It can be got from the Table 1 that the pollutant includes two parts: The pollutants emits in the producing process of material units, such as some resource units (material or energy), related consumption is p_i, the corresponding carbon emission factor is k_i, thus, the carbon emission for producing this material is $p_i * k_i$; The generated pollutants during the manufacturing process is $\{q_{s+1}, q_{s+2}, \cdots, q_t\}$.

Accordingly, the corresponding carbon emissions of the manufacturing units can be get from following formula:

$$cf_i = \sum_{j=1}^{l} p_{ij} * k_{ij} + \sum_{k=s+1}^{t} q_{ik} * f_{ik} \quad (11)$$

In the formula 11, p_{ij} is the consumed resource of manufacturing unit U_i, k_{ij} is the corresponding carbon emission factor, q_{ik} is the produced waste, and f_{ik} is the carbon emission factor of the waste.

This model considers not only recycling and utilizing of resources (including material and energy), but also the intermediate resource form of manufacturing system, it is capable of calculating complicated carbon emission situation.

Table 1 The carbon emission information table based on IOA

			Product/ Intermediate product				Recycling resources				Outsourcing resources			
			q_1	q_2	…	q_h	q_{h+1}	q_{h+2}	…	q_s	q_{s+1}	q_{s+2}	…	q_t
Intermediate product	p_1	k_1	C_{pp}				C_{pr}				C_{pw}			
	p_2	k_2												
	…	…												
	p_m	k_m												
Recycling resource	p_{m+1}	k_{m+1}	C_{rp}				C_{rr}				C_{rw}			
	p_{m+2}	k_{m+2}												
	…	…												
	p_n	k_n												
Outsourcing resources	p_{n+1}	k_{n+1}	C_{op}				C_{or}				C_{ow}			
	p_{n+2}	k_{n+2}												
	…	…												
	p_l	k_l												

5 CONCLUDING REMARKS

The descriptive matrix of material flow is proposed to analysis the characteristics of raw material, intermediate products, finished products and recycling resources. The e-p method and e-f/s method are raised. Furthermore, on the basis of analyzing the characteristics of material flow and energy flow, the carbon footprint calculation method of manufacturing system is provided, with the carbon emission information table based on IOA. The table considers not only recycling and utilizing of the resources (including material and energy), but also the intermediate resource form of manufacturing system. It is capable of calculating complicated situation of carbon emission.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

► HS Matthews, CT Hendrickson, CL Weber. The importance of carbon footprint estimation boundaries[J]. Environmental Science & Technology, 2008, 42(16): 5839-5842.

► Simon Perry, Jiri Klemes, Igor Bulatov. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors [J]. Energy, 2008,33(10):1489-1497.

► Christopher L. Weber, and H. Scott Matthews. Quantifying the global and distributional aspects of American household carbon footprint [J]. Ecological Economics, 2008, 66(2-3): 379-391.

► Bauer D J, Thurwachter S, Sheng P S. Integration of environmental factors in surface planning: part 1 -- mass and energy modeling [J]. Transactions of NAMRI/SME, 1998, 26: 171–176.

► Munoz A, Sheng P S. An analytical approach for determining the environmental impact of machining processes[J]. Journal of Materials Processing Technology, 1995, 53(3-4): 736-758