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A carbon efficiency method to evaluate the environmental burden of a workshop based on energy footprint and carbon footprint

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Abstract *Due to the huge consumption of materials and energy during machining processes, reduction of carbon emissions of workshops is an essential key to decrease the environmental burden of various manufacturing systems. To achieve this, the first step is to devise methods to calculate and evaluate the carbon emissions of workshops. In this paper, a workshop is decomposed into three levels from bottom to top, i.e. the facility level, the workpiece level and the workshop level, and the energy footprint and carbon footprint of each level are quantified based on the life cycle assessment method (LCA). Then three carbon efficiency indicators which consider production quantity and economic return are proposed. At last, the carbon efficiency method is applied in a workshop of gear machining to verify its feasibility and applicability. The results show that the carbon efficiency of a workshop fluctuates slightly in time and it is mainly related to the key workpiece which has high carbon efficiency, so it is more effective to reduce the carbon emission to adjust the machining parameters of key processes or cut down the production quantity of products with high carbon emission.*

Keywords: *carbon efficiency; carbon footprint; energy footprint; workshop*

1 Introduction

Nowadays, the world economic development consumes more and more energy and natural resources, and meanwhile has a growing impact on the environment. For example, the increasing emission of CO2 makes crucial contribution to globe warming. In 2010 the global CO2 emissions were 3.32×10^{10} tons, while China's emissions reached 8.33×10^{9} tons (about 25% of world's CO2 emissions), with a 10.4% increase over the year 2009 [1]. According to the International Energy Outlook 2010 [2], the global energy related CO2 emissions are estimated to be 43% higher in 2035 than the levels in 2007, assuming no new policies were imposed. Manufacturing, as the backbone of industrialized society, is one of the main energy consumers and greenhouse gas (GHG) contributors. The energy consumption in China's manufacturing sector accounted for about 60% of the total consumption [3]. Therefore, the reduction of carbon emissions in manufacturing processes has been the essential key to achieve low carbon manufacturing in China.

In order to evaluate the environmental burden of manufacturing processes comprehensively, energy footprint (EF) and carbon footprint (CF) were applied in [4, 5, 6], and showed that selection of machining parameters and machine tools largely dominate the energy consumption and carbon emission. However, few researchers tied the EF and CF to parts' production and economic value. Furthermore, since the energy consumption and carbon emission of a workshop are dynamic with the change of the market demand, it is also a key point of reducing carbon emission to study the relationship between the EF, CF and the batch.

2 Related work

Since environmental emissions of a workshop are mainly caused by energy consumption, a large number of studies on the potential of efficiency-enhancing measures and theoretical intervention options have been undertaken. Rahimifard et al. [4] modeled the detailed breakdown of energy required to produce a single product to provide greater transparency on energy inefficiencies throughout a manufacturing system and find the improvements in production and product design. Mouzon et al. [7] developed operational methods for the minimization of the energy consumption of manufacturing equipment. He et al. [8] analyzed the energy consumption characteristics driven by task flow in machining manufacturing system and proposed a modeling method of task-oriented energy consumption for machining manufacturing system. In other words, researchers have studied the energy consumption from different levels of manufacturing processes, such as machine tools, parts, tasks and so on.

Except the energy consumption, many other production activities of a workshop can also generate carbon emissions, such as coolant and lubricant oil consumption of a machine tool, cutting tool wear, liquid waste disposal, etc. Many different methods are proposed to evaluate the carbon footprint of a production process. In the aspect of carbon emission assessment of machining processes, Branker and Jeswiet [9] proposed a new economic model for optimum machining parameter selection in a milling example, and Narita et al. [6] developed an environmental burden analyzer for machine tool operations which can evaluate an NC program from the view point of an environment burden. Cao et al. [10] presented a carbon efficiency approach to quantitatively characterize the life-cycle carbon emissions of machine tools, in which carbon efficiency is defined as the ratio of capacity or service value provided by a machine tool to the corresponding carbon emissions. Fang et al. [11] established a new mathematical programming model of the flow shop scheduling problem, which considers peak power load, energy consumption, and associated carbon footprint in addition to cycle time. However, the carbon emission assessment method of a workshop has hardly been studied in the past literature.

In this paper, a workshop is decomposed into three levels from bottom to top, i.e. the facility level, the workpiece level and the workshop level, and the energy footprint and carbon footprint of each level are quantified based on the life cycle assessment method (LCA). In order to evaluate the carbon efficiency of a workshop from different perspectives, three carbon efficiency indicators which consider production change and economic value are proposed. At last, the presented method is applied in a workshop of gear machining to analyze and evaluate the carbon emission of different parts and the workshop in different periods.

3 Calculation of EF and CF of a workshop

A workshop is a huge manufacturing system which consists of machine tools, people, energy, materials, etc. The inputs of a workshop are various blanks, energy and auxiliary materials. The outputs are semi-finished or end parts, waste materials or effluent and carbon emission, as illustrated in Fig. 1. Based on the characteristics of a workshop, it can be mainly discomposed into three levels from bottom to top, i.e. the facility level, the workpiece level and the workshop level. The facility level represents every single machine which can perform a kind of processing task, such as turning, milling, wire cutting, stamping, bending, grinding, boring, drilling, laser cutting, automatic welding, etc. In terms of the workpiece level, each workpiece covers a series of processing and transportation from a blank to a semi-finished or end part, which is generated by a process flow and machines in the facility level. On the top, the workshop level involves all the machine tools, workpieces, lighting and heating and other facilities.

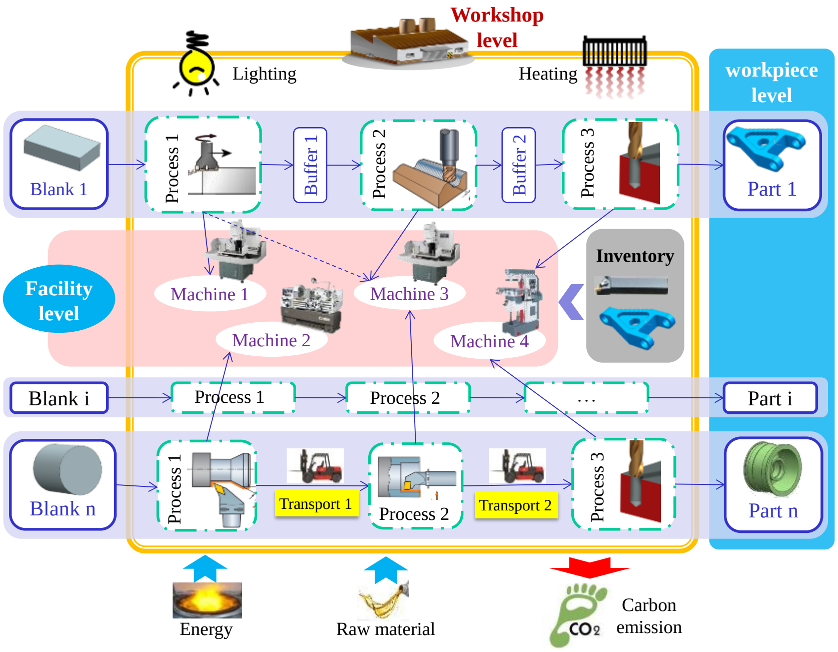

Figure 1 The hierarchical structure of a workshop

3.1 EF and CF of the facility level

Although different machine tools have different functions, the energy consumption of a machine tool could roughly be classified by two categories from the view point of the growth of a part's value, i.e. energy consumption of material removal (MR) and assistant energy consumption (AE). When a machine tool is machining a workpiece, only the energy consumption of material removal can change the value of the workpiece directly, while other energy consumption activities just maintain the normal operation of a machine tool, such as spindle accelerating, air cutting, tool changing and the stand-by stage, as shown in Fig.2. Moreover, for a certain machine tool, the power of some stages is fixed, such as stand-by stage and spindle accelerating which are unrelated to processing states.

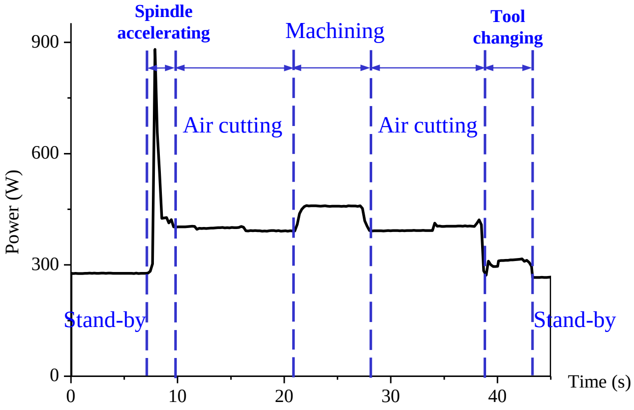

Figure 2 The power profile of a machining process

Referring to Fig.2, the EF of a normal process could be denoted as Eq.1:

$$EF^{mach} = MR + AE \tag{1}$$

$$MR = SEC \cdot V = (C_0 + C_1 / MRR) \cdot V \tag{2}$$

$$AE = n_{SA} \cdot SA + n_{TC} \cdot TC + P_{ac} \cdot t_{ac} \tag{3}$$

where SEC, MRR and V represent the specific energy consumption, material removal rate and the removal volume, respectively; SA and TC are the energy consumption of spindle accelerating and tool changing every time; n_{SA} and n_{TC} denote the times of spindle acceleration tool-changing and P_{ac} represents the power of a machine tool during air cutting stage.

In terms of the CF of a process, except the energy consumption, auxiliary material consumption of workpiece machining and cutting tool wear of machine tools will also generate the carbon emission, as shown in Eq.4. During the processing, the auxiliary materials mainly contain coolant and lubricant oil. The coolant is generally circulated by coolant pump and will decrease bit by bit because some of the coolant is adhered to the metal chips. For lubricant oil, it is mainly used for a spindle and a slide way of a machine tool, and minute amount of oil is infused to the spindle part and the slide way in decided intervals [6], which is shown in Eq.5. Besides, the CE of cutting tools is estimated from the viewpoint of tool life, as shown in Eq. 6. Some cutting tools, particularly those for a solid end mill, are recovered by regrinding after reaching their life limit.

$$CF^{mach} = EF^{mach} \cdot emf^{el} + CE^{au} + CE^{tool} \tag{4}$$

$$CE^{au} = \frac{t}{T^{cool}} \cdot IC^{cool} \cdot emf^{cool} + \frac{t}{T^{lu}} \cdot LO^{lu} \cdot emf^{lu} = t \cdot \omega^{au} \tag{5}$$

$$CE^{tool} = \frac{t}{T^{tool} \cdot (N^{gr} + 1)} \cdot (CE^{prod} + N^{gr} \cdot P^{gr} \cdot emf^{el}) = t \cdot \omega^{tool} \tag{6}$$

where CF^{mach}, CE^{au}, CE^{tool} and CE^{prod} represent carbon emission of a machine, auxiliary material, cutting tool wear and cutting tool production, respectively; emf^{el}, emf^{cool} and emf^{lu} are the carbon emission factors of electric energy, coolant and lubricant oil; IC^{cool} and LO^{lu} stand for the initial coolant quantity and lubricant oil quantity of a machine; T^{cool}, T^{lu} and T^{tool} represent the mean interval of coolant update and lubricant oil discharge of a machine and the tool life; N^{gr} and P^{gr} are the total number of tool re-grinding and energy consumption of the cutting tool re-grinding; ω^{au} and ω^{tool} represent the coefficients of carbon emissions of auxiliary materials consumption and cutting tool wear, and t is the processing time.

3.2 EF and CF of the workpiece level

According to the characteristics of a workpiece processing, the energy consumption mainly comes from two parts, i.e. the direct energy consumption (DE) and indirect energy consumption (IE). The DE is defined as the energy consumed by various processing, e.g. turning, milling, wire cutting etc., whereas the IE is the energy consumed by activities which are unrelated to the processing, e.g. transportation, storing, etc., which is represented in Eq. 7. The energy consumption due to transportation processes in a workshop is related to the mode and the distance of transportation. Different transportation machines will consume different amount of energy, which is expressed in Eq. 8. Furthermore, there is a buffer to place workpieces temporarily for each machine tool, and a processing will go through a number of buffers which also consume energy. The energy consumption attributed to a workpiece in a buffer can be calculated based on multiplying the energy consumption of the buffer per hour by the storage time of the workpiece, which is shown in Eq. 9.

$$EF^{part} = \sum\nolimits_{j=1}^{p} (DE_j + IE_j) = \sum\nolimits_{j=1}^{p} (EF_j^{mach} + EF_j^{log} + EF_j^{buffer}) \tag{7}$$

$$EF_j^{log} = K_j^{tr} \cdot L_j^{tr} = K_j^{tr} \cdot (\left|x_j - x_{j-1}\right| + \left|y_j - y_{j-1}\right|) \tag{8}$$

$$EF_j^{buffer} = T_j^{buffer} / 60 \cdot EC_j^{buffer} \tag{9}$$

where EF^{part}, EF_j^{log} and EF_j^{buffer} represent EF of a workpiece, a transportation process and a buffer, respectively; K_j^{tr} and L_j^{tr} are the specific energy consumption of a transportation process and the transportation distance; (x_j, y_j) stands for the position coordinate of a machine tool; T_j^{buffer} and EC_j^{buffer} are the energy consumption of a buffer per hour and the storage time of a workpiece.

Since the CF of a workpiece processing mainly comes from its energy consumption, the CF is expressed in Eq.10.

$$CF^{part} = EF^{part} \cdot emf^{el} \tag{10}$$

3.3 EF and CF of the workshop level

For a workshop, its EF also comes from the inventory and the energy consumption of stand-by stage, except machining workpieces, which is expressed in Eq.11. For an inventory, the energy consumption is similar to the buffer. A few machine tools will be in stand-by stage to waiting for the next process for a certain scheduling plan, as expressed in Eq.13. Based on the stand-by energy consumption, an energy-saving model is proposed to determine whether machine tools should be on or off when they are idle for a certain amount of time [12], so its energy consumption cannot be neglected for a workshop.

$$EF^{shop} = \sum_{i=1}^{n} EF_i^{part} + EF^{inv} + EF^{standby} \tag{11}$$

$$EF^{inv} = \sum EC_j^{inv} \cdot T^{makespan} / 60 \tag{12}$$

$$EF^{standby} = \sum P_k^s \cdot t_k \tag{13}$$

where EF^{inv} and $EF^{standby}$ represent the energy consumption of an inventory and the stand-by stage; P_k^s and t_k stand for the idle power of a machine tool and the stand-by interval of the machine tool.

In terms of the CF of a workshop, apart from the energy consumption, many resources are consumed in a workshop, such as water, oxygen etc.

$$CF^{shop} = EF^{shop} \cdot emf^{el} + \sum Q_l^{rs} \cdot T_l^{rs} \cdot emf_l^{rs} \tag{14}$$

where Q_l^{rs}, T_l^{rs} and emf_l^{rs} represent the usage amount of a resource during unit time, the usage time and the carbon emission factor of the resource, respectively.

4 Carbon efficiency indicators of a processing workshop

For a processing workshop, there are many kinds of products which have different production lot sizes and the production quantity of each product may change with the market demand. Considering these situations, it is not objective enough to only use EF or CF to evaluate the environmental burden of a workshop. Therefore, based on the concept of the value-stream mapping (VSM) and eco-efficiency, three carbon efficiency indicators which consider production lot sizes and economic return are proposed. Through the indicators, the carbon efficiency of different products in different periods can be estimated, which can be used to adjust the productive process of a workshop, such as batch configuration, production scheduling, process planning and so on.

4.1 The processing carbon efficiency (PCE)

The VSM is used to describe the utilization efficiency of carbon emission of a workshop. The VSM divides production activities into value-added and non-value-added activities to create a map identifying bottleneck problems of production process. In order to calculate the carbon efficiency of a workshop, material removal processes are defined as the value-added activities, and other activities as non-value-added activities. So the PCE is defined as the ratio of carbon emission of all the MR to the total carbon emissions of the workshop, as expressed in Eq.15.

$$\lambda_1^{plant} = \frac{CF^{MR}}{CF^{shop}} \tag{15}$$

4.2 The production rate carbon efficiency (PRCE)

To combine the outputs of a workshop with carbon emission, we introduce the concept of Eco-efficiency which is defined as being achieved by the delivery of competitively-priced goods and services that satisfy human needs and result in an acceptable quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity [13]. The eco-efficiency can be calculated based on the value of a product or service divided by the environmental influence. Based on the eco-efficiency, the PRCE of a product can be expressed as follows:

$$\lambda_2^{plant} = \frac{Q}{CF^{part}} \tag{16}$$

where Q is the production rate of a product, CF^{part} is the mean carbon emission in unit time and λ_2^{plant} donates the PRCE.

4.3 The economic return carbon efficiency (ERCE)

Based on the concept of eco-efficiency, the ERCE is defined as the ratio of economic return of a workshop in a period to the total carbon emissions, as shown in Eq.17. Economic return can be understood as the economic benefits created by all the products during a certain time, which may vary with the change of the market demand.

$$\lambda_3^{plant} = \frac{\sum PR_i \cdot Q_i}{CF^{shop}} = \frac{\sum PR_i \cdot f_i(t)}{CF^{shop}} \tag{17}$$

where Q_i is the production quantity of the i th kind of product, CF^{shop} is the total carbon emission during a certain time, $f_i(t)$ is the production curve of the ith kind of product and λ_3^{plant} donates the ERCE.

5 A case study

In this paper a workshop which mainly carries out the rough machining of gears is studied for demonstrating the application of the proposed carbon efficiency approach. The workshop contains a digital controlled lathe (M_1), a drilling machine (M_2), a gear-hobbing machine (M_3) and a warehouse.

To calculate the CF and carbon efficiency of the workshop, the following settings are considered:

(1) Since the AE, P^s and ω^{au} of a machine have little effect on the total carbon emission of the machine, we assume that they are constant while processing different workpieces. The basic parameters of the machines are listed in Table 1. In terms of auxiliary resources in the workshop, we only consider the water consumption, and the Q^{water} and EC^{inv} of the warehouse are also listed in Table 1;

Table 1 The primary parameters of the workshop

Machine Parameters	AE (kJ)	$P^s (kW)$	$\omega^{au} (kgCO_2 - e / h)$
M_1	14	2.31	0.15
M_2	20	4.56	0.076
M_3	32	3.95	0.188
Workshop Parameters	$EC^{inv} (kW)$ 0.8	$Q^{water} (L / h)$ 35	

(2) According to the order recorders, three typical types of gears machined by these machine tools are selected to evaluate the carbon emission and carbon efficiency of the workshop. The basic parameters of three types of gears are listed in Table 2. The production quantities of the gears in three different periods are listed in Table 3;

Table 2 The base parameters of three types of gears

Parameters	Gear 1	Gear 2	Gear 3
Modulus(mm)	3	2.5	3
No. of teeth	30	40	25
Tooth width(mm)	30	30	30
Diameter of bore(mm)	22	25	13
Gear material	HT200	45#steel	HT200
Earning (Yuan)	8.4	6.1	3.3
Production rate(set/h)	15	21	18

Table 3 The production quantities of the gears in different periods

Gear	Period 1	Period 2	Period 3
Gear 1/set	100	200	250
Gear 2/set	200	350	200
Gear 3/set	150	50	100

(3) Each type of the gear has three processes, i.e. turning, drilling and gear-hodding, and each process could be executed on different machines. The processing parameters of each process are listed in Table 4, which contain the processing time $t(s)$, the removal volume $V(cm^3)$, *SEC* (kJ / cm^3) and $\omega^{tool} (kgCO_2 - e / h)$ of cutting tools.

Table 4 The processing parameters of each process

Machines	M_1				M_2				M_3			
Parameters	t	V	SEC	ω^{tool}	t	V	SEC	ω^{tool}	t	V	SEC	ω^{tool}
Gear 1	21	6.62	5.12	0.162	16	11.40	7.52	0.058	42	0.95	7.49	0.250
Gear 2	13	7.54	6.67	0.144	20	14.73	4.19	0.062	35	0.88	5.27	0.194
Gear 3	11	4.18	3.85	0.122	13	3.98	6.24	0.068	26	0.79	6.15	0.228

5.1 Results and discussion

First, based on the proposed calculation method of EF and CF, the carbon emission of the gears are obtained as illustrated in Fig. 3. It can be clearly seen that the carbon emission of Gear 1 is more than that of other gears, and Gear 3 generates the least carbon emission, which is about 0.108 $kgCO_2-e$. In terms of processes, the gear-hobbing is the most carbon-intensive in the machining processes of a gear, which is responsible for about 40%-50% of carbon emission of each gear. Therefore, the machining parameter adjustment and optimization of the gear-hobbing are more effective to reduce the carbon emissions of gears, especially for Gear 3.

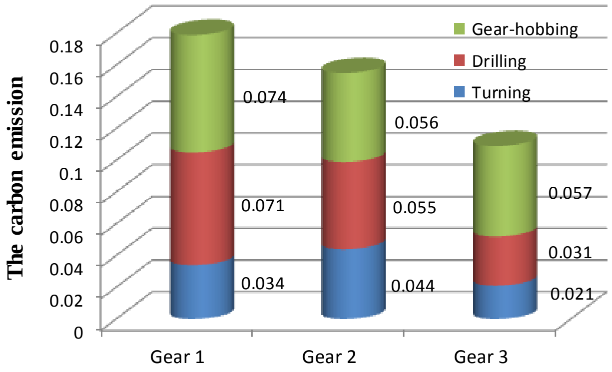

Figure 3 The carbon emission of the gears and processes

In Period 1, the carbon emission and PREC of the gears are calculated based on the production rate, which is shown in Fig. 4. The total carbon emission of Gear 2 in period 1 is the most among the three gears, which is up to 31.15 $kgCO_2-e$, because its production quantity is larger than others from Table 3. Moreover, the PREC of Gear 3 is 9.22 $set/kgCO_2-e$, which is the highest. By comparing the PREC with the carbon emission of a gear, they have an inverse proportion relationship. For the workshop, its PREC has a linear combination relationship with the production quantities of the gears, and varies with time because the PREC of each gear is different.

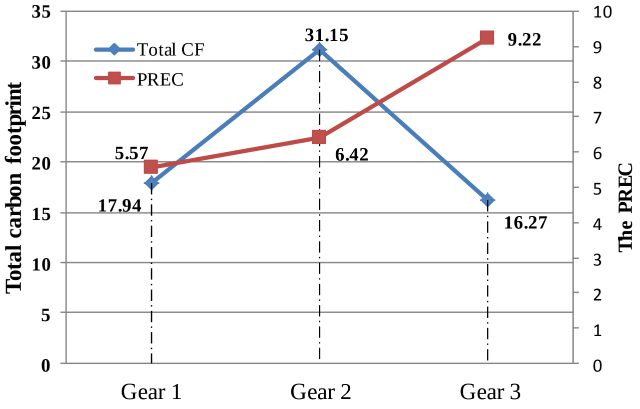

Figure 4 The total carbon emission and PREC of each gear in Period 1

Finally, to evaluate the carbon emission and carbon efficiency of the workshop from different perspectives, the CF, PCE and ERCE of the workshop are obtained, as illustrated in Fig. 5. The workshop in period 2 generates the most carbon emission (95.82 $kgCO_2-e$), and its CF of material removal processes which are the value-added activities is also the largest (65.65 $kgCO_2-e$). The PCEs of the workshop in different periods change little, which is 65.74%, 68.51% and 68.08% successively. So the CF of the workshop does not have a direct relationship with the PCE. To analyze the influence factors of the PCE, the PCE of each gear need to be calculated. In addition, we can find that the ERCE of the workshop increases from 39.09 $Yuan/kgCO_2-e$ to 42.03 $Yuan/kgCO_2-e$ and only the production of Gear 1 increases from period 1 to period 3, so it can be concluded that the more Gear 1 is produced, the higher the ERCE of the workshop becomes. In contrary, the ERCE of Gear 3 is only 30.56 $Yuan/kgCO_2-e$, which is much shorter than Gear 1, whose ERCE is 46.93 $Yuan/kgCO_2-e$. Therefore, it is an efficient method to increase the production quantity of Gear 1 to improve the ERCE of the whole workshop.

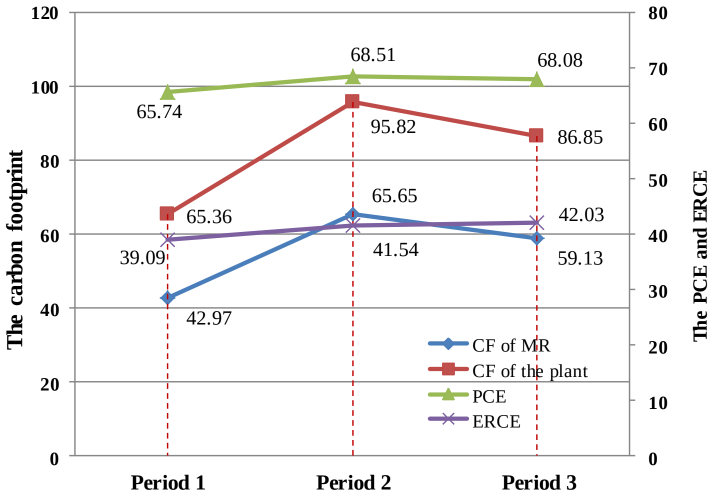

Figure 5 The carbon footprint, PCE and ERCE of the workshop

6 Conclusions

In order to evaluate the carbon emission of a workshop, it is decomposed into three levels from bottom to top, i.e. the facility level, the workpiece level and the workshop level, and the EF and CF of each level are quantified based on the LCA. Through expanding the concept of the VSM and the eco-efficiency, three carbon efficiency indicators which consider production quantity and economic value of a workshop are proposed to analyze the carbon efficiency of different products in different periods. Compared to other existing approaches such as carbon footprint and eco-efficiency, the proposed carbon efficiency method involves utilization rate of carbon emission, production lot sizes and economic return which can evaluate the environmental burden of a workshop from multiple perspectives. At last, a use case of a workshop which carries out the rough machining of gears is studied for demonstrating the application of the proposed carbon efficiency approach.

The results show that the carbon efficiency of a workshop fluctuates slightly in time and it is mainly related to the key workpiece which has high carbon efficiency. So three methods can be taken by workshop users to reduce carbon emission:

(1) The machining parameter adjustment and optimization of key process are more effective to reduce the carbon emission, such as the gear-hobbing of Gear 3 in the case study;

(2) For a workshop, it is also an effective approach to cut down the production quantity of products with high carbon emission;

(3) Taking economic return and carbon emission into consideration, the production quantity of products with high ERCE need to be increased to improve the ERCE of the whole workshop.

Future research in this area will include the verification of the accuracy of EF and CF calculation methods and the establishment of some effective carbon efficiency indicators of workpieces and processes to find the carbon-intensive factors at the bottom of a workshop. Furthermore, based on the proposed carbon efficiency method, some optimization methods can be used to optimize the production lot size or the scheduling plan to reduce the carbon emission.

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