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Procedia Manufacturing 43 (2020) 175–182

Procedia MANUFACTURING

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17th Global Conference on Sustainable Manufacturing

Research on Extended Carbon Emissions Accounting Method and Its Application in Sustainable Manufacturing

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Abstract

Carbon-Emission Accounting (CEA) is an important assessment method for sustainable manufacturing, which mainly focuses on raw materials, energy and waste disposal factors but ignores labor and capital factors. However, the generation process of labor and capital inevitably produce Carbon Dioxide Emissions (CDE). Referring the Extended Exergy Accounting method, the calculation model of extended carbon dioxide emissions factors of capital and labor is established based on the standard CDE per capita, total population, annual working hours, intermediate money M2 and total annual wage S, etc. Then the Extended Carbon-Emission Accounting (ECEA) method is proposed based on the current CEA method, accounting labor, capital, raw materials, energy and all other environmental related factors. Comparatively analyzing on grinding and hard-turning process of a lathe spindle part is studied, the result shows ECEA method is more reasonable and suitable for sustainable manufacturing than CEA method.

Keywords: Carbon Emission; Labor; Capital; Extended; Accounting;

1. Introduction

With the rapid development of modern industry, human beings manufacture an unprecedented levels of industrial products, and simultaneously consume a lot of energy and materials, and produce a large amount of waste solid, liquid, and gaseous waste. A large amount of greenhouse gases (GHG) is emitted into the atmosphere resulting in the greenhouse effect, which leads to human beings facing serious global warming problems. Nowadays, governments

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10.1016/j.promfg.2020.02.132

and people are aware of the importance of environmental issues, and paying more and more attention to issues of sustainable development [1, 2].

Usually, the Carbon Footprint (CFP) method is used to evaluate the CDE of the manufacturing process, which is historically defined as "*the total set of GHG emissions caused by an organization, event, product or person*"[3, 4]. The CFP method is widely used to measure CDE values as carbon dioxide equivalents (CO_2e), which is suitable for a process's sustainability assessment and is also suitable for product's life cycle assessment [5, 6]. It mainly focuses on the raw materials, energy, environment inputs (waste disposal, environmental remediation), products and waste effluent or residue, but ignores the factors such as labor force, capital (equipment depreciation & maintenance cost, factory site lease, etc.).

In fact, the labor and capital are the important factors in manufacturing. And the process of producing labor itself needs to consume food, electricity, fuel, water and other resources during their daily life, which means CDE simultaneously. Similarly, during the capital generation process, it needs consuming energy, labor, material and other resources with CO_2 emitting simultaneously. So the CDE of capital and labor should not be ignored.

Zhang proposed a method to calculate a labor's CDE per worker-hour through the country's total annual CDE and the annual impact CDE assessed by using process-based or hybrid economic input-output life cycle analysis method[7]. But the annual impact CDE is also not clear, and it is hard to confirm the exact CDE value. Zhu proposed a method to calculate the personal CDE standard value by conducting an investigation on the individual's basic necessities, but this value is not the labor's CDE [8].

In labor and capital's energy/exergy accounting research, Sciubba and Chen proposed an extended exergy accounting model to evaluate capital and labor as exergy/energy [9-11]. In the model, the relationship between labor's exergy with personal minimum exergy, total labor hours, the total population and total exergy is established. Then, the relationship between capital exergy and labor exergy and economic indicators is established. However, the exergy approach does not accurately reflect environmental impacts (CDE) in the manufacturing process, but it provides a good way to calculate labor and capital's CDE value.

Therefore, combined with Zhu, Zhang Sciubba and Chen's method, an Extended Carbon-Emission Accounting (ECEA) method is proposed in this paper [9-11]. The ECEA method is based on the CFP approach, but it's extended. In the ECEA method, the labor, capital raw material, energy and environmental input are calculated as extended carbon dioxide emissions (Ex-CDE).

2. ECEA Method

2.1. Production indicators carbon emission in manufacturing

In ECEA analysis, the first step is to determine the production indicators in the manufacturing process. As shown in Fig.1, the main input indicators are: *labor* ***L*** (working hours); *capital* ***K*** (equipment depreciation & maintenance cost, factory site lease, etc.); *material* ***M*** (product materials such as raw materials and semi-finished products; non-product raw materials such as cutting tools, coolant, lubricants, etc.); *energy E* (electricity, compressed air energy, solar energy, etc.) and *environmental* ***O*** (waste disposal, environmental remediation resources); and the output indicators are: *product* ***P*** (product, by-product) and *effluent* E_{ff} (solid waste, waste liquid, waste gas, waste heat, etc.). There may also exist partial by-products and waste recycled as process's input. The CDE of the manufacturing process can be expressed as equation (1).

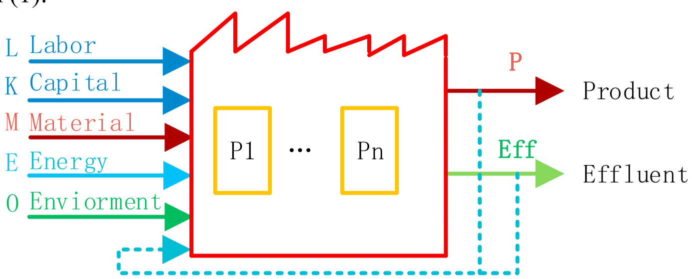


Fig.1 Mechanical manufacturing process production indicators

$$\mathrm{C}(\mathrm{t}) = f\left(L, K, M, E, O, P, E_{ff}, t\right) \tag{1}$$

2.2. Calculation of Ex-CDE

The CFP is the most widely used carbon emission calculation method, which is originated from the concept of ecological footprint [5, 6]. By using this method, the CO_2e of all production indicators can be calculated, consisting of direct emissions, indirect emissions [5, 6]. Referring to the .PAS2050 specifications, the Ex-CDE value is calculated through equation (2), where m_i is the amount of production indicators and EF_i is the extended carbon emissions factor of the each input [12].

$$\mathrm{C}_{Ex-CDE} = \sum m_i EF_i \tag{2}$$

In equation (2), m_i is also a function of ***L, K, M, E, O, P*** and ***Eff***. The amount of *material **M***, *energy **E***, *environmental **O***, *product **P*** (product, by-product) and *effluent **Eff*** (solid waste, waste liquid, waste gas, waste heat, etc.) be measured by means of weighing equipment, energy meter, timing equipment or volume measurement equipment. In *labor **L***, m_i can be measured by accumulating processing time and necessary auxiliary time of unit part. The average cost of equipment depreciation & maintenance cost, factory site lease per work-hour can be calculated, then the m_i of *capital **K*** can be calculated by average cost per work-hour multiplying the sum of processing time and necessary auxiliary time of unit part.

3. Extended Carbon Emission Factor

3.1. Labor's extended carbon emission factor

Extended carbon-emission factor is also derived from the carbon emission factor (CEF). The CEF is defined as the amount of GHG generated by the consumption of unit mass. It is an important parameter for characterizing GHG emission characteristics of a particular energy, and also it is the basis for CFP calculation [12]. It correlates data on activities with GHG emissions, where the data is the quantitative amount of GHG emissions activities measured in CO_2e per unit mass (kgCO_2e/kg, kgCO_2e/L, etc.). The CEF includes the sum of the amount of CO_2e per unit mass including mining, processing and use [13]. Extended the current CEF, the extended carbon emission factor (Ex-CEF) of labor and capital are to be modelled.

Referring to Sciubba's viewpoints，"*In any Society, a portion of the gross global influx of exergy resources E_{in} is used to sustain the workers who generate Labor*", a hypothesis is established similarly that "*a part of the total CDE is used to include workers generate labor*". This hypothesis is equivalent to that a human society may survive only as long as it produce a net flux CDE to sustain its population.

The total CDE of the society C_{Total} includes people's basic necessities, agriculture, mining, industry, service industry and other aspects. While the CDE to maintain social development can be defined as sustainable CDE C_{Used}, which is the total carbon emission consumed by the entire population (workers + unemployed),and it is a fraction α (the first econometric coefficient) of the total CDE C_{Total}. The relationship between them is shown as equation (3), and the sustainable CDE C_{Used} can be calculated by using equation (4).

$$C_{Used} = \alpha C_{Total} \tag{3}$$

$$C_{Used} = c_{prm} N_h \tag{4}$$

Where, N_h is the total population of country, c_{prm} is the standard CDE value per capita. The value c_{prm} of some country can be obtained from literature, such as 4.6 kgCO_2e/h in United States [7]. And also c_{prm} can be calculated by the survey data, by which Zhu calculated the basic CDE per capita in China is 3.63tons/yr [8]. Then the Ex-CEF EF_{lab} of the labor can be calculated through equation (5).

$$EF_{lab} = \frac{C_{Used}}{N_{wh}} = \frac{C_{Used}}{N_w W_h} \tag{5}$$

Where, EF_{lab} is the Labor Ex-CEF, N_{wh} is the whole society labor work-hours per year; N_w is the amount of labor; W_h is the amount of work-hours of a labor per year. Thus, the first econometric coefficient α can be calculated as equation (6)

$$\alpha = \frac{C_{Used}}{C_{Total}} = \frac{EF_{lab} N_w W_h}{C_{Total}} \tag{6}$$

Taking China as an example, the total population was 1.37509×10^8 in 2015, the urban employment was 5.0419×10^8 people, and the rural employment labor (farmer) was 2.703×10^8 people[14]. By referring to Chen's calculation method[9], consider that the agricultural labors of China are not working full-time, and its work-hours with a factor of 0.5. Assuming the legal work-hours of a labor is 2008 work-hours per year, the total work-hours of China in 2015 is 1.2838×10^{12} hours. The standard CDE value per capita in China is 3.63×10^3kg/yr, and the China total CDE is 10.4G tons in 2015 [8, 15]. The EF_{lab} and α can are calculated as shown in Table.1

Table.1 EF_{lab} and α in China (2015)

N_h	Urban employment	Rural employment	N_{wh} (h)	C_{Used} (kgCO_2e)	C_{Total} (kgCO_2e)	EF_{lab} (kgCO_2e /h)	α
1.375E+09	5.042E+08	2.703E+08	1.284E+12	4.990E+12	1.047E+13	3.887	0.477

3.2. Capital's extended carbon emission factor

Referring to Sciubba viewpoints of exergy, the second econometric coefficient β is considered as a "financial ratio" or "financial amplification factor compared to the gross cumulative wages", as shown in equation (7) [9-11].

$$\beta = \frac{M2 - S}{S} \tag{7}$$

$M2$ (Intermediate money) comprises $M1$ and, in addition, deposits with original maturities of up to two years and deposits redeemable at notice of up to three months [9-11]. Depending on their degree of liquidity, such deposits can be converted into components of narrow money, but in some cases there may be restrictions, such as the need for advance notification, delays, penalties or fees. S is the gross cumulative wages [9-11]. In extended exergy accounting method, Sciubba propose a hypothesis that "the amount of exergy required to generate the net monetary circulation within a society is proportional to the amount of exergy embodied into labor"[9-11]. The hypothesis is equivalent to that the extended exergy value of each monetary unit of salary is equal to the extended exergy value of the unit of net monetary circulation. A similar hypothesis is proposed as the extended exergy accounting method is that "that the extended carbon emission value of each monetary unit of salary is equal to the extended carbon emission value of the unit of net monetary circulation." So the Ex-CEF of capital EF_{cap} can be calculated through equation (8) accordingly.

$$EF_{cap} = \frac{\beta C_{Total}}{M2} = \frac{\beta N_{wh} EF_{lab}}{M2} \tag{8}$$

In 2015, the China's $M2$ was 1.392×10^{14}CNY, the gross cumulative wages S was 1.1201×10^{13} CNY. The EF_{cap} and β can is calculated as shown in Table.2

Table.2 EF_{cap} and β in China (2015)

$M2$ (CNY)	S (CNY)	N_{wh} (h)	C_{Used} (kgCO_2e)	EF_{cap} (kgCO_2e /CNY)	β
1.3920E+14	1.1201E+13	1.284E+12	4.9899E+12	0.410	11.427

3.3. Raw materials, product, energy, environmental and effluent's extended carbon emission factors

Raw material and product's Ex-CEF

As the expansion of CEF, the Ex-CEFs of raw materials, product, energy, environmental resources and effluent are exactly the same with its CEFs. So these factors can be obtained from literatures, where the carbon emissions factors of some commonly materials consumed in turning and grinding process including cutting fluids, grinding fluids, grinding wheels, inserts, and water, as shown in Table.3 [16,17].

Table.3 Carbon emissions factors of material consumption

	Steel	Grinding wheels	Inserts	Cutting fluids	Grinding fluids	Water
Ex-CEF		$kgCO_2e/kg$			$kgCO_2e$ /L	
Value	2.69	33.7	29.6	2.85	0.978	0.19

Energy's Ex-CEF

In this paper, the electricity is considered as the only input energy. The electric energy CEF has a close relationship with the power grid structure, where different power grid have different CEF [17]. The National Development and Reform Commission Department of Climate Change of China has researched to determine the Chinese regional power grid baseline CEF. In this paper, the CEF for East China Regional Power Grid is 0.70285 $kgCO_2e/kWh$ [18].

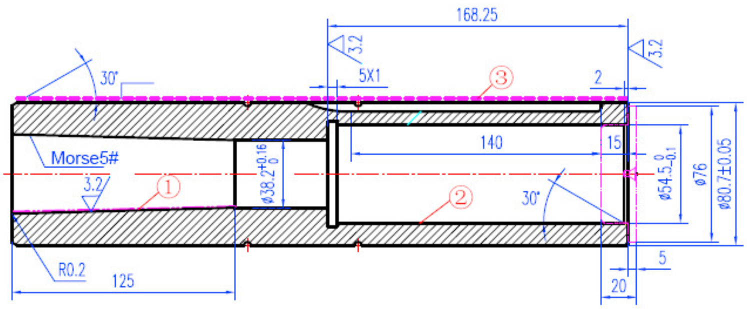
Environment and effluent's Ex-CEF

The environmental CDE is mainly from waste disposal, environmental remediation. For metal cutting and grinding, the main waste disposal is the grinding waste fluid, cutting waste fluid, iron scrap, insert or wheel debris. The idea method is to recycle the available materials from the solid waste, and collect the waste flux and process to harmless by the professional company. According to the literature [17], the CEF of waste cutting fluid is 0.2 $kgCO_2e/L$, and the CEF of iron scrap is 0.361 $kgCO_2e/kg$.

4. Case Study-- Choice of hard turning or grinding

4.1. Background and experimental scheme

In recent years, with the development of hard turning machine tools, the quenched high hardness parts can be machined by using hard turning lathe with high surface accuracy and there exists a tendency to partially replace grinding. An lathe spindle part is shown as Fig.2. The original process scheme (**Scheme 1**) is as followed: (a) Cut Down, (b) Rough Turning, (c) Heat Treatment, (d) Turning, (d) Benching, (e) Drilling Holes , (f) Milling Groove, (f) Milling Ring Groove, (g) Benching, (h) Heat Treatment, (i) Cylindrical Grinding , (j) Drilling Holes, (k) Benching, (l) Bore Grinding, (m) Bore Grinding, (n) Cylindrical Grinding→Finish Bore Grinding→Finish Cylindrical Grinding. The underlined processes (l),(m),(n) are the rough grinding process of the three surfaces, they are: ① Morse taper bore, ② bore and ③cylindrical surface as shown in Fig.2. These three surfaces each has an over 0.5mm hard layer with hardness over HRC52, 0.15mm processing margin in diameter. The new process scheme (**Scheme 2**) is to replace grinding with hard turning.



Surfaces to be machined：① Morse taper hole 5#; ② Bore; ③ Cylindrical surface

Fig.2 A lathe spindle part

In **Scheme 1** the bore grinding machine tool MK2110 is manufactured by China Linhai Tianxing Machine Tool Co., Ltd, and the cylindrical grinding machine tool MK1320is manufactured by China Beijing Guangyu Dacheng CNC Machine Tool Co., Ltd. In **Scheme 2** the hard-turn machine tool CY-CTC40100 is manufactured by Yunnan CY Group Co., Ltd.

4.2. Production indicators consumption

In order to comparatively process analyzing with ECEA method, the first step is to confirm the production indicators. The production indicators of grinding and hard-turning process is shown as Fig.3. The resources consumption in the manufacturing process is shown in Table4. In this paper, the consumption of the labor (work-hour per part) is the sum of each process total time calculated with an additional 25% of the manufacturing process time.

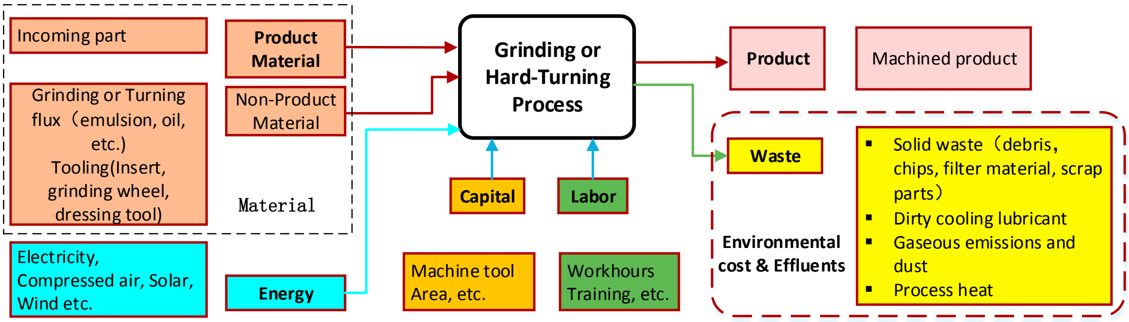


Fig.3 Production indicators of grinding and hard-turning process

Table.4 Resource consumption in the manufacturing process. (m_i)

			Scheme 1			Scheme 2		
			①	②	③	①	②	③
Labor		Process time (min)	6	6	7.5	3	3	3
		Total time (min)）	7.5	7.5	9.375	3.75	3.75	3.75
		Work hour per part (h)		0.406			0.188	
Capital		Machine type	MK2110		MK1320		CY CTC40100	
		Machine price (CNY)	72,000		84,000		460,000	
		Annual maintenance (CNY)	2,160		2,520		13,800	
		Annual depreciation (CNY)	4,800		5,600		30,667	
		Floor area (m^2)	8		7		30	
		Factory rental costs（CNY/m^2.yr）			360			
		Equivalent total cost per part（CNY）		1.642			4.056	
Material	Product	Steel (kg)			0.173			
	Non-product	Wheel or insert (pc)	0.067	0.042	0.003	0.010	0.017	0.013
		Coolant (L)	0.010	0.010	0.013	0.007	0.007	0.007
		Water (L)	0.200	0.200	0.267	0.133	0.133	0.133
Energy		Mean power (kw)	2.1		2.8		4.8	
		Process energy consumption (kwh)	0.21	0.21	0.35	0.24	0.24	0.24
		Energy consumption per part (kwh)		0.77			0.72	
Environment		Waste cutting fluid per part (L)		0.7			0.42	
		Iron scrap per part (kg)		0.173			0.173	
		Waste wheel or tool per part (pc)	0.067	0.042	0.003	0.010	0.017	0.013

In capital, the machine tools and the factory site cost (Equivalent total cost per part) is evaluated in CNY. The machine tool costs is include two parts: machine depreciation cost and machine maintenance cost. The depreciation cost per work-hour is calculate as the machine tool total dividing the total 15 years (15*2008 = 30120h); the maintenance cost per work-hour is calculate as 3% of machine tool acquisition cost dividing the work-hours per year (2008 work-hours). The machine tool cost per part is calculated by multiplying the cost per work-hour and the work-hour per part. The factory site cost per part is calculated same as the machine tool cost, the floor area multiplying the rental cost per work-hour, where the rental cost per work-hour is calculated by annual rent cost dividing the work-hours per year (2008 work-hours).

The product material is the semi-finished product of the preceding process, and the output product is the semi-finished product of the subsequent process. In this paper, it assumes the input material is the net loss amount of product.

The weight of the preceding process semi-finished product is 8.834kg, the weight of the finished product this process is 8.661kg, that is, the product material input is 8.834-8.661=0.173kg. The amount of cutting inserts, grinding wheel, coolant fluid is calculated as the average consumption from a 3000 pieces production. The amount of CBN grinding wheel consumption is calculated as the mean value of total consumption including newly purchase and abrasive re-plating deposition when abrasive thickness down to 20% of the original thickness.

The energy is calculated by process mean power multiplying the process time. For environmental input, the cutting fluid and tool damage is completely damaged, and the amount of non-product input corresponds to the input.

4.3. Data process

The extended carbon-emission factor of this case is shown as Table.5. According to equation (2), the Ex-CDE value can be calculated. The Ex-CDE of Scheme 1 and Scheme 2 are calculated, shown in Table.6, they are 3.741 and 3.697 respectively. If labor and capital not considered, the traditional CDE value (excluding labor and capital) are 1.490, 1.295 respectively. The Ex-CDE pie chart of each resource is shown as Fig.4.

Table.5 Extended carbon-emission factor (EF_i)

	Labor	Capital	Material						Energy	Environment	
Factor	EF_{lab}	EF_{cap}	Steel	Wheel	Insert	Cutting fluid	Grinding fluid	Water	Electricity	Waste fluid	Iron scrap
unit	$kgCO_2e/h$	$kgCO_2e/CNY$		kg- CO_2e/kg			$kgCO_2e/L$		kg CO_2e/kWh	$kgCO_2e/L$	$kgCO_2e/kg$
value	3.887	0.410	2.69	33.7	29.6	2.85	0.978	0.19	0.70285	0.2	0.361

Table.6 CDE and Ex-CDE（kgCO2e）

Scheme	Labor	Capital	Steel	Tool	Coolant	Water	Energy	Waste Fluid	Iron scrap	CDE	Ex-CED
1	1.579	0.673	0.465	0.242	0.033	0.006	0.541	0.140	0.062	1.489	3.741
2	0.729	1.674	0.465	0.116	0.057	0.004	0.506	0.084	0.062	1.294	3.697

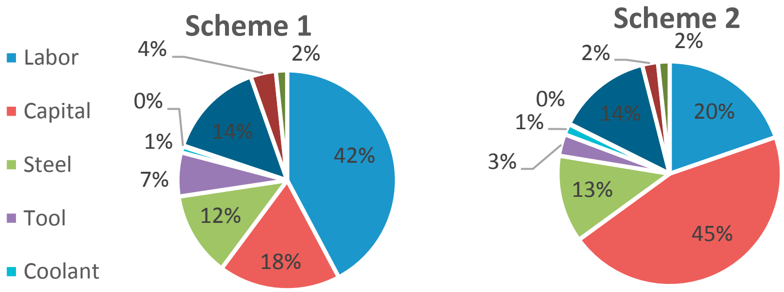


Fig.4 The Ex-CDE pie chart of each resource

4.4. Results and conclusion

The comparative analysis shows that the sum of labor and capital's Ex-CDE value in both schemes accounting for more than 60%. In **Scheme 2**, the total Ex-CDE value of slightly lower than **Scheme 1,** and its CDE value is lower. The reason is that **Scheme 1** is a labor relatively dense production and the equipment investment demand is lower. And then, only considering the traditional environmental impact (by referring its CDE value), the **Scheme 2** is better, but when considering the capital and labor's Ex-CDE, the both schemes are roughly equal. It is because that less capital or less labor means more sustainable.

5. Conclusions

Based on the current CFP method, this paper proposes an ECEA method, by which the capital and labor indicators can be calculated as Ex-CDE. As the labor, capital, material, energy and environment inputs are accounted as the unified unit of measurement, it can be used for manufacturing process environment evaluation and optimization. The case study shows that the ECEA method comprehensively considers labor, capital, materials, energy and the environment, etc., which can reduce miscalculation of taking labor-intensive or capital-intensive production methods as the best environmental impact.

The impact of economic benefits is not considered in the method of this paper. The comprehensive evaluation and analysis of the environmental and economic benefits of the manufacturing process should be carried out in the actual analysis. And the weights of factors is to be considered to distinguish importance of different factors, such as environmental or resource penalties. These will be researched in follow-up study.

Acknowledge

The project was supported by Construction, Reference Implementation and Verification Platform of Reconfigurable Intelligent Production System, China (2017YFE0101400).

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