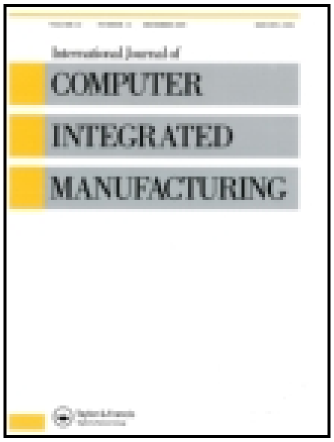

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As the most important and controversial phase of life cycle assessment, life cycle impact assessment (LCIA) has drawn the most attention. How to reflect the spatial characteristics of environmental impacts have become a significant problem, which is urgently needed to be solved to improve the transparency and the reliability of LCIA, especially for the distinct diversity of environments in China. Based on the multi-environmental spatial dimension, this paper proposes a new LCIA method under the framework of ISO14040. First, pollutants released or materials consumed in the life cycle of a product are related to spatial characteristics in order to reflect the diversity of the regional environment. The calculation method of the space characteristic coefficient is presented by analysing the endurance capacity of the regional environment and environmental standards. Second, midpoint and endpoint categories are combined and their relationships are discussed according to the environmental mechanism. Third, normalisation references are proposed that can reflect the latest and most detailed knowledge of environmental science. Also, the distance-to-target method is selected as the weighting method and a single index could be obtained after the weighting. Finally, this LCIA method is employed to study electro-motors in China.

Keywords: life cycle impact assessment (LCIA); multi-environmental spatial dimension; space characteristic coefficient; impact categories

1. Introduction

Life cycle assessment (LCA) has rapidly developed and is internationally used as a life cycle engineering technique in industry and by authorities (Wanyama *et al*. 2003). Life cycle impact assessment (LCIA) is the most important phase of LCA, which aims at evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

LCIA methodologies were developed in the early nineties. In order to reduce the confusion between different methodologies, the ISO 14040 standard came up with some basic principles, which are not detailed standardisation. In recent years, especially in Europe, some groups have presented their methods based on different backgrounds.

Global manufacturing increasingly faces decision challenges of how to better manage the dependencies between different activities that take place either locally or across different locations (Liu *et al*. 2011). Results of environmental impacts of production are different with different enduring effects on the environmental impacts in different regions. However, few available LCIA methods fulfil the increasing demand for reflecting spatial characteristics (Jolliet *et al*. 2003). Most of the LCIA systems were developed based on environmental data pertinent to one specific region such as Europe or America. Hauschild *et al*. (2008) analysed several influential LCA methodologies, including Eco-indicator 99, CML 2000 and EDIP 2003.

Due to the rapid and continuing growth of China's economy, China has become the major manufacturing base for the world market. This also brought about a rapidly deteriorating environment at the national level and serious environmental problems that are being found in numerous industrial parks in China. Therefore, the environmental impact of products should be urgently examined in China. However, Yang and Nielsen (2001) as well as Li *et al*. (2008) pointed out that there are no suitable LCIA methods for China because of the region-specific nature of environmental problems and the lack of basic data.

2. Knowledge of prior work

According to the location of impact category indicators in the environmental mechanism, there are two types of LCIA methodologies: the midpoint approach and the endpoint approach (Bare *et al*. 2000, Heijungs

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et al. 2003). The former describes the environmental impacts of the product by midpoint parameters which are related to facts and phenomena, such as CML2000 and EDIP (Guinee *et al.* 2002, Hauschild and Potting 2005). The midpoint parameters are calculated in the environmental model, so their uncertainty is low. The endpoint approach directly reflects problems of humans and society by endpoint parameters, such as health and ecosystem quality. These approaches are based on background information in order to assess the actual precise damage (Steen 1999, Goedkoop and Spriensma 2001). However, application of these technologies may be costly and time-consuming. Hayashi *et al.* (2006) and Rosenbaum *et al.* (2007) tried to merge midpoint and endpoint models in a consistent framework to combine the advantages of both concepts. In most methodologies, space is only divided into global, region and local types (Hauschild *et al.* 2008), which are embodied in the normalisation process by choosing different normalisation references. However, these spatial characteristics are not presented in the calculation of category indicator results. Furthermore, the impacts in different areas caused by the same LCI result cannot be distinguished in the midpoint approaches. Even in endpoint approaches, the three spatial types are not sufficient to reflect the true impacts in a complicated environmental region such as China.

Normalisation and weighting are optional elements of LCIA in ISO 14040. The normalisation references used in the EDIP method are the impacts to which society exposed the environment in the year 1990. Moreover, the weighting factors are fixed on the basis of the political reduction targets for the impact categories in question. Yang and Nielsen (2001) proposed a method of China product's LCIA based on EDIP before the issuance of ISO standards. They chose the year 1990 as the normalisation reference and defined the weighting system under the object of the environmental policies in 2000. The uncertainty of this method is high because lots of basic data are lacking and pollutants are inadequately represented in the inventory. Due to these deficiencies in the existing LCIA methods, this study focused on classification, characterisation and normalisation, which are suitable for a China-oriented LCIA methodology of products.

3. An LCIA method based on the multi-environmental spatial dimension

This method includes five steps: space analysis, classification, damage analysis, normalisation and weighting. The framework of the LCIA method is illustrated in Figure 1.

3.1. *The division of environmental spaces*

In the life cycle of products, from raw materials extraction to different disposal after the lifespan, the

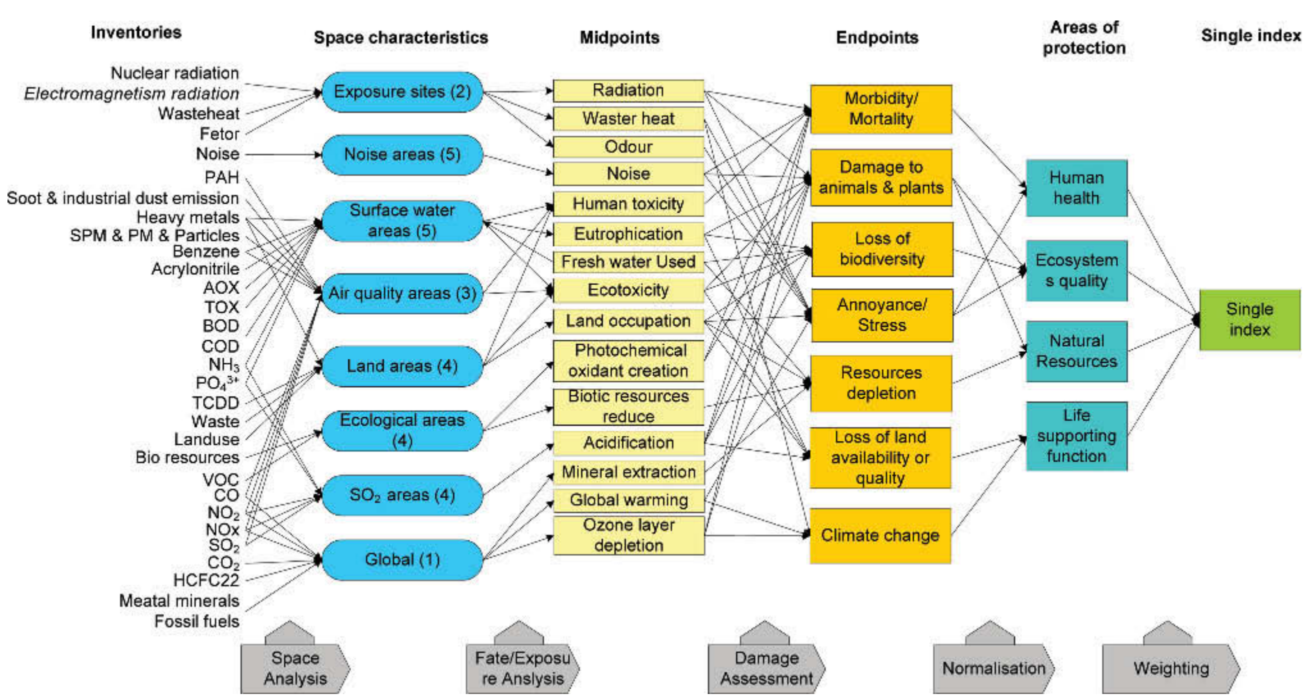

Figure 1. The framework of the LCIA method.

LCI mainly includes four types: resources depletion (e.g. water, land, materials and energy), impacts matters (e.g. CO_2, SO_2 and NO_X), toxicity matters (e.g. benzene and heavy metals) and annoyance/stress matters (e.g. noise and fetor). Most of the environmental impacts of these inventories are related to regional characteristics. Hence, environmental spaces should be considered in the LCA processes and their types should be classified according to the LCI and the categories.

In order to apply a comparable scale to reflect the spatial characteristics of the impact categories, the environmental spaces were divided into eight types, as shown in the Figure 1. The eight environmental space types are as follows: exposure sites, noise areas, air quality areas, surface water areas, land areas, ecological areas, SO_2 and acid rain control areas and global type. The relations of space types, life cycle inventories and the midpoint impact categories also shown in Figure 1, are many-to-many relations.

Every environmental space can be subdivided into some functional areas according to China region-specific and environmental standards, as shown in the Table 1. Because the internal mechanism between the environment and space cannot so far be thoroughly understood, the environmental standards of China are the most appropriate references for the division of environmental space types, such as environmental quality standard for noise (GB3096), surface water (GB3838), soils (GB15168), ambient air quality standard (GB3095) and emission standard of air pollutants for thermal power plants (GB13223). Gao (1995) discussed the division of ecological areas in China.

3.2. *The environmental spatial characteristic coefficient*

In the processes of the LCA, the space characteristics must be quantified and should be reflected in the calculation of the characterisation. Considering the LCI processes which include spatial information, we can imitate the application of characterisation factors and use the environmental spatial characteristic coefficients (SCCs) in the statistics of LCI data.

Table 1. Environmental space types.

Space types	Functional areas	Identifier
Exposure site	Non workplace	0
	Workplace	I
Noise areas	Especially keeping quiet, e.g. sanatorium, nature reserve	0
	Keeping quiet, e.g. school, hospital, office	I
	Keeping quiet at house, e.g. business, residential area	II
	Need to prevent industrial noise, e.g. factory, warehouse	III
	Need to prevent traffic noise, e.g. neighbourhood traffic roads	IV
Air quality areas	Nature reserve areas, scenic areas, sanatorium	0
	Residential area, business area, rural area, general industrial park, indoors	I
	Special industrial park, traffic hub	II
Surface water areas	Nature reserve areas, headwaters	0
	Primary headwater region, rare hydrobiont habitat, spawn areas	I
	Secondary headwater region, fishery, swimming water areas	II
	Industrial water, non-exposure amusement water	III
	Waste water, sewage	IV
Land areas	Soil quality needs to be kept at natural background level, e.g. nature reserve areas, headwater region	0
	Soil quality is not a hazard for persons, plants and environment, e.g. farmland, meadow	I
	Soil quality could only sustain plants growth	II
	Areas used for residential, commercial purposes and general industrial purposes	III
Ecological areas	Nature reserve areas, Qinghai-Tibet plateau, Southwest plateau	0
	Northwest plateau The three north shelterbelt areas, prairie region, scenic areas	I
	Rural areas, non industrial cities, areas used for residential or commercial purposes	II
	Industrial cities	III
SO_2 and acid rain control areas	East of China	0
	Midland of China	I
	Northwest of China	II
	Southwest of China	III
Global	No subdivision	0

The environmental SCC is an indicator, a relatively easy method, which reflects the differences of the endurance capacities of environment impacts in the areas. The coefficient is the ratio of the limits for environmental endurance capacities between the assessment area and the norm area. Functional areas that have strong endurance capacities for environment impacts are generally chosen as the reference norm spaces. The bigger the numerical value of the coefficient is, the weaker the environmental endurance capacities.

The environmental SCC is calculated via comparing the target limits to the reference limits in standards, as follows:

$$\mathrm{SCC} = \left(\frac{\mathrm{SLR}_{\mathrm{avg}}^2 + \mathrm{SLR}_{\mathrm{max}}^2 + \mathrm{SLR}_{\mathrm{min}}^2}{3}\right)^{-\frac{1}{2}} \tag{1}$$

where SLR_{avg} is the average single limit ratio of the impacts and SLR_{max} is the maximum single limit ratio. For the global categories such as mineral extraction, global warming and ozone layer depletion, the value of SCC is 1.

The SLR_{avg} can be calculated as

$$\mathrm{SLR}_{\mathrm{avg}} = \frac{\sum_i \frac{\mathrm{SL{-}LS}_i}{\mathrm{SL{-}MS}_i}}{\mathrm{n}}, \tag{2}$$

where SL_MS_i is one single limit of reference standard, SL_LS_i is the single limit of local standard and n is the limit item's number.

The maximum single limit ratio (SLR_{max}) is presented as

$$\mathrm{SLR}_{\mathrm{max}} = \frac{\mathrm{SL\_LS}}{\mathrm{SL}_{\mathrm{min}}}, \tag{3}$$

where SL_{min} is the minimum single limit of the impact and SL_LS is the single limit of local standard or background datum.

The minimum single limit ratio (SLR_{min}) is presented as

$$\mathrm{SLR}_{\mathrm{min}} = \frac{\mathrm{SL\_LS}}{\mathrm{SL}_{\mathrm{max}}}, \tag{4}$$

where SL_{max} is the maximum single limit of the impact.

In the life cycle of products, various contaminations are released into the ambient air. The air qualities of the local environment are divided into three functional areas according to the ambient air quality standard of China (GB3095), as marked 0, I and II in Table 1. The SCCs of air quality areas can be calculated using the earlier method, as illustrated in the Table 2.

From Table 2, we can see that the SCCs of air qualities are different in different functional areas which can cause different results of the category indicator under the same release of contaminants. These different impact results are in accorded with actual environmental phenomena.

Similarly, the environmental spatial scale coefficients of the other space types can be calculated, as listed in Table 3.

3.3. *Classification*

The released pollutants and consumed materials in the inventory can be attributed to 15 impact categories at the midpoints level, as illustrated in the Table 4. The environmental impacts of the same kinds of products can be compared at

Table 2. The spatial characteristic coefficients of air quality areas.

Contamination items	Concentration limits[1] (mg/m^3)			SLR_{avg}		SLR_{max}		SLR_{min}		SCC	
	II[2]	I	0	I	0	I	0	I	0	I	0
SO_2	0.25	0.15	0.05	0.76	0.624	1	1	0.6	0.2	1.244	1.449
TSP	0.5	0.3	0.12								
PM10	0.25	0.15	0.05								
NO_x	0.15	0.1	0.1								
NO_2	0.12	0.08	0.08								
CO	6	4	4								
O_3	0.2	0.16	0.12								
Pb	0.001[3]	0.001[3]	0.001[3]								
B[a]P	0.01	0.01	0.01								
F	0.007	0.007	0.007								

Note: [1]The average concentration limits in a day except for Pb. [2]The norm standard and the SCC of class C areas is 1. [3]The average concentration of Pb in a year.

Table 3. Environmental spatial characteristic coefficients.

Space types	Functional areas	SCC
Exposure site	0	2.003
	I	1
Noise areas	0	1.451
	I	1.303
	II	1.183
	III	1.084
	IV	1
Air quality areas	0	1.449
	I	1.244
	II	1
SO_2 and acid rain control areas	0	2.209
	I	1.617
	II	1.209
	III	1
Land areas	0	8.707
	I	3.116
	II	1.831
	III	1
Ecological areas	0	9.35
	I	2.806
	II	1.433
	III	1
Surface water areas	0	2.472
	I	1.629
	II	1.547
	III	1.395
	IV	1
Global	0	1

midpoint levels. For the different kinds of products, the environmental impacts must be compared via endpoints. These seven endpoint categories are related to 15 midpoints under the environmental mechanism.

In order to calculate the potential contribution to impact categories, many equivalents have been chosen for the substances and the equivalency factors which have been accepted by most researchers in the environmental assessment of products. However, some categories such as eco-toxicity, human toxicity and biotic resource reduction are related to lots of substances that are emitted from a product system. The impact properties of each individual substance depend on many factors including the amount and the circumstances of emissions and the people or situation concerned. There are no equivalencies factors commonly internationally accepted for these categories which can express the substances' impact potentials (Hauschild and Wenzel 1998).

3.4. Calculation of environment impact potential

The category indicator result (CIR) can be calculated as

$$\mathrm{CIR}_{\text{midpoint category}} = \sum_i \mathrm{LCIR}_i \times \mathrm{SCC}_i \times \mathrm{CF}_i, \tag{5}$$

where LCIR is the result of life cycle inventory in the environmental space, SCC is the spatial characteristic coefficient and CF is the characterisation factor.

3.5. The normalisation system

To make a comparison of the various environmental impacts from a product system, it is necessary to compare them with a common reference. The reference must be an impact on the environment, which is common to all impact categories and with known consequences for the environment.

It is important to involve the latest and detailed knowledge of environmental science for the normalisation reference. Since the year 1990, many data and some theories have changed. Especially in China, lots of environmental statistic that could not be obtained in 1990 can be found at the National Bureau of Statistics of China or local government. Therefore, the year 2000 has been chosen as the reference year in this method.

The environmental impact potential per person in the 2000 year ($\mathrm{EIP}_{\mathrm{RN},2000}$) is presented as

$$\mathrm{EIP}_{\mathrm{RN}2000} = \frac{\mathrm{EIP}_{j,2000}}{\mathrm{POP}_{2000}}, \tag{6}$$

where $\mathrm{EIP}_{j,2000}$ is the total impact potential of the j impact category. Pop_{2000} is the population of China for the regional impact categories and population of the world for the global categories in the year 2000.

Therefore, the impact potential of a product on the j category in the life cycle can be expressed as

$$\mathrm{EIP}_{\mathrm{PN},j} = \frac{\mathrm{CIR}j}{T \times \mathrm{EIP}_{\mathrm{RN},2000}}, \tag{7}$$

where $\mathrm{EIP}_{\mathrm{PN}}$ is the impact potential of the product after normalisation, and T is the life cycle of the product.

3.6. Weighting

The distance-to-target method is selected as the basic weighting method due to its capability of integrating policies in the weighting system. Based on this, the latest environmental policies and economic target in China's 11th Five Year Plan and China's National Mid-term and Long-term Development Plan can be included to obtain the reduction target, and then the relevant weighting factors are elicited by the quotient between the reference levels and the target levels.

The weighting factor (WF) is defined as the ratio of the impacts potential for the actual emissions in 2000 to the impacts potential for the target emissions in the year 2010.

$$\mathrm{WF}_j = \frac{\text{Impacts potential for actual emissions in reference year (2000)}}{\text{Impacts potential for target emissions in target year (2010)}}, \tag{8}$$

So, the environmental impact index (EII) can be calculated as

$$\mathrm{EII} = \sum_j \mathrm{EIP}_{\mathrm{PN},j} \times \mathrm{WF}_j, \tag{9}$$

4. Case study

As the major manufacturing base for the world market, China's electromechanical products are mainly power accessories for lots of machines. The electric power consumed by these motors is about 50% of the total power in China (Zhao 2007). So, the environmental impacts are should be seriously considered.

A kind of electromotor (type: Y80M1-4-0.55), Y80 for short, has been analysed using the method presented earlier. This motor's power is 0.55 kW and is manufactured by a factory in Yantai, which has two branches related to Y80 located in Rongcheng and Suzhou. This motor is mainly used in blower fans, water pumps and other small sized machines.

4.1. *The defined scope of Y80 LCA*

This study mainly analysed three life cycle stages of Y80, raw materials acquisition (including electricity production), manufacturing and usage, as shown in Figure 2. The other stages are not considered because of lack of enterprise sales data and discarded data.

There are nearly 30 parts in Y80 and its raw materials include steel, aluminium, copper and a little

Table 4. The midpoint categories and endpoint categories.

Midpoint categories	Category indicator result	Endpoint categories
Radiation	Radiant intensity equivalency (SV, Joules per kilograms)	Morbidity/mortality; damages to animals and plants; annoyance/stress
Waster heat	Joules per functional unit	Annoyance/stress; climate change
Odour	Kilograms of C_4H_8S equivalents per functional unit	Annoyance/stress
Noise	Equivalent continuous A-weighted sound pressure level [dB(A)]	Morbidity/mortality; damages to animals and plants; annoyance/stress
Human toxicity	Kilograms of equivalent substances emitted to air, water and soil.	Morbidity/mortality
Eutrophication	Kilograms of nitrogen equivalents per functional unit	Damages to animals and plants; loss of biodiversity; loss of land availability or quality
Fresh water used	Kilograms of fresh water equivalents per functional unit	Loss of biodiversity; resources depletion
Eco-toxicity	Kilograms of equivalents emitted to air, water and soil	Damages to animals and plants; loss of biodiversity; loss of land availability or quality
Land occupation	Square meters of cultivated land equivalents per functional unit	Loss of biodiversity; annoyance/ stress; resources depletion; loss of land availability or quality
Photochemical oxidant creation	Kilograms of C_2H_4 equivalents per functional unit	Morbidity/mortality; damages to animals and plants
Acidification	Kilograms of SO_2 equivalents per functional unit	Morbidity/mortality; damages to animals and plants; loss of land availability or quality
Mineral extraction	Kilograms of iron equivalents per functional unit	Resources depletion
Global warming	Kilograms of CO_2 equivalents per functional unit	Annoyance/stress; climate change
Ozone layer depletion	Kilograms of CFC–11 equivalents per functional unit	Morbidity/mortality; damages to animals & plants; Climate change

rubber and plastic. Eighty percent of the whole motor is made from metal. The other materials, such as insulating material, sealing material and plastic, are little, and are not analysed in this paper.

In the manufacturing stage, the data of emission gases were distributed according to the working hours and materials consumption after air pollutants in the workshop were measured. The difference of environmental impacts on persons and time were not considered in this study.

4.2. Analysis of the life cycle scenarios and environmental spatial characteristics of Y80

The rough casting parts, such as the motor frame and terminal box, were produced in the casting factory and finished in the motor factory. And the other parts were manufactured in the factory including machining, insulating, painting and assembling. Life cycle scenarios and their probability of Y80 are shown in Table 5.

Environmental spaces of Y80 include resource areas, air quality areas, surface water areas, land areas, ecological areas, SO_2 areas and noise areas. Environmental spatial characteristics are shown in Table 6.

4.3. Life cycle inventory analysis of Y80

Metal materials consumption was calculated according to the parts' net weight as shown in Table 7 because metal chips can be almost completely recovered and reused. These metals were classified by general

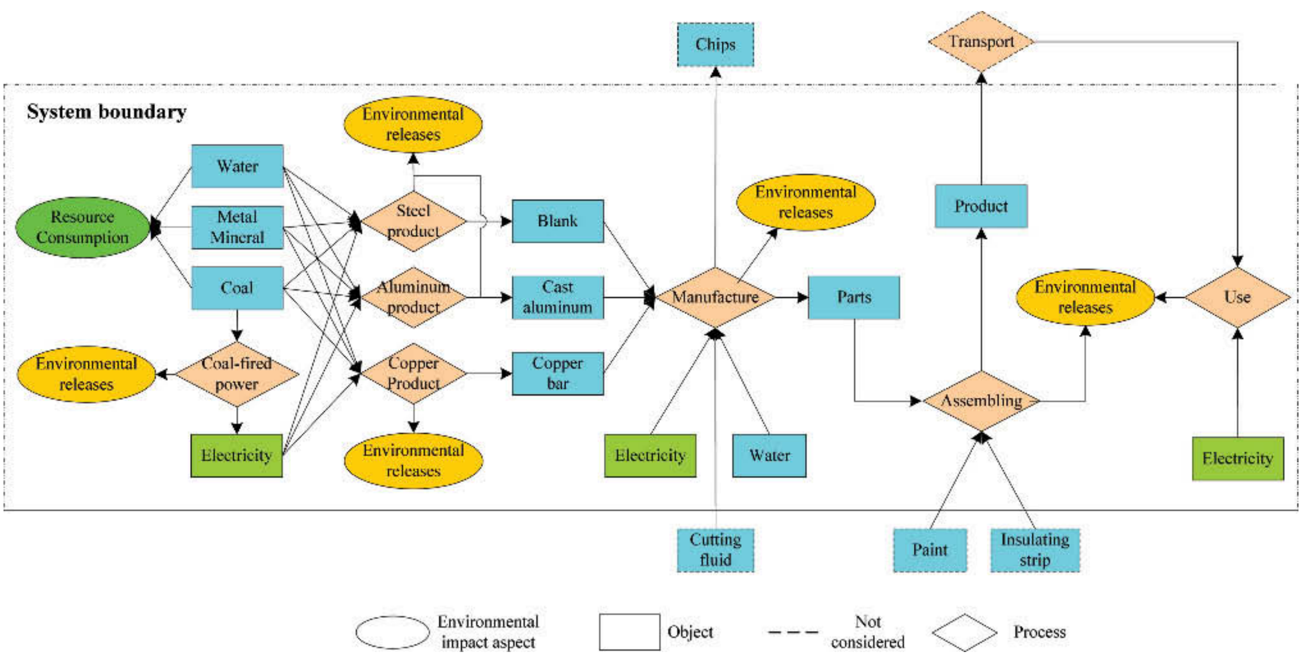

Figure 2. The system boundary of Y80 LCA.

Table 5. Life cycle scenarios and statistical probability of Y80.

Life cycle stages	Sites			Persons	Ambient
Raw materials acquisition, t_1					
Steels	Shandong 0.6	Jiangsu 0.2	Shanghai 0.2	Workers	Industrial park 1.0
Coppers	Shandong 0.4	Henan 0.3	Jiangsu 0.2	Workers	Industrial park 1.0
Aluminium	Shandong 1.0	–	–	Workers	Industrial park 1.0
Manufacturing, t_2					
Cast irons	Rongcheng 0.5	Yantai 0.3	Jiangsu 0.1	Workers	Industrial park 1.0
Machining	Rongcheng 0.8	Suzhou 0.2	–	Workers	Urban areas 1.0
Cooling fan	Rongcheng 0.4	Jiangsu 0.6	–	Workers	Urban areas 1.0
Standard parts	Rongcheng 0.5	Jiangsu 0.5	–	Workers	Urban areas 1.0
Use, t_4					
Blower fans	Shandong 0.1	Hebei –	Jiangsu 0.1	Patients	Hospital 0.3
Machines	Shandong 0.1	Shanxi 0.1	Jiangsu 0.1	Workers	Urban areas 0.3
Water pumps	Shandong 0.2	Henan –	Jiangsu 0.1	Farmers	Rural 0.2

Table 6. Environmental spatial characteristics of Y80.

Environmental impact factors	Life cycle stages	Spatial areas	Environmental spatial characteristic coefficients
Mineral resource	Mineral extraction	0	1
Coal resource	Mineral extraction	0	1
Water resource	Raw material acquisition	III	9.62
	Thermal power	III	9.62
	Manufacturing	III	9.62
Air pollution	Raw material acquisition	I	0.6194
	Thermal power	II	0.6194
	Manufacturing	I	1
Acidification and SO_2	Raw materials extraction	II	1.209
	Thermal power	II	1.209
	Manufacturing	I	1.617
Water pollution	Raw material acquisition	IV	0.717
	Thermal power	IV	0.717
	Manufacturing	III	1
Land pollution	Raw material acquisition	V	0.015
	Thermal power	V	0.015
	Manufacturing	V	0.015
Noise	Manufacturing	V	0.845
	Usage	III	0.916

Table 7. The metal mineral consumption of Y80.

Metals	Parts	Net weight (kg)	SCC	Fe equivalent factor	Consumption (kg.Fe/Kw)
Steel	Silicon steel sheet	6.9	1	1	33.956
	Shaft	1.62			
	Frame	7			
	End cover (two)	2.56			
	Standard parts	0.036			
	Terminal box cover	0.56			
Aluminium	Cast aluminium	0.28	1	0.88	0.448
Copper	Enamelled wire	1.02	1	4.86	9.013

Table 8. The energy consumption of Y80.

Stages	Electricity (kwh)	Coal (kg)	Heavy oil (kg)	Steam (kg)	Coal gas (m^3)	Standard coal (kg)
Raw material extraction	38.081	48.872	0.335	4.225	0.305	51.476
Manufacturing	7.64	–	–	–	–	3.087
Usage	28,000	–	–	–	–	11,312
Total	28045.721	48.872	0.335	4.225	0.305	11366.563

categories and not subdivided, for example, 45, HT150 and silicon, are regarded as simply steel.

Thermal power is the main type in China's electricity structure which generates 80% of the total energy, especially in Shandong Province. So, thermal power is regarded as all electricity consumption in the life cycle of Y80. The energy consumption is shown in Table 8. The energy consumption data of the raw materials came from official documents (Di *et al*. 2005, Jiang *et al*. 2006, Wang *et al*. 2006, Zhang and Wu 2009).

Fresh water used is shown in Table 9. Only new water was calculated in the inventory. The data of new fresh water used in raw material acquisition are from the documents (Wang *et al*. 2006, Zhang and

Table 9. Fresh water used for Y80.

Life cycle stages	New fresh water used	Fresh water used (m^3/kw motor)
Raw material acquisition		
Steel production	5.09 m^3/t	0.173
Aluminium production	21.1 m^3/t	0.011
Copper production	168.09 m^3/t	0.312
Energy production		
Thermal power	3.1×10^{-3} m^3/kwh	8.822
Manufacturing		
Machining workshop	1.25×10^{-3} m^3/kw	0.00125
Punching workshop	1.1×10^{-3} m^3/kw	0.0011
Assembly workshop	1.2×10^{-3} m^3/kw	0.0012
Total		9.322

Table 10. Environmental releases of Y80.

Pollutants	Raw material acquisition						Energy production		
	Steel production		Aluminium production		Copper production		Thermal power		
	Generation rate (kg/t)	Emission (kg)	Generation rate (kg/t)	Emission (kg)	Generation rate (kg/t)	Emission (kg)	Generation rate (kg/kwh)	Emission (kg)	Manufacturing (kg)
CO_2	2250	76.402	2487	1.266	18381.8	34.089	1.07	3044.9	2.66×10^{-3}
SO_2	2.887	9.8×10^{-2}	11.74	6×10^{-3}	1298.1	2.407	9.93×10^{-3}	28.258	1.25×10^{-4}
NO_X	–	–	–	–	54.1	0.1	6.46×10^{-3}	18.383	6.52×10^{-5}
CO	–	–	467.94	0.238	–	–	1.55×10^{-3}	4.411	–
CH_4	–	–	–	–	–	–	2.60×10^{-3}	7.399	–
C_2H_4	–	–	–	–	–	–	–	–	2.61×10^{-3}
NMVOCs	–	–	–	–	–	–	4.87×10^{-4}	1.386	–
Benzene	–	–	–	–	–	–	–	–	2.12×10^{-3}
Smoke	2.216	0.075	1.745	1×10^{-3}	–	–	2.02×10^{-2}	57.483	–
As	–	–	–	–	–	–	2.00×10^{-6}	5.69×10^{-3}	–
Cd	–	–	–	–	–	–	1.27×10^{-8}	3.61×10^{-5}	–
Cr	–	–	–	–	–	–	1.69×10^{-7}	4.81×10^{-4}	–
Hg	–	–	–	–	–	–	8.78×10^{-8}	2.49×10^{-4}	–
Ni	–	–	–	–	–	–	2.50×10^{-7}	7.11×10^{-4}	–
Pb	–	–	–	–	–	–	1.76×10^{-6}	5×10^{-3}	–
V	–	–	–	–	–	–	2.88×10^{-6}	8.2×10^{-3}	–
Zn	–	–	–	–	–	–	2.40×10^{-6}	6.83×10^{-3}	–
SS	0.414	0.014	–	–	–	–	–	–	1.76×10^{-5}
NH^{4+}	0.025	8×10^{-4}	–	–	–	–	–	–	2.15×10^{-4}
COD	0.251	8.5×10^{-3}	–	–	–	–	–	–	1.41×10^{-4}
Phenol	1.7×10^{-4}	1.7×10^{-5}	–	–	–	–	–	–	–
Waste water	–	–	–	–	403.7*t*	0.745*t*	–	–	7.6×10^{-3}
Solid waste	460	15.62	371.22	0.189	228.3	0.423	–	–	–
Dust	91	3.09	–	–	–	–	–	–	0.339

Note: En dashes represent lack data or no emission.

Table 11. The LCIA of Y80.

Impact categories		Equivalents	Units	Category indicator results	Reference values/person/year	Normalization	Weighting	Sustainable indicator
Resources depletion	Mineral depletion	Fe	T	0.0434	15.958	2.72×10^{-4}	0.4	0.21
	Energy consumption	Standard coal	T	11.367	238.967	4.76×10^{-3}		
	Fresh water used	Fresh water	m^3	9.322	1.82×10^{3}	5.12×10^{-4}		
Ecological impacts	Global warming	CO_2	kg	5281.2	4200	0.125	0.3	
	Acidification	SO_2	kg	52.842	13.9798	0.378		
	Eutrophication	NH_3	kg	1.069	88.27	1.21×10^{-3}		
	Photochemical oxidant creation	C_2H_4	kg	19.654	20	9.8×10^{-2}		
	Eco-toxicity	Cr^{6+}	kg	0.081	4.41	1.84×10^{-3}		
Human health effects	Carcinogenicity	Methylbenzene	kg	2.12×10^{-3}	6.53×10^{-3}	3.24×10^{-2}	0.3	
	Respiratory illness	Dust	kg	2.253	3.923	5.74×10^{-2}		

Wu 2009, Ruan *et al.* 2010). The data in energy production are from the literature (Peng and Han 2010).

The main environmental releases of Y80 in its life cycle are listed in Table 10. The release data of the raw materials acquisition and electricity produced were the industry data (Di *et al.* 2005, Wang *et al.* 2006, Zhang and Wu 2009, Ruan *et al.* 2010).

The noise hazard was not included in the LCA of Y80 because the quantitative model of noise impacts is not currently fully developed.

4.4. LCIA of Y80

Environmental impacts of Y80 include resource consumption (metal, electric energy and water consumption), ecological impacts (green house gas emission, ozone depletion and acidification) and the effects on personal health (hearing impairment and respiratory illness).

The capita reference value of photochemical oxidant is 20 kg per year in China which is the same as the European reference in 1990. The water pollutants contain ammonia nitrogen and COD of industrial and living waste water. The results evaluated based on multi-environmental spaces of Y80 LCA are shown in Table 11.

The comparison of results without environmental space characteristics is shown as Figure 3. Four conclusions are drawn from Table 11 and Figure 3 as listed as follows:

(1) Impacts of electricity consumption are most notable, which last through the whole life cycle of Y80 and are mostly provided by coal-fired power. The electricity production releases lots of pollutants, such as SO_2, CO_2, NO_x and dust cause acidification, global warming, photochemical oxidant creation and ozone layer depletion.
(2) Dust is the primary cause of respiratory illness which comes from energy production and casting parts machining. Especially, the dust concentration is high in the machining workshop because of the deficiency of protective equipment and dust extraction.
(3) Water consumption and acidification are obviously different when considering spatial characteristics. The reason is that the sites in the three life cycle stages belong to water deficient areas and SO_2 and acid rain control areas. In terms of photochemical oxidant creation and eutrophication, the impacts are decreased because of the high value of the background environment.

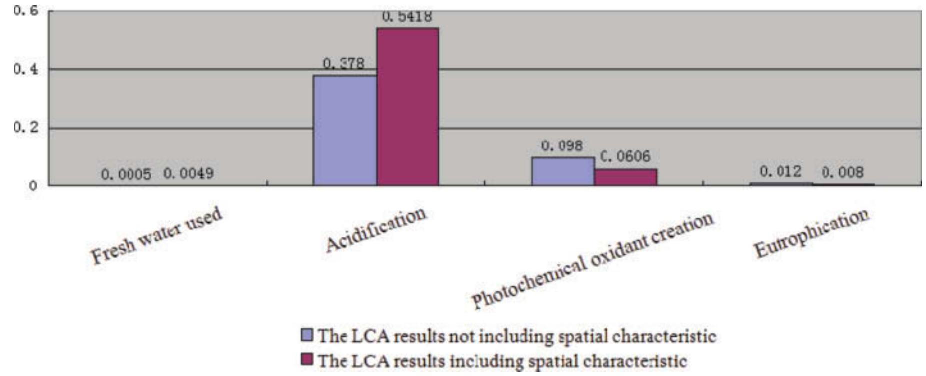

Figure 3. Comparison of two LCA results of Y80.

(4) The concentration of benzene is high in the painting workshop because the motor uses lots of paint such as insulating paint and finishing paint. The personal health effects of paint should not be neglected.

5. Conclusions

This paper tries to unite the midpoints and the endpoints in order to utilise their advantages for different assessment targets. However, further research should be continued such as the relation of midpoints and endpoints, and the indicators of endpoints. The method of multi-space scale partition and the calculation of the spatial characteristics coefficients presented in this paper are based on the China environmental standards and rationally consider the different spatial characteristics of these categories. The impact categories chosen are adaptable to most products especially electromechanical products.

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This paper is extended from the conference paper on the 5th International Conference on Responsive Manufacturing (ICRM) 2010, Green Manufacturing, as follows:

- All the eight environmental space types are listed and discussed in detail.
- The method of SCCs is revised and is applied in the Table 3.
- The SCCs of air quality areas are illustrated by adding Table 2.
- Only the Y80, not two types of motors, is studied and the case study is extended and rewritten.

References

Bare, J.C., *et al.*, 2000. Life cycle impact assessment midpoints vs. endpoints: the sacrifices and the benefits. *International Journal of Life Cycle Assessment*, 5 (5), 319–326.

Di, X., Nie, Z., and Zuo, T., 2005. Life cycle emission inventories for the fuels consumed by thermal power in China. *China Environmental Science*, 25 (5), 632–635.

Gao, M., 1995. An approach to the regionalization of ecological environment in China. *Chinese Journal of Ecology*, 14 (2), 37–43.

Goedkoop, M., and Spriensma, R., 2001. *Eco-indicator 99, a damage oriented method for life cycle impact assessment*. Methodology report. 3rd ed. Amersfoort, the Netherlands: PRé Consultants. Available from: http://www.pre-sustainability.com/content/reports [Accessed 23 February 2012].

Guinee, J.B., Gorree M., Heijungs R., *et al*., 2002. *Handbook on life cycle assessment: operational guide to the ISO standards, series: eco-efficiency in industry and science*. Dordrecht: Kluwer.

Hauschild, M., and Potting, J., 2005. *Spatial differentiation in life cycle impact assessment – the EDIP2003 methodology*. Copenhagen, Denmark: The Danish Ministry of the Environment, Environmental Protection Agency. Environmental News No. 80.

Hauschild, M., *et al*., 2008. *Analysis of existing environmental impact assessment methodologies and indicators related to life cycle assessment* (working draft 0.8). Available from: http://lct.jrc.ec.europa.eu/eplca

Hauschild, M., and Wenzel, H., 1998. Environmental assessment of products. Vol. 2: *Scientific background*. London, UK: Chapman & Hall.

Hayashi, K., *et al*., 2006. Expanded damage function of stratospheric ozone depletion to cover major endpoints regarding life cycle impact assessment. *International Journal LCA*, 11 (3), 150–161.

Heijungs, R., *et al*., 2003. Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. Report of the first project phase: design of the new method Livermore, the Netherlands: Leiden University. Available from: http://www.leidenuniv.nl/cml/ssp/publications/recipe_phase1.pdf [Accessed 23 February 2012].

Jiang, J., *et al*., 2006. Life cycle assessment of metallic copper produced by the pyrometallurgical and hydrometallurgical processes. *Journal of Lanzhou University of Technology*, 32 (1), 19–21.

Jolliet, O., *et al*., 2003. IMPACT 2002+: a new life cycle impact assessment methodology. *International Journal of LCA*, 8 (6), 324–330.

Li, F., Li, J., and Li, J., 2008. A LCIA weighting system based on china environmental policy and local manufacturing industry situation. In: *Proceedings of the 16th IEEE international symposium on electronics and the environment*, 19–22 May, San Francisco, CA. San Francisco, CA: IEEE Computer Society.

Liu, S., Young, R.I.M., and Ding, L., 2011. An integrated decision support system for global manufacturing co-ordination in the automotive industry. *International Journal of Computer Integrated Manufacturing*, 24 (4), 285–301.

Peng, G., and Han, M., 2010. Evaluation and analysis of the crisis level of water resources for thermal power industry. *Refrigeration Air Conditioning & Electric Power Machinery*, 31 (4), 73–78.

Rosenbaum, R., Margni, M., and Jolliet, O., 2007. A flexible matrix algebra framework for the multimedia multipathway modeling of emission to impacts. *Environment International*, 33 (5), 624–634.

Ruan, R., Zhong, S., and Wang, D., 2010. Life cycle assessment of two copper metallurgical processes: bioheap leaching and flotation-flash smelting. *Multipurpose Utilization of Mineral Resources*, (3), 33–37.

Steen, B., 1999. *A systematic approach to environmental priority strategies in product development (EPS), version 2000: general system characteristics*. CPM report. Gothenburg, Sweden: Chalmers University of Technology.

Wang, Z., *et al*., 2006. Life cycle assessment study of aluminum. *The conference of China materials research*, Beijing.

Wanyama, W., *et al*., 2003. Life-cycle engineering: issues, tools and research. *International Journal of Computer Integrated Manufacturing*, 16 (4–5), 307–316.

Yang, J.X., and Nielsen, P.H., 2001. Chinese life cycle impact assessment factors. *Journal of Environment Science*, 13 (2), 205–209.

Zhang, F., and Wu, G., 2009. Life cycle assessment of steel production in China. *Business China*, (12), 173–174.

Zhao, Y., 2007. A summarization of energy efficiency standards for Chinese motor. *Standards Information of the World*, (8), 30–33.