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Study of the environmental impacts based on the "green tax"—applied to several types of building materials

Xing Wu[a,*], Zhihui Zhang[a], Yongmei Chen[b]

[a]*Department of Construction Management, Tsinghua University, Beijing, China*
[b]*Department of Environmental Science and Engineering, Tsinghua University, Beijing, China*

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Abstract

This paper presents a method using building materials' environmental profiles to assess their environmental impacts based on the life-cycle assessment (LCA) framework. In this method, the environmental impacts are categorized and the "green tax" is used to study the inter-seriousness across different categories. The green tax including the pollutant tax and resource tax is the shadow price of pollutants or resources, revealing the social willingness-to-pay (WTP) for them. The green tax of a specific pollutant could be modified if the local special preference is considered. The final assessment result produced by this method represents the social WTP for the environmental impacts of the building material.

Keywords: Environmental impact; Green tax; LCA; Shadow price; WTP

1. Introduction

Buildings have great environmental impacts, and thereinto building materials play an important role. Adalberth investigated a number of Scandinavian buildings, finding that about 20% of energy consumption of a building during its life cycle comes from building materials [1]. Recently, the discussion of "green building" and "green building materials" has gained wider and wider attention. This paper presents the research work of a project financed by the National Science Foundation of China. Part of this research is aimed to use the life cycle assessment (LCA) framework to assess the environmental impact of building materials. Based on the study of Gong [2], who is also a member of the research team and has investigated the embodied environmental profiles, i.e. the pollutant emission profiles and the resource consumption profiles, of a number of building materials (including three types of cement and five types of structure steel manufactured in Beijing), this paper attempts to establish a method using the environmental profiles to assess environmental impacts.

2. LCA framework and weighting approaches

LCA is a well-known method for assessing the environmental impacts of products and services from a cradle to grave perspective [3]. Society of Environmental Toxicology and Chemistry (SETAC) is the first international organization who have studied the LCA principle systematically and put forward a LCA framework—the SETAC Triangle [4]. ISO then also proposed another LCA framework [5]. The first three steps of their frameworks are almost the same: goal and scope definition, inventory analysis, impact analysis. However, the last step in the SETAC Triangle is "improvement assessment" while that in ISO is "interpretation". Investigating the environmental profiles, as Gong [2]

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*Corresponding author. Tel.: +86-10-6277-5928; fax: +86-10-6277-1132.
E-mail address: wuxing98@mails.tsinghua.edu.cn (X. Wu).

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has already done, only completed the first two steps of the LCA procedures. This paper focuses on the third step, also the most important step—the impact analysis, which can be further divided into three substeps:

- Classification: different inputs and outputs are assigned to different impact categories such as acidification, eutrophication etc., based on the expected types of impacts to the environment.
- Characterization: relative contributions of each input and output to its assigned impact categories are assessed and the contributions are aggregated within the impact categories
- Valuation (usually called as weighting): seriousness is weighted across impact categories. Of the above three substeps, this paper focuses mainly on the third, for valuating is thought to be more subjective and thus more controversial.

Weighting approaches can be either quantitative or qualitative. This paper considered to adopt the quantitative one. According to Lindeijer, the quantitative weighting approaches can be further classified into five main groups: proxy, technology, panels, monetization, and distance-to-target [6].

Proxy approaches use a few quantitative measures, stated to be indicative for the total environmental impact [6]. The Ecological Footprint may be a typical technology approach for estimating the biologically productive area necessary to support current consumption patterns [7]. However, these two approaches cannot be seen as a professional weighting method and with little application [8].

In the panel approach, people are asked to judge seriousness across categories subjectively and empirically through questionnaires or face-to-face communications, and the application is then done in the Delphi or Analytic Hierarchy Process such as the studies of Ruby et al. [9] and Ong et al. [10].

The distance-to-target approach is applied in many well-known LCA methods such as the EDIP [11], Eco-Indicator95 [12], etc. For each category, an administrative or "sustainable" target is defined and the distance from the current level to the target is simply thought to be the weighting factor. However it only reveals the inner-seriousness within a category instead of the inter-seriousness across categories. So it is not a real weighting approach essentially [8].

The monetization approach is based on the idea that the seriousness across categories can be measured by money. For example, in the EPS system, the willingness-to-pay (WTP) of today's OECD inhabitants to restore impacts of each category, i.e. the WTP to avoid changes, is applied as the weighting factor and the market price is used for some categories. If the market prices are unavailable in some cases, values can be obtained in an indirect way by using some methods like the travel cost method or the hedonic pricing methods or contingent valuation method [13]. However, this mixture of different valuation methods lacks consistency and seems problematic.

As mentioned, the WTP is normally related to the avoidance of something—somebody is willing to pay some money in order to avoid something. However, the social WTP differs from the individual's WTP for it is relevant to the political environmental monitoring target (limits). Finnveden pointed out that the social WTP can be derived by studying the society's efforts to avoid damage or the costs of reducing emissions to a decided emission limit [8]. At this point, the "green taxes" levied on the emissions or exploited resources are thought to reveal the social WTP for environmental damage and thus can be used as the weighting factors. The Tellus system, for instance, employed a weighting methodology focusing on the social WTP, using both data on emission taxes and marginal costs for reducing emissions down to decided emission limits [14], but only a few kinds of pollutants emitted into air or water were involved and the natural resources were excluded.

With the consideration of the data availability and the easiness of implementation, a modified monetization approach, which has taken into account the distance-to-target factors, is employed in this research.

3. Assessment framework

3.1. Impact categories

In the classification substep of impact analysis, the environmental impacts are allocated to two safeguard areas—ecosystem and resources, and further divided into twelve categories (nine of them are in the safeguard area of ecosystem) as Table 1. It is still controversial whether the human health be a separate safeguard area or belong to ecosystem [15]. However, it is considered here to be included within the ecosystem for convenience. For the safeguard area of resources, classification is more complicated because there are thousands of types of resources in the world, such as water, oil, metal, wood, etc. For building materials only three big families, however, are involved—water, fossil energy sources and industrial mineral resources. Fossil energy sources consist of petroleum, natural gas and coal. The industrial mineral resources considered for manufacturing building materials are iron, aluminum, manganese and limestone.

The substep of characterization is simpler and relatively much less controversial for the potential impacts of a pollutant can be directly measured by experiment or survey. The data of characterization in

Table 1
Environmental impact categories

Impact category	Indicator	Indicator unit
Ecosystem damage		
Globe warming	CO_2	kgeq. C
Ozone layer depletion	CFC-11	ODP kg[a]
Acidification	SO_2	kgeq. SO_2
Eutrophication	NO_3^-	kgeq. NO_3^-
Airborne suspended particles	Airborne suspended particles	kg
Solid wastes	Solid waste	kg
Photochemical smog	C_2H_4	kgeq. C_2H_4
Waterborne toxicities	Lead	kgeq. lead
Waterborne suspended substances	Waterborne suspended substances	kg
Resource depletion		
Depletion of water resources	Water	m^3
Depletion of fossil energy sources	Standard coal	kgeq. SCE[b]
Depletion of industrial mineral resources	Iron/aluminum/manganese/limestone	kg

Note: a. ODP refers to the ozone depleting potential based on the potential of CFC-11; b. SCE is the abbreviation of the term "standard coal energy".

this paper mainly come from Yang et al. [16] except those specified.

Defining the weighting factors is a more difficult job. The weighting factors discussed here reveal the social WTP for the present per unit environmental damage. Assuming that the environmental damage is linear with environmental impacts, it can be measured by the indicator unit of each category, as shown in Table 1. Here the social WTP is based on the "green tax".

3.2. Shadow prices of pollutants

Welfare economists state a point that pollutant emissions cause the external diseconomies because the environment is traditionally thought to be common goods. However, if based on the Coase Theorem, the environment is no longer considered to be common but the society has the exclusive proprietorship of the environment; anyone who discharges pollutants or exploits resources must pay the proprietor for using the environment. The payment is so-called green taxes or environment charge or Pigovian Taxes and the diseconomies can be thus internalized by this payment.

But how to determine the green tax is controversial. In economics, the green tax is thought to be the pollutant's shadow price. Fig. 1 illustrates how the shadow price of a pollutant is determined. The horizontal axis represents the emission volume of the pollutant while the vertical axis represents price. Curve AA refers to the marginal environmental damage caused by the pollutant and Curve CS_0 refers to the polluters' marginal return. Obviously the emission increases with the expansion of production. According to the law of diminishing marginal return, Curve CS_0 is right-handed downwards. The environmental damage discussed here actually means a type of social attitude to emission (or environmental damage). When the emission is little, the society generally pays little attention to an extra unit emission but with the increase of the emission, the social attitude to it becomes more and more intolerant. However, the emission is associated with offering products and services which are necessary for living, so eventually there is a compromise, i.e. the intersecting point of two curves in Fig. 1, indicating the optimal emission level (S_1) and the suitable tax rate (T_1) (i.e. the shadow price). Apparently, the social attitude to the environmental damage becomes less tolerant with the improvement of living standard. The tax level actually reflects the social willingness to accept for the environmental damage.

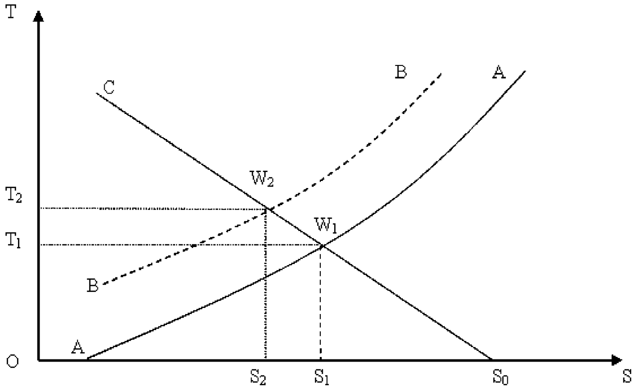

Fig. 1. Determination of the pollutant's shadow price (green tax).

Each five years, the Chinese government revises the administrative emission limits (limits for the annual total emission volume of a series of important pollutants), which is further allocated to each province as the target of the environmental protection. The emission limits set for the year of 2005 was announced in 2002. To achieve the goal of this new national emission limits, the pollution levy system of China was also reformed greatly. Therefore, the tax in the new pollution levy system reveals the present countrywide social WTP for the environmental damage. The pollutant tax rates adopted in this paper are all from CNDPC et al. [17].

Usually, the local social WTP for the environmental damage caused by some specific pollutants is special, e.g. the local limit for sulfur dioxide tends to be stricter in a place if it suffers from acidification severely. This paper takes Beijing as a case to study the special local social WTP. As shown in Table 2, the emission limits of several pollutants prescribed by Beijing administration are much stricter than the national limits, for the living standard in Beijing is almost the highest in the country, and the social attitude towards the environmental damage is also more critical. Thus for some specific pollutants, the tax rates prescribed nationally cannot really reflect that special local social WTP and should be modified according to the local emission limits in order to reflect that special local social WTP.

The modification of the pollutant tax can be illustrated in Fig. 1: Curve AA refers the national social attitude; Point T_1 refers to the national tax rate; Point S_1 refers the national limit; Curve BB refers the special local attitude. So the optimal emission level moves to S_2 (local emission limit) and the reasonable tax rate (shadow price) moves from T_1 to T_2. Since the marginal return is downwards, there must exist a point (S_0) which presents the emission level corresponding to the spontaneous summit of production level if there were no external restrains (e.g. nonexistence of the green tax and other relevant regulations). Assuming the marginal return is linear with emission, we have:

$$\frac{T_2 - T_1}{S_1 - S_2} = \frac{T_2}{S_0 - S_2} \tag{1}$$

$$T_2 = T_1 \cdot \frac{S_0 - S_2}{S_0 - S_1}. \tag{2}$$

To obtain the modified tax T_2, S_0, which means the ideal emission level of 2005 without any external restrains, should be determined first.

Fig. 2 shows the emission scenarios of sulfur dioxide, COD, flue dust, industrial ashes and powders as well as the change of GDP in Beijing from 1985 to 2002. In the 1980s, the environmental issue was not stressed as much as nowadays, so it can be seen that before the early 1990s the emission level ascended gradually with the increase of the GDP. However, peaks appeared in the 1990s and after that, the emissions of these pollutants all descended. The change was the result of effective regulations implemented for the environmental protection.

The emission level is thought to be positively correlative with the GDP without external restrains. So the 2005's ideal emission levels (S_0) can be estimated based on the pre-peak phase of the emission curves shown in Fig. 2, providing that the social attitude to emissions and environmental policy remain the same as in the early 1980s.

Fig. 3 shows an imaginary emission scenario of sulfur dioxide by 2005. If there were no external restrain, by mathematically simulating, the emission volume of sulfur dioxide in 2005 is predicted to be 530,000 tons

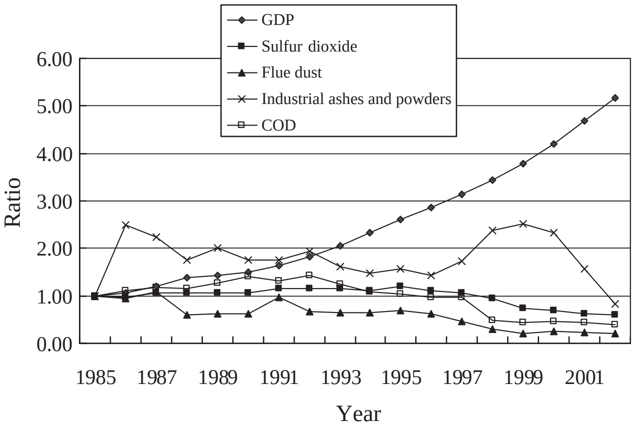

Fig. 2. Emission scenarios of several pollutants and the change of GDP during in Beijing (1985–2002).
Sources: [19], the same to following figures (Figs. 3–6).

Table 2
Emission limits and tax rates of several pollutants in Beijing

Pollutant	National[a] ($\times 10^6$ kg)	Local[a] ($\times 10^6$ kg)	Tax rate[b] yuan/kg	Modified tax rate (yuan/kg)
SO_2	178.1	134.4	0.63	0.71
COD	130.0	107.1	0.70	0.71
NH_3-N	31.0	30.4	0.80	0.89[c]
Flue dust	90.0	60.2	0.28	0.31
Industrial ashes and powders	59	46.9	0.15	0.20

Source: a. [18], b. [17]. *Note*: c. Due to the unavailability of data on ammonia-nitrogen, the modification rate of COD is used for its calculation.

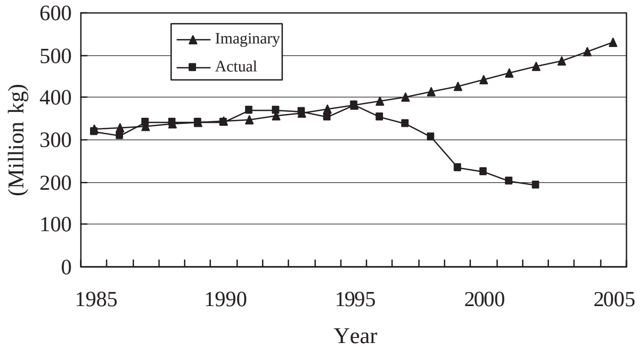

Fig. 3. Emission scenario of sulfur dioxide.

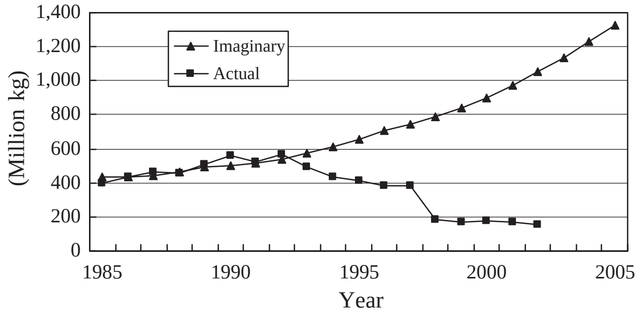

Fig. 4. Emission scenarios of COD.

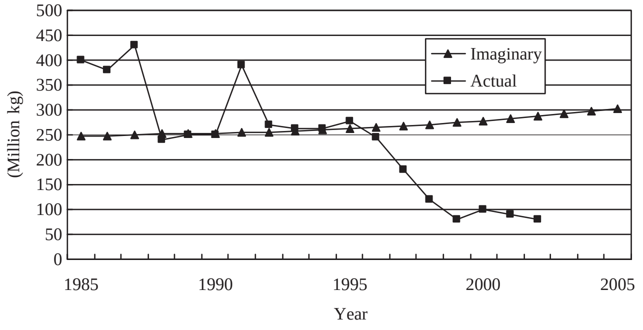

Fig. 5. Emission scenarios of flue dust.

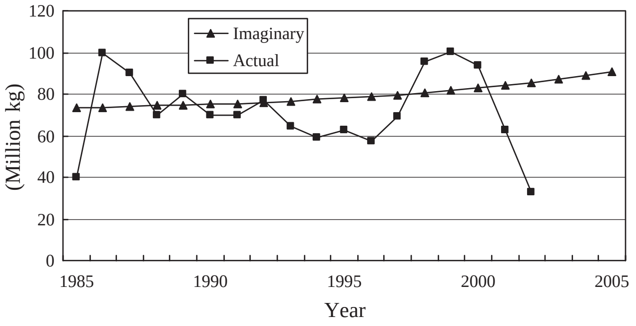

Fig. 6. Emission scenarios of industrial ashes and powders.

(S_0), far beyond the local emission limit (134,100 tons). Similarly, Figs. 4–6 shows the imaginary emission scenarios of COD, flue dust, industrial ashes and powders respectively. According to Eq. (2), the modified taxes can be thus calculated as shown in Table 2, which reflect the special local social WTP for the environmental damage caused by those specific pollutants and are employed when discussing the weighting factor of categories in this paper.

3.3. Shadow prices of resources

In China, exploiting natural recourses need to pay the resource tax, which is also called as "royalty" or "depletion premium", diversified according to the scarcity of resources. The determination of the resource tax is also illustrated by Fig. 1. To do this, let Curve AA refer to the marginal environmental damage due to the depletion of a resource and Curve CS_0 refer to the marginal return from exploiting natural resources. The scarcer a resource is, the greater the marginal environmental damage while the less the marginal return. The resource is a living necessity, so there is also a compromise (intersecting) point, indicating the shadow price of this resource, i.e. the resource tax. The resource taxes adopted in this paper are all from CMF [20].

3.4. Weighting across impact categories

In this paper, the weighting factor is mainly based on the green tax which reveals the social WTP for the environmental damage. While, the polluting potentials of pollutants should also be considered: the stronger the potential of a pollutant, the greater its seriousness. We define the potential coefficient to be the ratio of the potential of a pollutant to the total potentials of all pollutants in an impact category in a year, as

$$e_{ij} = \frac{f_j \cdot a_j}{\sum_j (f_j \cdot a_j)}, \tag{3}$$

where e_{ij} is the potential coefficient of pollutant j in impact category i; f_j the polluting potential per unit of pollutant j, measured by each category's indicator unit; a_j the annual emission volume of pollutant j (the average of the year 2000, 2001 and 2002). Then, the weighting factor of an impact category can be defined as

$$w_i = \sum_j (e_{ij} \cdot c_{ij}), \tag{4}$$

where w_i is the weighting factor of impact category i; c_{ij} the tax rate of pollutant j in impact category i, measured by the each category's indicator unit for consistency.

3.4.1. Globe warming

Globe warming and the ozone layer depletion are worldwide environmental problems. Though having

Table 3
Data of acidiferous pollutants and the calculation of the weighting factor for acidification

Pollutant	Acidiferous potentials[a] (kgeq. SO_2/kg) *a*	Emission volume[b] ($\times 10^6$ kg) *b*	Potential coefficient *c*	Tax rate[c] (yuan/kgeq.SO_2) *d*
SO_2	1	205.6	0.32	0.71
NO_x	0.70	512.7	0.56	0.90
NH_3	1.88	38.0	0.11	0.035

Note: Potential coefficient $c = (a \cdot b)/\Sigma(a \cdot b)$; weighting factor $w = \Sigma(c \cdot d)$ and the tax rate is the modified tax rate. *Source*: a. [15], b. [27], c. [17] (including those modified shown in Table 2), the same to the following tables except those specified.

Table 4
Data of trophic pollutants and the calculation of the weighting factor for eutrophication

Pollutant	Trophic potential (kgeq. NO_3^-/kg) *a*	Emission volume ($\times 10^6$kg) *b*	Potential coefficient *c*	Tax rate (yuan/kgeq. NO_3^-) *d*
NH_3-N	4.01	38.0	0.56	0.22
TP	32	2.6	0.30	0.06
COD	0.23	167.2	0.14	3.13

Note: Potential coefficient $c = (a \cdot b)/\Sigma(a \cdot b)$; weighting factor $w = \Sigma(c \cdot d)$.

signed the UNFCCC[1] and the Kyoto Protocol[2] , China, as a developing country, did not promise any specific quantitative emission-reducing responsibility, i.e. no specific administrative emission limit for greenhouse gases and thus no carbon tax. Therefore, the social WTP for the globe warming cannot be readily obtained.

Fankhauser estimated the total loss caused by the globe warming to be US$ 16.7 billion in China, accounting for 4.7% of GDP in 1988 [21]. And some researchers provided a predictive greenhouse gas emission scenario from 2000 to 2030 in China [22]. According the research there were 893.31 million tons carbon emission in the year of 2000. Assuming the same rate of GDP loss and considering the price changes, the cost (loss) in 2000 is about RMB ¥198.8 billion. Thus, the total social loss distributed to each kilogram carbon is about RMB¥0.22, which to some degree reveals the social acceptable loss due to the nonexistence of carbon tax and other measures. It is a type of social WTP and can be used as the weighting factor of the globe warming.

3.4.2. *Ozone layer depletion*

China has also signed the international convention for protecting the ozone layer and has made the detailed schedule for eliminating the ozone-depleting substance (ODS) [23]. This eliminating program has already been financed by the Multilateral Fund (MF).[3]

Though there is no CFC tax yet, China is in the way of eliminating ODS. According to the World Bank Office in Beijing, 113 projects were carried by 2002, aiming at eliminating 105,064.54 ODP[4] tons of ODS, financed by the MF with a total fund of US$ 202,074,170 [24]. Money invested to these projects can be seen as the social WTP. So the average cost of eliminating ODS is about US$1.92 (RMB¥15.92) per ODP kilogram. This can be used as the weighting factor of the category.

3.4.3. *Acidification*

Different acidiferous pollutant has different potential and sulfur dioxide is the most important acidiferous pollutant. Nitrogen oxide (NO_x) is another important acidiferous pollutant emitted from automobiles or industrial process. For the situation in Beijing, Shen and Zhang predicted the automobile's emission scenario (including carbon monoxide, nitrogen oxide and volatile organ compounds) from 2000 to 2010 [25] and Han et al. made an investigation showing that 40% of nitrogen oxide came from automobiles [26]. Based on these data and according to Eq. (4) (treated in Table 3), the weighting factor of acidification can be estimated to be

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[1] UNFCCC: United Nations Framework Convention on Climate Change.

[2] Kyoto Protocol: Kyoto Protocol to the United Nations Framework Convention on Climate Change.

[3] The Multilateral Fund (MF) is firstly defined in the Montreal Protocol (London Revision) in 1990 and functions since 1991.

[4] ODP means the ozone depletion potential based on the potential of CFC-11.

0.74 (yuan/kgeq.SO_2), meaning the social WTP for per unit damage of acidification is RMB¥0.74.

3.4.4. Eutrophication, airborne suspended particles and solid wastes

Eutrophication, caused by some compounds containing nitrogen and phosphor, is a great hazard to lake, river and offing. In general, total nitrogen (TN), total phosphor (TP), ammonia-nitrogen (NH_3-N) and chemical oxygen demand (COD) in water are the most important trophic pollutants. Using the data in Table 4, the weighting factor of eutrophication is calculated to be 0.58 (yuan/ kgeq.NO_3^-).

Table 5
Data of air suspended particles and solid wastes and the calculation of the weighting factors for them

Pollutant	Emission volume (10^6 kg) *a*	Potential coefficient *b*	Tax rate (yuan/kg) *c*
Flue dust	90.5	0.57	0.31
Industrial ashes and powders	67.6	0.43	0.20
Industrial solid wastes	233	0.07	0.025
Household garbage	3087	0.93	0.06

Note: Potential coefficient $b = a/\Sigma a$, e.g. $0.57 = 90.5/(90.5 + 67.6)$; weighting factor $w = \Sigma(b \cdot c)$.

Airborne suspended particles consist of flue dust and industrial ashes and powders. Solid wastes come from industrial productions and people's everyday life. Their potentials are equivalent if they are in the same mass. According to Table 5, the weighting factors of these two categories are 0.26 (yuan/kg) and 0.06 (yuan/kg) respectively.

3.4.5. Photochemical smog

When hydrocarbon and nitrogen oxide in the air are irradiated by sunlight, and if also combined with vapor, a type of nattier blue smog appears, called the photochemical smog. Photochemical smog is severely harmful to human and plant. Carbon monoxide and volatile organic compounds (VOCs) emitted from automobiles and industrial process are main curses of the photochemical smog. Though nitrogen oxide plays an important role in inducing the photochemical smog, it functions actually only as a catalyst and excluded from this category.

The current pollution levy system only focuses on the emissions from industries, while the emissions from automobiles are not yet involved. The imposed stricter off-gas monitoring criteria on automobiles in Beijing forces people pay more for their cars' off-gas. According to the automobile emission criteria set by Beijing administration, Yang and Wang estimated the corresponding charge levels should be: VOC: 1.30 yuan/kg; CO: 0.30 yuan/kg [28].

Table 6
Data of photochemical pollutants and the calculation of the weighting factor for photochemical smog

	Emission volume[a] ($\times 10^6$ kg) *a*	Photochemical Potential (kgeq. C_2H_4/kg.) *b*	Potential coefficient *c*	Tax rate (yuan/kgeq. C_2H_4) *d*
CO (Automobile)	2233	0.03	0.16	10.00
CO (Industry)	1311	0.03	0.09	1.20
VOC (Automobile)	402	0.6	0.57	2.17
VOC (Industry)	149	0.5	0.18	2.60

Note: Potential coefficient $c = (a \cdot b)/\Sigma(a \cdot b)$; weighting factor $w = \Sigma(c \cdot d)$; *Source*: a. [25] and [26].

Table 7
Data of toxic pollutants the calculation of the weighting factor for waterborne toxicities

Pollutant	Toxic Potential (kgeq.lead/kg) *a*	Emission volume (kg) *b*	Potential coefficient *c*	Tax rate (yuan/kgeq. lead) *d*
Hydrargyrum	500	0	0.00	2.80
Cadmium	10	13	0.00	14.00
Sexivalent chromium	1	137	0.00	35.00
Lead	1	357	0.00	28.00
Arsenic	1	1	0.00	35.00
Cyanide	10	1,980	0.05	1.40
Oil	1	362,333	0.83	7.00
Volatile hydroxybenzene	10	5,183	0.12	0.875

Note: Potential coefficient $c = (a \cdot b)/\Sigma(a \cdot b)$; weighting factor $w = \Sigma(c \cdot d)$.

For emission from industry, however, only the tax on carbon monoxide is available (0.036 yuan/kg). Approximately, the tax on VOCs from industry can be determined as the same as that from automobiles. The weighting factor of photochemical smog is calculated to be 3.41 (yuan/kgeq.C_2H_4) through Table 6.

3.4.6. Waterborne toxicities and suspended substances

Waterborne toxicities are caused by some waterborne toxicoids such as lead, arsenic, etc. They are very dangerous to human health. According to Table 7, the weighting factor of waterborne toxicities is 6.04 (yuan/ kgeq.lead).

Mainly generated from industrial processes, especially from the process of producing building materials, waterborne suspended substances are nontoxic, but they severely harm the water. Only one pollutant—suspended substances (SS) exists in this category, so the weighting factor of this category is just the tax rate of SS—0.175 (yuan/kg) [17].

3.4.7. Depletion of water resources

The water resources are made up of surface water and ground water. The distribution of water is greatly imbalanced. So the water resource fee differs greatly in places, reflecting diverse social WTP for water consumption. Beijing is a city extremely lack of water, so the water resource fee there is pretty high. According to Table 8, the weighting factor is calculated to be 0.56 (yuan/m^3).

Table 8
Data of water resources and the calculation of the weighting factor for depletion of water resources

	Annual consumption[a] ($\times 10^6$ m^3) *a*	Potential coefficient *b*	Water resource fee[b] (yuan/m^3) *c*
Surface water	1,180	0.31	0.35
Ground water	2,593	0.69	0.65

Note: Potential coefficient $b = a/\Sigma a$, e.g. $0.31 = 1180/(1180+2593)$; weighting factor $w = \Sigma(b \cdot c)$. *Source*: a. [29] (average from 2000 to 2002) , b. [30].

3.4.8. Depletion of fossil energy sources

As typical and important unrenewable resources, fossil energy sources consist of coal, petroleum and natural gas. The energy potential of different energy sources are measured by the "standard coal energy". According to Table 9, the weighting factor of this category is estimated to be 3.79E-3 (yuan/ kgeq.SCE).

3.4.9. Depletion of industrial mineral resources

Iron, aluminum, manganese and limestone are important industrial raw materials, especially for producing building materials. The resource tax levied on the ore of iron, aluminum, manganese and limestone are RMB¥17.10, 20.00,2.00 and 2.00 pre ton, respectively [20], used as the weighting factors readily.

3.4.10. Summary

From the above discussion, the weighting factors for all of the 12 categories are estimated and listed in Table 10.

4. Application to building materials

With the established assessment framework, this paper attempts to complete the environmental impact assessment of the building materials based on their environmental profiles. Gong has investigated a quite few typical production process of cement and steel. By the procedures of LCA framework, a list of environmental profiles of major building materials was accomplished in his research as shown in Table 11–13 [2].

4.1. Cement

With environmental profiles listed in Table 11, the environmental impacts of three types of cement, marked as A, B and C, were investigated and calculated in Table 12.

It can be seen that the environmental impact of Cement A is the biggest. The producer has to pay RMB¥99.94 to the society for the right of using environment in order to produce per ton of this cement. In other words, it is the social WTP for the environ-

Table 9
Data of fossil energy sources and the calculation of the weighting factor for this category

	Annual consumption[a] ($\times 10^6$ kg) *a*	Energy Potential[b] (kgeq.SCE/kg) *b*	Potential coefficient *c*	Tax rate[c] yuan/kgeq.SCE *d*
Coal	26,387	0.714	0.60	0.98×10^{-3}
Petroleum	7244.6	1.429	0.33	8.40×10^{-3}
Natural gas	1606 ($\times 10^6$ m^3)	1.330 (/m^3)	0.07	6.17×10^{-3}

Note: Potential coefficient $c = (a \cdot b)/\Sigma(a \cdot b)$; weighting factor $w = \Sigma(c \cdot d)$; *Source*: a. [19] (average from 2000 to 2002), b. [16], c. [20].

Table 10
Weighting factor of each impact category

Category	Weighting factor	Unit
Ecosystem damage		
Globe warming	0.22	yuan/kgeq. C
Ozone layer depletion	15.92	yuan/ODP kg
Acidification	0.74	yuan/kgeq. SO_2
Eutrophication	0.58	yuan/kgeq. NO_3^-
Airborne suspended particles	0.26	yuan/kg
Solid wastes	0.06	yuan/kg
Photochemical smog	3.41	yuan/kgeq. C_2H_4
Waterborne toxicities	6.04	yuan/kgeq. lead
Waterborne suspended substances	0.175	yuan/kg
Resources depletion		
Water resources	0.56	yuan/m^3
Fossil energy sources	3.79E-3	yuan/kgeq.SCE
Iron/aluminum/manganese/limestone	0.017/0.02/0.002/0.002	yuan/kg

Table 11
Environmental profiles of cement (g/t cement)

	Cement A	Cement B	Cement C
CO_2	1,041,557	920,028	677,680
SO_2	280.4	254.1	201.6
NO_x	1609	1434.6	1087.4
CO	388.6	356.1	292.2
COD	35.4	31.1	22.4
SS	50.9	45.6	34.9
Oil	1.4	1.3	1.1
Powders	2244	2016	1565
Raw coal	218,120	189,420	14,350
Iron	32,960	28,840	20,600
Limestone	1,230,600	1,075,200	760,200

Table 12
Environmental impacts of cement

Category		Cement (per ton)		
		A	B	C
Ecosystem damage	(yuan)	96.33	85.40	63.55
Globe warming	(kgeq. C)	93.43	82.79	61.57
Acidification	(keq. SO_2)	1.04	0.93	0.71
Eutrophication	(kgeq. NO_3^-)	1.26	1.13	0.85
Airborne suspended particles	(kg)	2.24	0.58	0.53
Waterborne toxicities	(kgeq. lead)	0.01	0.01	0.01
Waterborne suspended substances	(kg)	0.01	0.01	0.01
Resources depletion	(yuan)	3.61	3.15	2.26
Fossil energy sources	(kgeq.SCE)	0.59	0.51	0.39
Iron ore	(kg)	0.56	0.49	0.35
Limestone	(kg)	2.46	2.15	1.52
Total	(yuan)	99.94	88.55	65.81

Table 13
Environmental profiles of steel (kg/t steel)

	Steel A	Steel B	Steel C	Steel D	Steel E
CO_2	4339	3589	3551	3755	4524
SO_2	56.6	46.6	46.1	48.7	58.6
NO_x	34.8	28.9	28.6	30.3	36.3
CO	202.8	160	158.4	167.4	200
CH_4	225.4	187.3	185.3	196.3	233.4
COD	28.2	23.5	23.3	24.6	29.2
SS	876.2	727.9	721	762.2	907.6
Oil	1.43	1.22	1.12	1.22	3.33
Powders	150.1	124.6	123.4	130.5	156
Solid wastes	81158	67420	66784	70600	83957
Raw coal	3713.78	3076.64	3047.94	3220.14	3857.28
Petroleum	10.66	7.58	7.52	7.64	11.6
Natural gas	2.37	1.94	1.91	2.06	2.44
Iron	3318.66	2757.31	2730.53	2887.09	3432.99
Manganese	61.99	51.5	50.99	53.89	64.1
Limestone	327.6	273	268.8	285.6	340.2

mental impacts caused by producing pre ton of this cement.

4.2. Structure steel

Five types of structural steel, marked as A, B, C, D and E, were investigated. The environmental impact assessment results were shown in Table 14. It can be seen that the environmental impacts of steel are much greater than those of cement. The reason is obviously that the production of steel is much complicated and energy-consuming than that of cement. The impacts of Steel E are the greatest. The producer has to pay RMB¥6693.9 for the right of using environment in order to produce per ton of this type of steel.

5. Conclusions

This paper has developed a method to assess the environmental impact of building materials based on their environmental profiles. Thereinto the evaluation of the seriousness across environmental impact categories is a key step, which has been discussed here in great detail. According to the Coase Theorem, the society is assumed to be the proprietor of the environment and thus the environment user has to pay the society for some rights of using environment such as discharging pollutants or exploiting natural resources. This payment is defined in the paper as green tax. The weighting factor based on green tax reveals the social WTP for environmental damage and thus the final assessment outputs have an exact economic meaning, i.e. the social WTP for the environmental damage caused by the building materials being assessed. The method, as well as the weighting factors, certainly can also be applied to

Table 14
Environmental impacts of steel

Category		Building steel (per ton)				
		A	B	C	D	E
Ecosystem damage	(yuan)	6452.28	5357.94	5305.61	5611.03	6693.9
Globe warming	(kgeq. C)	1290.89	1070.41	1059.12	1121.58	1342.51
Acidification	(keq. SO_2)	59.87	49.43	48.91	51.73	62.16
Eutrophication	(kgeq. NO_3^-)	31.03	25.75	25.52	27.03	32.31
Airborne suspended particles	(kg)	39.03	32.4	32.08	33.93	40.56
Solid wastes	(kg)	4869.48	4045.2	4007.04	4236	5037.42
Waterborne toxicities	(kgeq.lead)	8.64	7.37	6.76	7.37	20.11
Waterborne suspended substances	(kg)	153.34	127.38	126.18	133.39	158.83
Resources depletion	(yuan)	67.32	55.9	55.36	58.53	69.68
Fossil energy sources	(kgeq.SCE)	10.12	8.38	8.3	8.77	10.51
Iron ore	(kg)	56.42	46.87	46.42	49.08	58.36
Manganese ore	(kg)	0.12	0.1	0.1	0.11	0.13
Limestone	(kg)	0.66	0.55	0.54	0.57	0.68
Total	(yuan)	6519.6	5413.84	5360.97	5669.56	6763.58

assess products other than building materials providing that their environmental profiles are available.

It should be noted that, though the green tax can be set consistently countrywide, the social WTP for a specific environmental damage may differs in places. Along with green tax, non-monetized measures, such as the ban against using the coal rich of sulfur and inefficient industrial boilers can also be implemented for the purpose of environmental protection. The green tax sometimes needs to be modified according to the specific local preferences. To modify the tax rates, two assumptions were made in this paper. One is that the marginal return curve is linear as shown in Fig. 1. The other is that the ideal emission level without external restrains could be obtained based on the historical emission data when the environmental issue is not serious.

This paper uses the current pollution (resource) levy system to measure the social WTP in Beijing. However, some people pointed out that the pollutant tax rate is underestimated while the resource tax seems a bit heavy [31]. Anyway, the tax rate per se is not very significant for what we are concerned more important is the method.

Only two safeguard areas are discussed. The integrality of the assessment framework for the ecosystem safeguard areas seems better than that of resources. The assessment of the resource depletion is still a big problem in the application of LCA.

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