A LIFE CYCLE ASSESSMENT METHOD FOR BUILDINGS

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ABSTRACT

Green building has come to be a goal of building design now. Since sustainable performance of building involves lots of aspects, an integrated index is needed to evaluate it comprehensively. Building environmental impact assessment (EIA) based on life cycle assessment (LCA) theory is a well-known method to do this. However, when it is used in China, two main difficulties should be overcome: lack of uniform assessment method and lack of basic data. Aiming at this and combining Chinese special situation, EIA based on damage oriented method is propounded and Building Environment Load Evaluation System (BELES) is founded. All of the environmental impacts are finally classified into four endpoints: Resource Exhaustion, Energy Exhaustion, Human Health Damage and Ecological Damage. Resource scarcity factor and energy quality coefficient are considered. Weight system is determined by investigation to national experts. This method and framework can be useful guidance to building design, especially to green building assessment.

KEYWORDS

life cycle assessment, environmental impact, BELES, buildings

BACKGROUD

Sustainable development concept brings forward new requirement for buildings, and then green building becomes one of the hot topics in building field. Sustainable performance of green buildings involves several aspects of building performance, such as energy consumption, resources consumption and pollutant emission. Different scheme may have advantage in different aspect, then how to evaluate building with an integrated index becomes focus of scholars.

Building sustainable performance is evaluated comprehensively mainly by analysis of its environmental load (EL) both home and abroad, which is the numerical result of environmental impact assessment (EIA) of object or process. The total EL of the building can be obtained through EIA in all aspects of the building. The higher the total EL is, the larger the environmental impact of the building is. At present, building EIA can be classified into two categories: one is qualitative assessment with part quantitative assessment, for example, green building evaluation, EL is expressed with score; the other is totally quantitative assessment, for example, building life cycle assessment (LCA), EL is expressed with pollutant amount or pollution level. There are far more qualitative assessment researches than quantitative ones, but qualitative assessment is not able to show the real amount of EL, conclusion from it is always disputed. Therefore, more and more quantitative assessments based on LCA have been adopted in recent years.

Some scholars in China have done some researches about building LCA. Data collection work and inventory analysis on energy resource and main building materials have been carried out. There are also methodology study and some application study. But generally speaking, building LCA in China is still at the beginning phase. Lack of data is the main problem. Besides, there is no uniform EIA method, weighting definition method, formatted database or tools for LCA framework and application.

Aiming at the above problems of domestic building LCA and combining the special situation of China, EIA based on endpoint damage method is proposed and environmental load evaluation system for buildings in China, Building Environmental Load Evaluation System (BELES), is founded in this paper.

BELES

Life cycle assessment (LCA) is an internationally recognized method to evaluate environmental impacts. It is a process to evaluate the environmental burdens associated with a product, process, or activity throughout its life cycle. LCA framework consists of goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation (ISO. 1997). BELES is an application of LCA theory on buildings.

Goal and scope definition

The object of BELES is buildings and their activities in China, mainly including building materials, equipment, energy, whole building etc. Different object has different assessment scope. As for a whole building, its life cycle includes extracting and processing of raw materials, building materials production, transportation, building construction, operation, maintenance, recycling and final demolition; as for building materials, its life cycle includes raw materials extracting, transportation, building materials production, use, recycling and demolition.

Fig.1 shows the research scope of BELES. Inside the boundary is the object, the activities in building circle; outside the boundary is the natural ecological circle. All of the substance and energy exchange between the two circles should be studied. Based on the situation of China, BELES mainly analyze three types of environmental impacts: energy exhaustion, resources exhaustion and pollution, and the involved substances mainly are fossil fuel resources, mineral resources and pollutant.

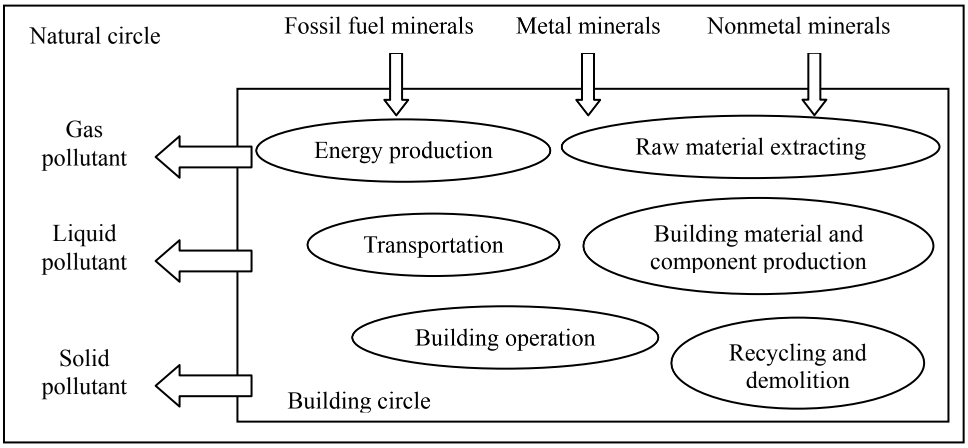

Fig.1 research scope of BELES

Date models

Two data models are used in BELES: inventory model and embodied energy model. Inventory model is the ideal and most common LCA data model described with detailed input and output amount of substances. But inventory data of many products in China are very hard to get, so embodied energy model is proposed. In this model, embodied energy is used as life cycle energy consumption of the product; environmental pollution from embodied energy use process in China is used as life cycle environmental pollution of the product; Amount of main raw materials of the product is used as its life cycle resources consumption. In BELES, inventory data model is used for main building materials, but embodied energy model for other general building materials, equipment and components.

EIA based on end-point damage method

EIA is classified into two categories, one is Mid-point impact assessment, the other is End-point impact assessment. The former only evaluate the direct environmental impacts, but not the indirect ones. It is the common assessment method at present, including three steps: classification, characterizing and quantification. The latter track to evaluate the terminal of environmental impact chain, including four steps: classification, damage classification, characterizing and quantification. BELES use End-point damage assessment method to quantified environmental load. There is no internationally uniform end-point classification now. In this paper, the end-points are classified into four categories: Resource Exhaustion (RE), Energy Exhaustion (EE), Health Damage (HD) and Ecological Damage (ED).

1. Resource exhaustion

Production of building materials and components consume large amount of raw materials, so RE is an important part of environmental impact of buildings activities. Some researches evaluate RE by adding up the weight of consumed main building materials directly (Tong 2003), however, this can not show the difference among various resources. In this paper, resources scarcity factor (SF) is introduced for RE assessment. There is still no uniform definition of SF; some are determined by reserves, and some by consuming speed. Besides, some renewable resources, such as land, forest, water and so on, are very scarce at current period because of the special situation of China. Therefore evaluation of these resources should be different from that of mineral resources. In BELES, SF is used to describe the exhausting extent of resources, and different calculation model for different kind of resources.

As for unrenewable mineral resources, SF is the direct ratio of resources consuming speed. According to the statistic data of mineral resources in China, the residuary available years (RAY) of each kind of resource can be worked out. Assuming SF of 1t iron is 1, than SF λ_i of resource i can be calculated with equation (1). Where L_{Fe} is RAY of iron (yr); L_i is RAY of resource i (yr).

$$\lambda_i = \frac{L_{Fe}}{L_i} \quad (1)$$

Table1 SF of unrenewable resources

resources	Reserve (t/per.)	RAY (yr)	SF
iron	16.53	190	1.000
tin	0.0014	84	2.254
copper	0.023	76	2.514
aluminium	0.542	345	0.551
cement lime	41.27	500	0.38
silica gel	0.911	434	0.437
salt	145.3	500	0.38
gypsum	44.92	500	0.38
marble	48	500	0.38

Because annual data are quite difficult to get, the result of reserve (National Statistic Agency, 2004) dividing the output of typical year (Anon.) is used to as the RAY after that typical year. The SFs of some resources are shown in table 1. It can be seen that metal mineral resources are relatively scarcer, but nonmetal mineral resources are abundant with RAY more than 200. When RAY exceeds 500, it is set to be 500, because reserve data are approximate data.

The production of some building materials, such as clay brick, will destroy the land. Land has been destroyed seriously in China, the area decreasing year after year, although it is renewable resources. Therefore these destroyed parts should be considered as the exhaustion of land resource, and be described with SF. The prime use of land is food production, serving raw materials is just additional use. So the two parts should be differentiated when calculating SF, as equation (2) shows.

$$\lambda_s = \frac{L_{Fe}}{(G_S - P \cdot P_S)/\Delta S} \quad (2)$$

Where G_s is total land area in China (ha), P_s is land area needed for minimum food production level (ha/per.), P is the population of China (per.), $\triangle S$ is the annual decreasing land area (ha/a), L_{Fe} is RAY (yr) of iron. The value of these parameters is obtained from relevant references (Chen 2002, Feng 2005), and finally λ_s is figured out to be 4.37。

Similar to land, Forest (except that can renew in a short period) and water are also renewable but currently scarce resources. Although there is no concept of RAY for them theoretically, SFs are assumed to be the inverse ratio of their reserves to indicate their scarcity and to unify SF concept. Then SF of forest and water can be determined with equation (3), also assuming SF of iron is 1. Where λ_j is SF of resources j, G_j is the reserve of resources j (t/per.); G_{Fe} is the reserve of iron (t/per.). SFs of renewable but currently scarce resources are show in table 2.

$$\lambda_j = \frac{G_{Fe}}{G_j} \quad (3)$$

Table 2 SF of renewable but currently scarce resources

resources	Reserve (t/per.)	RAY (yr)	SF
land	50	43	4.37
forest	4.3	—	3.844
water	2200	—	0.0075

Then building RE (kgFe eq) can be calculated with equation (4). Where G_i is the consumed amount of building material i (kg); R_{ij} is the amount of resources j consumed by unit building material i mass (kg/kg); λ_{ij} is the SF of resources j.

$$RE = \sum_i (G_i \cdot \sum_j (\lambda_{ij} \cdot R_{ij})) \quad (4)$$

2. Energy exhaustion

Energy exhaustion caused by consumption of fossil fuel resources. Although fossil fuel resources are also mineral resources, they should be evaluated respectively for its special use as energy. The traditional assessment only considers the difference of heat value among different energy resources, but ignore the difference of energy quality. Jiang Y et al (2004) proposed energy quality coefficient (QC) based on exergy analysis method of second law of thermodynamics. QC is the ratio of the useful work the energy could make over its total energy. To be used in buildings, the primary energy needs to be converted to be secondary energy by some dynamical equipment, like power plant, boiler, and distribution system. There is energy loss in converting process, so converting efficiency η should be considered. Then QC can be defined with equation (5). Where Q is the total energy the energy contains (MJ), W is the useful work the energy resource could make (MJ). According to heat-work conversion arithmetic of thermodynamic, QCs can be worked out, shown in table 3.

$$\lambda = \eta \cdot \frac{W}{Q} \quad (5)$$

Table3 energy quality coefficient

energy	QC	energy	QC
coal	0.35	geothermic water	0.07
oil	0.46	natural gas	0.52

Then EE (kgCe eq) of building activities can be calculated with equation (6). Where E_i is the consumed amount of energy i (equivalent coal amount converted by heat value, kgCe eq), λ_i is QC of the energy resource.

$$EE = \sum_i E_i \cdot \lambda_i \quad (6)$$

3. Health damage

Human Health Damage (HD) expresses the bad effect that environmental pollutants have on human health directly or indirectly. HD can be quantified. Murray et al (1994) collaborated with World Health Organization, with more than 100 experts in the world, worked on the global disease burden, and propounded an integrated index, Disability-Adjusted Life Year (DALY), to evaluate HD.

Among environmental pollution relevant to building activities, climate change, ozone layer depletion and respiratory system damage are main factors resulting in human health damage. Scholars in relevant field have done some research on the change of disease incidence and human mortality caused by these environmental impacts. Based on these researches, Eco-Indicatior99 (Goedkoop 2001) calculated DALY. Climate change mainly attributed to greenhouse gases. The research of Eco-Indicatior99 indicates global human health damage factor (HDF) of CO_2 from 2000 to 2100 is 2E-7 DALY/kg. HDFs of other greenhouse gases can be calculated, according to the global warming characterizing factors in equivalent potential model of EPA (Agency of US Environment Protection 1995). CFC-11 is a typical kind of pollution depleting ozone layer, HDF of it is 8.5E-4 DALY/kg. HDFs of other pollution depleting ozone layer can also be calculated according to the ozone layer depleting characterizing factors. HDF of CO that may damage respiratory system is 7.31E-7 DALY/kg. Some substance have more than one kind of damage, for example, CO is a kind of greenhouse gas and may also lead to respiratory diseases, so its HDF should be the sum of HDF of each kind. HDFs of pollution relevant to building activities are shown in table 4.

Table 4 global HDF of pollutants

pollutant	HDF (DALY/kg)	pollutant	HDF (DALY/kg)
CO_2	2.00E-7	TSP	8.03E-5
CH_4	5.00E-6	CFC-11	1.65E-3
NO_x	1.51E-4	CFC-12	2.40E-3
CO	1.13E-6	CFC-113	7.65E-4
SO_2	5.35E-5	HCFC-141b	1.54E-4
PM_{10}	3.75E-4	NMVOC	1.28E-6

Then HD of building activities can be figured out with equation (7). Where G_i is the amount of pollutant i (kg), H_i is HDF of this pollutant (DALY/kg).

$$HD = \sum_i G_i \cdot H_i \tag{7}$$

4. Ecosystem damage

Ecosystem Damage (ED) refers to the effect on biodiversity of biosphere caused by pollutant emission and ecological environment occupancy. There are mainly two ways in building activities that will lead to ecosystem damage. One is acid and eutrophic substances emission when using energy. In China acidification and eutrophication are mainly caused by inorganic substances due to deposition of SO2, NOx, such as sulphate, nitrate. The other is land occupancy or type change, for example, paving pipelines, burying waste, using as raw materials and so on.

Hamers et al (1996) propounded Ecosystem Damage Factor (EDF) to quantify and evaluate ecosystem damage. EDF is defined as the potentially disappeared fraction (PDF) of species in some region during some period, with unit PDF·m^2·yr. Where, PDF is the ratio of disappeared species number over former species number. Since there is no research to quantify the effect of SO_2, NO_x, or other pollutant on ecosystem in China, the research results of Eco-Indicator99 are adopted in BELES, which are shown in table 5.

Type change of land will lead to regional biodiversity change. Combining PDF, biodiversity change is used to evaluate ED of land occupancy in BELES, and simplified method is proposed based on the situation of China. In this method, the average species number of urban land is assumed as the species number of reference land. When the land is occupied, if its species number increases, then the ecosystem is improved; if its species number decreases, then PDF (α) of land use can be calculated with equation (8) and EDF (ε) with equation (9). Where C_r is land species number before occupancy, C_u is land species number after occupancy, T is lasting time of occupancy (yr), S is the area of occupied land (m^2).

$$\alpha = \frac{C_r - C_u}{C_r} \tag{8}$$

$$\varepsilon = \alpha \cdot T \cdot S \tag{9}$$

In our research, ED of land occupancy is evaluated by land plant diversity. This is because land damage always destroy plants directly, plant species number is bigger than animal species number, and is easier to obtain and more reliable. In EDF calculation, plant species number data of different type of urban land comes from reference (Meng X 2004), occupying time is assumed 50 years, and the results are show in table 5. For EDF calculation of solid wastes, assume that wastes are disposed with landfill, 20 m^3 building wastes with density 1500 kg/m^3 accumulated on per m^2 land.

Table 5 Ecosystem Damage Factor

Impact factor （1m^2）	EDF （PDF· m^2·yr）
SO_2（1kg）	1.041
NO_x（1kg）	5.713
Solid waste（1kg）	0.001
Paving road（1m^2）	9.32
Everglade or natral water occupancy	40.45
Shallow land-cover occupancy	30.09
Plantation and woodland depletion	40.45
Landfill land occupancy	30.09

5. Normalization

Meanings and Units of the four endpoints of environmental impacts are not same, so they need to be normalized by their background value for comparison and weighting. To find how much the environmental impact of the research object is in building industry is, the whole building industry should be taken as the background, and then the total environmental load (EL) per unit building area of China is taken as the background value in this paper.

Building industry EL of China mainly comes from two parts, one is building material production, and the other is building operating energy and water consumption. Output of building materials and living water consumption are obtained from national statistic almanac (2004), building construction and operating energy consumption is assumed to be 25% of the total energy consumption of the country, and the area of existing buildings in China is 42000 million m2. The background of building industry in China can be calculated according to the above analysis method. Table 6 shows the result.

Table 6 background value

	Background value
HD (DALY/m^2)	8.84E-5
ED (PDF·m^2·yr)	1.58
RE (kgFe eq/m^2)	53.95
EE (kgCe eq/m^2)	33.52

6. Weighting

Weighting factors indicate the relative importance of the four endpoints. In this paper, weighting factors are determined by investigation of 57 expects from design institutions, government departments, real estate industry and universities. Weighting factors are obtained by analysis of vote result. Table 7 shows the result.

Table 7 weighting factors of each endpoint

	HD	ED	RE	EE
weight	0.22	0.23	0.27	0.28

7. Environmental load calculation

According to the above method of classification, characterizing, normalizing and weighting, EL can be calculated with equation (10):

$$EL = \frac{RE}{B_{RE}} \cdot \omega_{RE} + \frac{EE}{B_{EE}} \cdot \omega_{EE} + \frac{HD}{B_{HD}} \cdot \omega_{HD} + \frac{ED}{B_{ED}} \cdot \omega_{ED} \quad (10)$$

Where RE is the total resources exhaustion value of the object (kgFe eq); EE is the total energy exhaustion value of the object (kgCe eq); HD is the total human health damage value of the object (DALY); ED is the total ecosystem damage value of the object; ω_{RE}, ω_{EE}, ω_{HD}, ω_{ED} are the corresponding weighting factors; B_{RE}, B_{EE}, B_{HD}, B_{ED} are the corresponding building industry background value.

To make it easy to be understood, the unit of EL is defined as "environmental load point" (point, pt for short).

APPLICATION

An assessment tool named Building Environmental Load Evaluation System (BELES) for building LCA in China has been developed, based on the above theory framework. Users can update and expand the database and set new data modules of building materials, equipment, energy etc by themselves, and add new project to describe a single building with its consumption of building materials, energy etc, and analyze EL of building materials, equipment or the whole building.

BELES has been used to analyze EL of building energy production and use, for example, coal-burned electricity generation, gas-burned heating etc, and life cycle EL of main building materials such as cement, steal, glass and so on. BELES has also been used to determine evaluation index of green building materials through life cycle EL analysis of many office and residential buildings. Besides, it has been used to optimize building envelop design too. For instance, Fig.2 shows the life cycle EL of cement calculated by BELES. It can be seen, EL of each endpoint in each phase of cement life cycle has been carried out, and the main environmental impacts of each phase are not same.

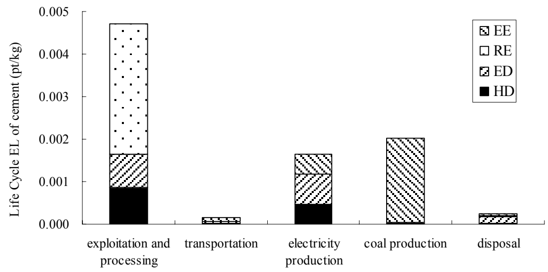

Fig.2 Life Cycle EL of cement

CONCLUSION

In this paper, method to evaluate environmental load of buildings and their relevant activities has been propounded, based on LCA theory and combining the special situation of China. EIA based on endpoint damage has been explained, and four endpoints, RE, EE, HD, ED, have been proposed. Scarcity factors are used for RE assessment, and are defined respectively for unrenewable resources and renewable but currently scarce resources. Quality coefficient is introduced in EE assessment to consider the difference of energy quality. In HD assessment, three mid-impact, global warming, ozone layer depletion and respiratory damage, are involved. In ED assessment, environmental impact of land occupancy is described by the change of land plant diversity. The weighting factors are determined by investigation to experts of building industry. The total EL of building industry in China, including EL of building materials production, building construction, operating energy consumption and living water consumption, is used as background value. Finally, an assessment tool, BELES, has been developed to assist calculation and analysis.

This assessment system has been proved feasible in many researches. It has been used for materials and energy consumption evaluation of green buildings and building efficiency design. In the future, with the expansion of database, BELES will be used in broader building field, evaluate environmental load of more buildings and relative activities, and promote sustainable development of building industry in China.

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