LIFE CYCLE GREEN COST ASSESSMENT METHOD FOR GREEN BUILDING DESIGN

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ABSTRACT

Life cycle green cost assessment (LCGCA) method, which can evaluate building environmental load and economic performance throughout its life cycle comprehensively, is propounded in this paper in order to guide green building design. In LCGCA, environmental load (EL) cost is proposed based on concept of environmental tax and counted into general building initial cost and operating cost, and then green payback time (GPT) could be worked out. With this method, an office building in Beijing is studied. The operating energy consumption, life cycle EL, life cycle cost (LCC) and GPT of different envelope schemes have been compared. The results indicate GPT is obviously shorter than the general payback time when EL cost is considered. Especially, the exterior shading scheme changes to be economically feasible through GPT evaluation. This assessment method is more suitable to guide green building design practice because environmental performance and economical performance are considered together.

KEYWORDS

Green building design, Environmental load, Green payback time, Life cycle cost analysis

BACKGROUND

Green buildings have got rapid development around the world in recent 10 years. Then how to evaluate green performance and determine green level of buildings becomes one of the research emphases. In China, green building design is still at beginning stage. Recently, domestic scholars begin to pay attention to building environmental impact and use life cycle assessment (LCA) method to quantify it in order to get evaluation index of green building. Moreover, some scholars try to use this method to guide building cooling and heating resources selection and envelope design (Li 2005, Lin 2004, Gu 2007), but researches like these are just a few part. However, when real projects in practice are designed, the research conclusion will not be considered, because economic performance is most important in market and better environmental performance sometimes leads to higher initial construction cost. To promote energy saving and environment protection in practice, national policy is needed. In some foreign counties, environmental tax has been is imposed to lead some industry to control and reduce pollution. Chinese government also has issued notification of beginning to study environmental tax imposition (Anon.) not long before. Although most environmental tax aims at energy production and use now, buildings will be involved in the future for its high energy and resources consumption. Then a comprehensive assessment method that can evaluate both environmental and economic performance of building is urgently needed. But there is no corresponding study in China yet. Some results of foreign study (Gluch and Baumann 2004) may not be used directly because of different status of China. Therefore, life cycle green cost assessment (LCGCA) method is propounded in this paper as an attempt to solve this problem.

LCGCA METHOD

LCGCA involves two indexes: building environmental load (EL) and building green cost (GC). EL (unit: point and pt for short) can be calculated with LCA method by Building Environmental Load Evaluation System (BELES) developed by Department of Building Science in Tsinghua University (Gu 2006). GC can be calculated according to life cycle cost analysis (LCCA) method. GC is different from the general cost which mainly includes initial cost (IC) and operating cost (OC). It also includes environmental load cost (ELC) which is the economic value of EL. The price of unit EL can be determined according to CO_2 price. Influenced by Clean Development Mechanism of Kyoto protocol, international carbon trade is very active at present, the general price of CO_2 is about 80RMB/t (trade in China) (Anon A). BELES analysis result shows EL of CO_2 is 0.463pt/t, so price of unit EL is 173 RMB/pt. Then ELC of building construction phase plus general IC comes to be green initial cost (GIC), and ELC of operation phase plus general OC comes to be green operating cost (GOC). With above calculation and redefinition, building environmental performance and economic performance are connected together. Finally the integrated evaluation index of LCGCA, green payback time (GPT), can be calculated with equations (1)-(6).

$$ELC = EL \cdot V_{pt} \quad (1)$$

$$GIC = ELC_c + IC \quad (2)$$

$$GOC = ELC_o + OC \quad (3)$$

$$-(GIC - GIC_0) = (OC - OC_0) \cdot P_G + (ELC_o - ELC_{o0}) \cdot P_{EL}$$

namely: $-\Delta GIC = \Delta OC \cdot P_G + \Delta ELC_o \cdot P_{EL}$ (4)

$$P_G = (\frac{1+e}{1+i} - (\frac{1+e}{1+i})^{N_G}) / (1 - \frac{1+e}{1+i}) \quad (5)$$

$$P_{EL} = (\frac{1+e_{EL}}{1+i} - (\frac{1+e_{EL}}{1+i})^{N_G}) / (1 - \frac{1+e_{EL}}{1+i}) \quad (6)$$

Where *EL* is building EL per unit floor area (pt/m^2), V_{pt} is price of unit EL (RMB/pt); ELC_c is ELC of construction phase per unit floor area (RMB/m^2) (all the other cost parameters in this paper refers to the cost of per unit area, no statement is made in the following text except special condition), ELC_o is ELC of operation phase (RMB/m^2); *IC* is general IC (RMB/m^2), *OC* is general annual OC (RMB/yr/m^2), *GIC* is GIC (RMB/m^2), *GOC* is annual GOC (RMB/yr/m^2), subscript "0" refers to GIC and annual GOC of base case; N_G is GPT (yr); P_G is discount coefficient of total OC in N_G years, it is a function of energy price growth rate *e* and bank rate *i*; P_{EL} is discount coefficient of total ELC in N_G years, it is a function of CO_2 price growth rate e_{EL} and bank rate *i*.

The difference value is used to calculate N_G, so there is no need to consider the same part of each scheme, only comparison of different part is enough to get results. The calculation workload can be simplified. The results of case study in this paper are all carried out with comparison of only different part of schemes.

Green building design can be optimized through comparison of GPT of each design scheme. If $GIC>GIC_0$ and $GOC>GOC_0$, it means the scheme not only increases GIC but also increases GOC, it is less green than the base case and should not be chosen; If $GIC<GIC_0$ and $GOC<GOC_0$, it means the scheme not only decreases GIC but also decreases GOC, it is more green and economic than the base scheme. There is no payback time for above two conditions in theory. If $GIC>GIC_0$ and $GOC<GOC_0$, N_G may be worked out, the greater it is, the longer the GPT is. When N_G is in an acceptable range, the scheme is greener than the base case and economically feasible in life cycle.

CASE STUDY

Investigation data show that energy consumption per unit floor area of commercial buildings is much more than that of residential buildings, besides, facade designs of commercial buildings are always complicated than that of residential buildings. Therefore, an office building in Beijing is taken as a study case in this paper. Several schemes of envelope design and energy saving strategy of it are analyzed. Energy consumption, life cycle environmental load (LCEL), life cycle cost (LCC) and GPT are compared respectively. In addition, the difference between GPT and general payback time (PT) are analyzed too.

The building has 30 floors with total area 49445m^2, and the first four floors are designed as annex. HVAC system of it is fan-coil unit plus fresh air system, centrifugal water chillers for cooling in summer and gas-fired boiler for heating in winter. The original envelope scheme is all-glass curtain wall and is taken as base case. All the schemes are described in table 1.

Table1 List of design schemes

	DESIGN SCHEME
case1	all-glass curtain wall, base case
case2	ARWW* 0.65 & aluminum curtain wall
case3	ARWW 0.45 & aerated concrete block
case4	glass curtain wall with louver and ventilation adjustable double-skin facade for south facade
case5	glass curtain wall with fixed exterior louver (500mm wide) for south facade, 4 layers for floor 1 and 4, 3 layers for the other floors

**ARWW is the area ratio of window over wall*

Building operating energy consumption analysis

1. Building load simulation

Building load is hourly simulated by an energy simulation software DeST (Designer's Simulation Toolkits) (Yan etc. 2004), which is also developed by Department of Building Science in Tsinghua University. According to the local design standard of public buildings (Ministry of Construction P.R.China 2005), different window thermal performance is required for different building ARWW scheme. Double skin facade and exterior louver shading schemes are designed for energy efficiency and better comfort based on the original scheme. Envelope thermal parameters of each scheme are shown in Table 2, and simulation results of building load are shown in Table 3.

Table2 Envelope performance of each scheme

	K* of WALL	K of ROOF	WINDOW	
			K	SC*
case1	0.80	0.54	1.6	0.45
case2	0.78	0.54	2.0	0.45
case3	0.75	0.54	2.3	0.55
case4	0.80	0.54	s*1.4/w*1.33	s0.11/w0.47
case5	0.80	0.54	1.6	hourly different

**K is heat transfer coefficient, W/(m^2·K),*
SC is shading coefficient of glass,
"s" stands for summer, "w" for winter

Table3 Results of building load simulation

	MAX HEATING LOAD	MAX HEATING LOAD	TOTAL HEATING LOAD	TOTAL COOLING LOAD
	(W/m^2)	(W/m^2)	(kWh)	(kWh)
case1	87.7	137.8	568575	3990996
case2	88.3	130.5	773416	3521657
case3	87.2	126.9	805122	3318760
case4	84.4	132.3	532965	3644480
case5	89.0	134.9	624631	3778845

2. Operating energy consumption

Different envelope scheme has different cooling and heating load, as well as different operating electricity and gas consumption. Building load affect not only energy consumption of cooling or heating units, but also electricity consumption of supply system (including pumps, fans etc.). A concept of TCOP (total coefficient of performance) is proposed to describe the total energy efficiency of cooling system. TCOP is the ratio of total cooling load in summer over total electricity consumption of cooling system. TCOP is quite difficult to be calculated precisely, it is greatly depend on the type of distribution system and equipment speciality. As for this building, it is estimated to be 2.5 according to energy consumption measurement and investigation to many office buildings in Beijing by our department. Because heating load of this building is much less than cooling load and the difference of heating pump electricity consumption among schemes is small, so it is not counted in the total electricity consumption of HVAC system. Then annual operating electricity and gas consumption can be worked out with equation (7)-(8). Where *TCOP* is TCOP of cooling system; CON_e is annual operating electricity consumption per unit floor area (kWh/yr/m^2); CON_g is annual operating gas consumption per unit floor area (m^3/yr/m^2); η_{boiler} is gas-fired boiler efficiency, is assumed to be 0.89 according to the local standard; r is heat value of natural gas, 8500kcal/m^3; Q_c and Q_h is the total cooling load in summer and heating load in winter respectively (kWh/m^2). The results are shown in Fig.1 and Fig.2.

$$CONe = \frac{Q_c}{TCOP} \quad (7)$$

$$CONg = \frac{Q_h}{\eta_{boiler} \times r} \quad (8)$$

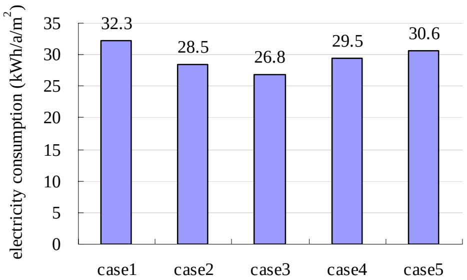

Fig.1 Operating electricity consumption

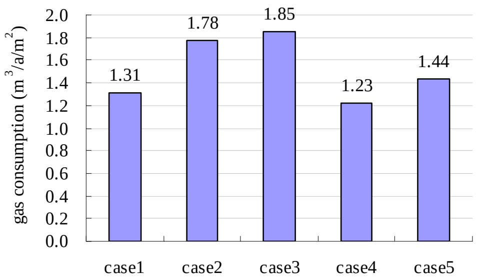

Fig.2 Operating gas consumption

It shows the smaller the ARWW (case2, case3) is, the less the electricity consumption is and the more gas consumption is. Energy consumption of double skin facade scheme (case4) is less than that of base case both in summer and in winter. Electricity consumption of exterior shading scheme (case5) is less than that of base case, but gas consumption is a little bigger since the fixed louver decrease solar heat gain in winter and makes heating load higher. Case3 has the least electricity consumption for its smallest ARWW, and case4 has the least gas consumption for its largest ARWW and higher SC of glass.

LCEL analysis

Each scheme is different only in exterior envelope design, so only EL of exterior walls and windows are considered when calculating building construction EL. There are many kinds of materials in envelop, but consumption of some kinds are just a little, so only consumption of main materials are counted for comparison. Besides, some building materials have shorter life-span than building, so they need to be replaced during building use life. Building lifespan is assumed to be 50 years, and curtain walls, double skin facade, exterior louver are assumed to be 40 years (IBEC 2004). Operating EL mainly comes from energy use of cooling and heating system. According to building materials consumption and building load, EL of construction, replacement and operation can be worked out with BELES. Then building LCEL of each scheme can be calculated. The results are shown in Table 4 and Fig.3.

Table 4 Building life cycle environmental load

	EL_c*	EL_r*	EL_o*	LCEL
	(pt/m^2)	(pt/m^2)	(pt/yr/m^2)	(pt/m^2)
case1	0.656	0.656	0.439	23.2
case2	0.700	0.700	0.406	21.7
case3	0.375	0.295	0.388	20.0
case4	0.775	0.775	0.402	21.6
case5	0.701	0.701	0.421	22.5

**The subscript "c" stands for construction phase, "r" for replacement and "o" for annual operation.*

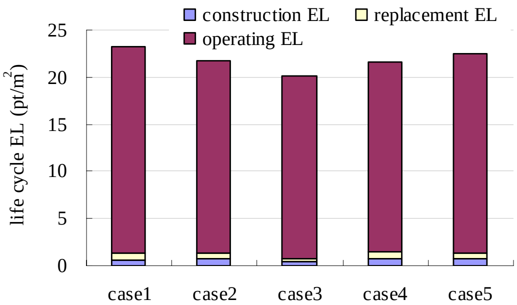

Fig.3 Building life cycle environmental load

It is found that, construction and replacement EL of case4 is highest, operating EL of base case is highest, and ELs of all phases of case3 are lowest. Although construction EL of case2, case4 and case5 are higher than that of base case, LCEL of them are all lower than that of base case. This means the increased construction and replacement EL of optimized strategy can be balanced out by the decreased operating EL, and the total life cycle environmental performance of these optimized schemes are better than that of base case.

LCC analysis

LCC of building contains many kinds of cost, such as IC, OC, maintenance and replacement cost and so on. In this case, IC, OC and replacement cost (RC) are considered. Cost for maintenance is not included because the type and amount of maintenance is difficult to estimate. Besides, there is just a little difference between the max heating and cooling load of each scheme, so the cost difference of cooling and heating source equipment is very small (the largest equipment cost difference is 3.3RMB/m^2) and can be ignored. Since there is only difference of exterior envelope among cases, IC calculation only includes this part. The total area of building facade is 19991m^2. The total length of aluminum louvers of case5 is 4729m. According to current cost analysis from curtain wall company, the cost of concealed-frame double-layer glass curtain wall is 1011.9 RMB/m^2; the cost of aluminum curtain wall of case2 is 642.9 RMB/m^2; the cost of aerated concrete block of case3 is 39.5 RMB/m^2; the cost of double skin facade of case4 is 2500 RMB/m^2; the cost of aluminum louvers of case5 is 600 RMB/m. Then IC and RC can be worked out. OC mainly is energy use cost. Electricity cost for cooling is calculated hourly according to time-differentiated electricity price in Beijing (Anon B), and natural gas cost for heating is calculated according to gas price 1.9 RMB/m^3 in Beijing.

LCC results of each scheme can be figured out with equation (9)-(11), where LCC is the LCC of building (RMB/m^2); N_r is the life-span of curtain wall and louver (yr), which is assumed to be 40 in this paper as stated before; RC is the RC of building materials (RMB/m^2); e_m is the growth rate of building materials price, is assumed to be 3% according to statistic data (Anon C); P_l is discount coefficient of total OC in building 50-year lifespan, it is a function of energy price growth rate e and bank rate i. e is assumed to be 5% according to the growth tend of electricity and gas price in Beijing in recent years, and i is assumed to be 6.12% according to the general bank rate in China in 2006 (Anon D). Then general payback time (PT) can be calculated with equations (12)-(13), where N is PT of scheme (yr); P is discount coefficient of total OC in N years. All the results are shown in table 5.

$$LCC = IC + RC \cdot \left(\frac{1+e_m}{1+i}\right)^{N_r} + OC \cdot P_l \quad (9)$$

$$P_l = \left(\frac{1+e}{1+i} - \left(\frac{1+e}{1+i}\right)^{50}\right) / \left(1 - \frac{1+e}{1+i}\right) \quad (10)$$

$$-(IC - IC_0) = (OC - OC_0) \cdot P \quad (11)$$

$$P = \left(\frac{1+e}{1+i} - \left(\frac{1+e}{1+i}\right)^{N}\right) / \left(1 - \frac{1+e}{1+i}\right) \quad (12)$$

Table 5 Life cycle cost analysis

	IC (RMB/m^2)	***RC*** (RMB/m^2)	***OC*** (RMB/yr/m^2)	***LCC*** (RMB/m^2)	**PT** (yr)
case1	409.1	409.1	34.0	1826.3	/
case2	355.9	355.9	31.2	1650.7	/
case3	192.2	183.4	29.8	1378.9	/
case4	593.1	593.1	31.1	1955.7	108
case5	466.5	466.5	32.6	1846.2	54

It shows that, both IC and OC of case2 are lower than that of base case, so does that of case3. Therefore there is no PT for these two cases in theory. LCC of these two cases are lower than that of base case. they have better economic performance. Case4 and case5 pay much in construction phase to get lower OC. But the PTs of them are all longer than 50-year building life-span and LCC of them are higher than that of base case, so in terms of economic performance with general meaning they are worse than the base case.

GPT analysis

As stated above, ELC is included in GC. According to the EL results, ELC of construction and operation phase of each scheme can be calculated, and then GIC and GOC can be worked out, consequently GPT, N_G, can be calculated with equation (4)-(6). Considering the uncertainty of CO_2 price growth rate e_{EL}, it is assumed to be 0 in calculation. The results are shown in Table 6.

Table 6 Green payback time analysis

	ELC_C (RMB/m^2)	***GIC*** (RMB/m^2)	ELC_O (RMB /yr/m^2)	***GOC*** (RMB /yr/m^2)	**GPT** (yr)
case1	113.4	522.5	75.8	109.8	/
case2	121.0	476.9	70.1	101.3	/
case3	64.7	257.0	67.0	96.7	/
case4	134.0	727.1	69.4	100.5	48
case5	121.1	587.6	72.8	105.4	24

It is found that, GIC and annual GOC of both case2 and case3 are lower than that of base case, so there is no PT for these two cases in theory, they are better schemes than base case in comprehensive performance of environment and economy. GPTs of case4 and case5 are obviously shorter than PTs of them when ELC is counted in. GPT of case5 turns to be 24 years, which means the exterior shading scheme is better than base case in comprehensive performance of environment and economy. GPT of case4 turns to be 48 years, however, it is longer than the life-span of curtain wall and louvers, so the double skin facade scheme is still economically unfeasible. This is because the double skin façade technique is very expensive under the current situation of China.

CONCLUSION

To evaluate environmental and economic performance of green building design comprehensively, a new assessment method, LCGCA, is proposed in this paper, which takes ELC into account and use GPT as an integrated evaluation index.

Based on the new method, a real office building in Beijing is studied. Several different schemes of envelope design have been compared from aspects of building operating energy consumption, LCEL, LCC and GPT. And different results can be obtained from different evaluation aspect.

1. Operating energy consumption: all the optional schemes (case2-5) have less operating energy consumption than initial scheme (base case).
2. LCEL: both construction and operation EL of case3 are lower than that of base case. Although construction EL of case2, case4 and case5 are higher than that of base case, LCEL of them are all lower. So all the optional schemes perform better in life cycle environmental impact than base case does.
3. LCC: case2 and case3 have lower LCC than base case, but case4 and case5 have higher. There is not PT for case2 and case3 in theory. PTs of case4 and case5 are longer than building life-span. So as general economy analysis is concerned, both double skin facade scheme and fixed exterior shading scheme are economically worse than base case.
4. LCGCA: GPTs of case4 and case5 are obviously shorter than PTs of them. GPT of case5 is 24 years, which indicates the fixed exterior shading scheme is better than base case in comprehensive performance of environment and economy. GPT of case4 is 48 years, however, is still longer than lifespan of curtain wall and louvers, which indicates double skin facade scheme is still economically worse than base case. As for case2 and case3, both GIC and GOC of them are lower than that of base case, there are no GPTs for them, they are better than base case in comprehensive performance of environment and economy.

It can be concluded, comparison results may be different from that of general economy analysis when ELC is considered. Since energy and pollution problem become more and more serious and environmental tax imposition is upcoming, environmental and economic performance of green building design should be evaluated comprehensively. Therefore LCGCA, which can meets this need, is worth being recommended to be the evaluation and guide tool for green building design in China.

What need to be explained is the conclusions in this paper are obtained from this special case, they may not suitable for other cases, and so special case needs special analysis. But LCGCA is a universal method. Besides construction EL and ELC only include the exterior envelope part, which is only a small part of the total construction system. So the value in this paper is not the total EL and ELC of the whole construction system. Consequently LCEL and LCC value in this paper is not the real value of the whole building either. Although this will not affect any of the conclusion for exterior envelopes is the only different part between each scheme, we will try our best to get more detailed data about the building and give total value of the whole building in future study. In addition, changing of energy price growth rate, building material price or bank rate will all affect the results of ELC, LCC, PT and GPT and further affect the conclusion, so sensitivity analysis of these affecting factors may be studied in our future work.

NOMENCLATURE

Abbreviation

EL	environmental load
ELC	environmental load cost
GC	green cost
GIC	green initial cost
GOC	green operating cost
GPT	green payback time
IC	initial cost
LCA	life cycle assessment
LCC	life cycle cost
LCCA	life cycle cost analysis
LCEL	life cycle environmental load
LCGCA	life cycle green cost assessment
OC	operating cost
PT	general payback time
RC	replacement cost
TCOP	total coefficient of performance

Symbol

CON_e	annual operating electricity consumption per unit floor area ($kWh/yr/m^2$)
CON_g	annual operating gas consumption per unit floor area ($m^3/yr/m^2$)
e	energy price growth rate
e_{EL}	CO_2 price growth rate
e_m	growth rate of building materials price
EL	building environmental load per unit floor area (pt/m^2)
ELC_c	environmental load cost of construction phase per unit floor area (RMB/m^2)
ELC_o	environmental load cost of operation phase per unit floor area (RMB/m^2)
GIC	green initial cost per unit floor area (RMB/m^2)
GIC_0	green initial cost per unit floor area of base case (RMB/m^2)

GOC	annual green operating cost per unit floor area (RMB/yr/m^2)
GOC_0	annual green operating cost per unit floor area of base case (RMB/yr/m^2)
i	bank rate
IC	general initial cost per unit floor area (RMB/m^2)
IC_0	general initial cost per unit floor area of base case (RMB/m^2)
LCC	life cycle cost of building per unit floor area (RMB/m^2)
N	general payback time (yr)
N_G	green payback time (yr)
N_r	life-span of curtain wall and louver (yr)
OC	general annual operating cost per unit floor area (RMB/yr/ m^2)
OC_0	general annual operating cost per unit floor area of base case (RMB/yr/m^2)
P	discount coefficient of total operating cost in N years
P_{EL}	discount coefficient of total environmental load cost in N_G years
P_G	discount coefficient of total operating cost in N_G years
P_l	discount coefficient of total operating cost in building 50-year lifespan
Q_c	total cooling load in summer per unit floor area (kWh/m^2)
Q_h	total heating load in winter per unit floor area (kWh/m^2)
r	heat value of natural gas, 8500kcal/m^3
RC	replacement cost of building materials per unit floor area (RMB/m^2)
$TCOP$	total coefficient of performance of cooling system
V_{pt}	price of unit EL (RMB/pt)
η_{boiler}	gas-fired boiler efficiency

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