Assessment of Building Greenhouse Gas Emissions Based on Hybrid Life-cycle Model

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Abstract. This paper constructs the building's hybrid life cycle model based on the traditional LCA model and EIO model, and uses it to measure and calculate GHG (Greenhouse Gas) emissions from buildings. This model divides the building life cycle into three stages, including materialization, utilization and dismantling. EIO model is used to calculate GHG indirect emissions, and LCA model is used to calculate GHG direct emissions. This method can be applied to effectively make use of the existing project cost data for calculation, thus overcoming the disadvantage of much workload arising from the traditional method. According to the calculation of one residential housing and comparison with the calculation result of LCA model, GHG emissions of this house are most serious in the stage of utilization; and in materialization stage, GHG emissions rely on the control over the emissions of upstream sectors and improvement of utilization efficiency of the applied materials. This model is able to provide new theoretical reference for the building GHG emissions.

Introduction

Man-made GHG emission is an important reason of global climate warming. The building industry consumed 40% of the world energy and discharged 36% of CO2. [1] The carbon emissions of all countries in the world are maintained around 1/3 of the total emissions. For example, building emissions of European Union (EU) in 2002 accounted for 13%, belonging to the fourth major emission source of EU; the emissions of residential building and personal traffic in the United States are 49% of the social emissions [1]; annual emissions of Chinese buildings in current stage reached 28% of total social emissions [2], and total emissions of CO2 account for 40% of the total social emissions [3]. In order to realize the Copenhagen emission reduction target of Chinese government, it is imperative to reduce the building's carbon emissions. However, regarding the method for measuring the building's carbon emissions, many countries in the world, such as America, Germany and the United Kingdom, have formulated their own measurement methods, but there is not one internationally general and recognized standard yet. [4] Therefore, researching the building's total life cycle carbon emissions will be of great guiding significance for the government's emission reduction decision and the carbon transactions in the future.

Reference Review

At present, major measurement models of the building's carbon emissions include whole-process life cycle assessment model (LCA) and environmental input-output model (EIO, also known as industrial correlation model). LCA model, including total life cycle and environmental emissions model established by Zhu Yan [5] and other persons, potentiality influence model of the building's carbon emissions established by Zhang Zhihui [6], and Assessment Framework System of Carbon Reduction Technology of Green Low-carbon Residential Areas in China [7] are calculated by using the product of energy, material consumption and the corresponding carbon emissions factors in the relevant construction stages. Leif [8] and Wu [9] from foreign countries took houses and office

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buildings as objects respectively to research total carbon emissions in the life cycle. In the application of LCA model, although the researchers have slightly different emissions factor values and carbon solidification in the process of building material production, they have basically same calculation thinking, that is, specific inventory data and large quantity of labor and materials are required to estimate the carbon emissions of one building. For this reason, some scholars and institutions use EIO model to evaluate the building's carbon emissions. Japan used this model very early, its official research institution constructed Provincial Building Research Institute, Japan Promotion Association for Human and Environmental Symbiosis, and Architectural Institute of Japan, which adopted input-output method in 1990 to estimate the carbon emissions and materials and energy consumption in construction stage and trial stage, and formed the subsequent LCCO2 computing system[10][11]. And Shimizu Corporation, Kashima Corporation, Obayashi Corporation and other non-governmental institutions in Japan respectively established actuarial and rough estimate models with EIO model in the middle of 1920s, but the estimate system is not open to the public. China's Chen Guoqian [12] established ecological system measurement method and database for the building's carbon emissions according to 2007 Input-Output Table of China; Chang Yuan [13] calculated the building's chemical energy and pollution emissions according to 2002 Input-Output Table; and the research of Ji Junping [14] proved that 97.1% emissions of the building industry emissions were stemmed from other sectors rather than direct emissions.

Because the calculation theories of two models are different, when these two models are used to evaluate the same building, there will be distinct discrepancies between their measurement results. LCA model adopts direct consumption and carbon emissions factors of energy and materials as calculation basis, the building's production stage involves miscellaneous material kinds, each producer's actual energy consumption is not same and hard to be counted, and the consumption of some materials and energy is easy to be neglected, so such model calculation is very difficult. The theoretical foundation of EIO model is “GHG emissions of object rely on those of several objects, and the relied objects are related with infinite objects”, indicating that, EIO model takes the entire system as research object, instead of single material or technology. However, this model can be only used to work out the average environmental load of the materials with certain industrial type, such as steel products, but cannot distinguish the environmental load of individual materials, such as reinforced bar and angle bar, and considered energy consumption of production equipment and other relevant materials, so the calculation result is usually bigger than that of LCA model. According to the statistical results of Japan, such as steel product category, the calculation result of EIO model was 1.111-1.287kg CO2/kg, and the measurement results of direct energy consumption showed that, section steel was 0.634-1.089kg CO2/kg, reinforced bar was 0.639-0.965kg CO2/kg, and steel plate was 1.599kg CO2/kg.

This paper tries to combine the advantages of EIO model and LCA model to establish hybrid evaluation model for counting the building GHG emissions, and reflect emissions level of Chinese buildings by using Chinese input-output table and emissions data. This model is applicable to the carbon emissions evaluation of residential houses, office buildings, commercial buildings and other kinds of new buildings, which can be utilized to evaluate the building life stages, estimate the direct emissions and indirect emissions, and make comparative analysis for the existing measurement model results.

Research Method

Life cycle framework of building

LCA refers to the analysis of environmental impact of one product in production, utilization, rejection and recycling stages, including energy utilization, resource consumption and pollutant emissions [15]. LCA contains 4 parts, which are respectively target and scope definition, inventory analysis, impact evaluation and result interpretation. In this paper, the boundary of building system includes building materialization, utilization and dismantling processes (See Fig. 1).

Greenhouse gas emissions of the building life cycle researched and counted this time contain direct emissions and indirect emissions (see Fig. 1). The building's direct emissions refer to the emissions generated during production and utilization, mainly including energy combustion in the building's materials production, construction, operation, and maintenance and dismantling stages; indirect emissions refer to the emissions generated by production chain sectors during the building materials production, construction and operation, namely, the sum of emissions in all upstream stages.

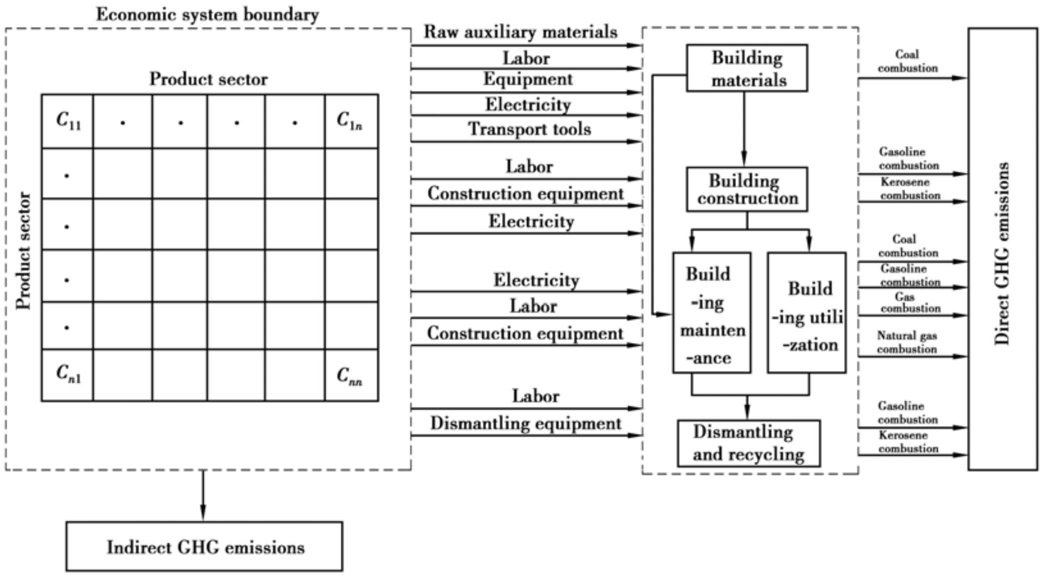

Fig.1 Direct and indirect emissions in the building life cycle

EIO (ecological input-output) model

Leontief [16] proposed EIO model for the first time in 1970 and used it in the research of industrial pollution emissions. Proops[17] analyzed CO2 emissions and control program selection with IO method. Vaze [18] calculated British EIO counting and forecasting. Chinese Li Li [19], Lei Ming [20] and Huang Xueliang [21] developed the research on resources - environment and energy - environment based on this model. This paper adopts the ecological input-output model proposed by Chen Guoqian[12], the basic hypotheses are: national economy sectors have direct proportion relationship between input and output; all equipment used for product production and service supply can be classified into certain particular sector; the calculate result indicates the environmental impact generated product production and service supply meeting the sector's final demand; import products and local products have the same environmental impact intensity. This model reformed the traditional economic input-output table, and put GHG emissions into consideration to obtain EIO table [22].

According to ecological input-output table, the ecological economic system contains n sectors and considers m kinds of GHG emissions can be represented as matrix form:

$$F + \varepsilon X = \varepsilon Y \quad (1)$$

Where, F means net GHG emissions matrix, X means economic input-output matrix, Y means local output matrix, and ε means GHG emissions intensity. Then GHG emissions intensity matrix can be indicated as:

$$\varepsilon = F(Y - X)^{-1} \quad (2)$$

Lead in unit output value direct GHG emissions intensity and technological and economic matrix A, as follows:

$$f = FY^{-1}$$

$$A = XY^{-1}$$

Then Expression (2) can be rewritten as:

$$\varepsilon = f(I - A)^{-1} \quad (3)$$

Where *I* is unit matrix, Expression $(I-A)^{-1}$ is called Leontief inverse matrix. This model only needs to multiply GHG emissions intensity of any product by the corresponding flow to get the GHG emissions reflected by this object.

Modeling concept of ecological input-output model is from top to bottom. The model takes national economy as system boundary, which contains the product's entire upstream stages, reflects the interrelation among economic sectors, and belongs to one measurement method on the basis of system theory. What should be emphasized is that, this model can only reflect the product's emission situation before final utilization and rejection stages, which is one effective indirect emissions measurement tool, but the direct emissions in final utilization and rejection stages should be calculate additionally. In addition, this method can only reflect the impact of production and demand in a particular year on emissions, but cannot embody the cross-year impact of production and demand on the pollutant emissions. So two disposal methods can be used, first, multiply the intensity of this year by direct emissions intensity change factor; second, multiply the intensity of this year by currency purchasing power factor. This paper adopts the second method for data disposal.

Hybrid life cycle assessment of building

Hybrid life cycle is to integrate LCA and EIO within one framework, which reserves pertinent calculation of LCA for direct emissions of fossil fuel, and effectively utilizes EIO model as well to reduce input of labor and materials during calculation and more effectively estimate the quantity of indirect emissions. According to the division of direct and indirect emissions, the building GHG emissions can be represented as:

$$GHG_L = GHG_{EIO} + GHG_P \tag{4}$$

$$GHG_{EIO} = \sum CI_i \times CTP_i \tag{5}$$

$$GHG_p = \sum EF_j \times E_j \tag{6}$$

GHG_L, GHG_{EIO}, GHG_P respectively mean total GHG emissions of the building's total life cycle, indirect GHG emissions calculated with EIO, and direct GHG emissions calculated with LCA. CI_i means the building's GHG emissions intensity corresponds to No. i labor, materials and equipment in all stages; and CTP_i means comprehensive total price corresponds to No. i labor, materials and equipment. This data can be obtained from project settlement data and daily payment account of the building. EF_j means carbon emissions factor of No. j common energy, and E_j means different energy kind.

According to the building life cycle stage, GHG emissions can be divided into materialization, utilization and dismantling stages, and the GHG emissions in all stages are respectively indicated with GHG_L, GHG_O and GHG_D.

$$GHG_L= GHG_L+ GHG_O+GHG_D \tag{7}$$

In the building's materialization stage, GHG_L includes two major emission processes of building materials and building construction. Building materials can be achieved by multiplying GHG emissions intensity worked out with EIO model by price of building materials in the list of quantities. Kerosene, gasoline and other direct emissions during construction can be calculated according to energy GHG emissions factor determined in National Guidelines for National Greenhouse Gas Emission Inventories published by Intergovernmental Panel on Climate Change (IPCC); and labor and machinery can be obtained from GHG emissions intensity, which is got by multiplying comprehensive unit price of labor and machinery in the list of quantities by EIO.

In the stage of the building's utilization, GHG_O consists of building maintenance and building operation. Emission calculation method of building maintenance and construction is same. Building operation mainly includes direct emissions caused by gasoline, kerosene, fire coal, gas and natural gas for building heating, cooking and air conditioning, as well as indirect emissions arising from building electricity, water and property management.

GHG_D in the stage of building dismantling is composed of building dismantling and construction waste disposal. The calculation method of GHG emissions in dismantling stage is as same as that of building construction process. In theory, construction disposal needs to consider that, part of building materials enter recycling process and have not been buried, so building recovery coefficient δ should be set. However, China still stays in the stage of low-level utilization of construction garbage[23], mainly recovers the building's steel products and part of building blocks, and the recovery proportion is not same in different places, so recovery coefficient δ can be determined according to the local actual situation.

Parameter Calculations

Data source

The calculation core of indirect emissions is the calculation of sector carbon emissions intensity. In accordance with input-output tables of 135 sectors published by the National Bureau of Statistics in 2007 and direct GHG emissions data of that year in China1, this paper uses EIO model to work out the national-level GHG emissions intensity (t/10,000 RMB). The total GHG in this paper is indicated with CO2-eq, which is the CO2 equivalent2 after conversion of CH4 and N2O.

The calculation core of direct emissions is the determination of fossil fuel carbon emissions factor. The release institutions of emissions factor mainly include IPCC, DOE/EIA (Department of Energy of the United States), IEEJ (Institute of Energy Economics Japan), Energy Research Institute of NDRC and Chinese Academy of Engineering (CAE). This paper mainly collects the emission factors of coal, gasoline, kerosene, diesel, gas and liquefied petroleum gas in relation to the building's direct emissions.

Main parameter

Parameters of direct emissions. Through collection of carbon emissions factors of main energy made by domestic and foreign research institutions, direct emissions factors caused by building energy consumption are as shown in the following Table 1. In order to guarantee the uniformity of energy emissions results, this paper suggests using the emission factors of IPCC Guidelines for National Greenhouse Gas Emission Inventories for calculation.

Table 1 Carbon emissions factor of main energy in building life cycle

Energy Type	Release Institution	Emission Factor/(kg $[CO_2]\cdot kg^{-1}$]
Coal[3]	IPCC Guidelines for National Greenhouse Gas Inventories	2.772
	DOE/EIA	2.574
	IEEJ	2.772
	Energy Research Institute of NDRC	2.741
	CAE	2.493
Gasoline	IPCC Guidelines for National Greenhouse Gas Inventories	2.031
Kerosene	IPCC Guidelines for National Greenhouse Gas Inventories	2.095
Diesel	IPCC Guidelines for National Greenhouse Gas Inventories	2.171
Liquefied petroleum gas	IPCC Guidelines for National Greenhouse Gas Inventories	1.849
Coke oven gas	IPCC Guidelines for National Greenhouse Gas Inventories	1.301
Natural gas	IPCC Guidelines for National Greenhouse Gas Inventories	1.644

There are two calculation modes for direct emissions during transport, first, measure and calculate according to transport tool and the actual transport distance; second, measure and calculate according to average transport distance after statistical analysis. In order to simply the calculation, this paper adopts the second method. According to the analysis of Chinese freight composition, average transport distance of main building materials and GHG emissions coefficients of different

[1] This data is estimated according to energy balance sheet of China of current year and the calculation method of IPCC Guidelines for National Greenhouse Gas Inventories. The specific calculation process is as shown in Reference [12].
[2] This equivalent is converted by using the proportion of CO_2:CH_4:N_2O=1:31:210 in global warming potential program (GWP).
[3] “Coal” called in this Table is raw coal and washed coal referred in IPCC Inventories.

transport modes are achieved (see Table 2, Table 3).

Table 2 the Average Transport Distance of Main Building Materials [24]

Building Materials	Transport Distance[km]	Building Materials	Transport Distance[km]
Sandstone	200	Glass	100
Cement	100	Wood	80
Steel products	125	Paint	80
Walling	60	Nonmetallic minerals	50
Ceramics	105	Concrete blocks	50

Table 3 the Emissions Coefficient of Different Transport Modes

Transport Mode	Greenhouse Gas Emissions Coefficient [kg/t·km]
Railway (diesel locomotive)	0.239
Highway (gasoline)	0.124
Highway (diesel)	0.166
Inland water transport	0.031

Parameters of indirect emissions. According to direct GHG emissions data in China in 2007[12,14] and sectoral input-output tables of 135 sectors in 2007, it is possible to establish 2007 ecological input-output table, and work out GHG emissions intensity of each sector. The emissions intensity values related to buildings are as shown in Table 4. During calculation, it is allowable to multiply the emissions intensity provided in Table 2 by the corresponding materials, labor and other amounts to get the corresponding GHG emissions. The corresponding sectors of the common materials, equipment and labor during construction are as shown in Table 5.

Table 4 Sector Greenhouse Gas Emissions Intensity[t/10k RMB]

Sector No.	Sector Name	Total Greenhouse Gas (GWP) [t CO_2=eq/t]
009	Mining-beneficiation industry of non-ferrous metal mines	3.89E+00
010	Mining-beneficiation industry of nonmetallic mines and other mines	3.48E+00
027	Bast fiber textile, tiffany textile and fine processing industry	3.42E+00
032	Wood processing and wood, bamboo, rattan, palm and grass product industry	3.63E+00
034	Papermaking and paper product industry	3.60E+00
037	Petroleum and nuclear fuel processing industry	7.47E+00
042	Paint, printing ink, pigment and similar product manufacturing industry	5.37E+00
043	Synthetic materials manufacturing industry	5.95E+00
044	Special chemical product manufacturing industry	6.46E+00
047	Chemical fiber manufacturing industry	5.48E+00
048	Rubber product industry	4.40E+00
049	Plastic product industry	5.42E+00
050	Cement, lime and gypsum manufacturing industry	1.56E+01
051	Cement and petroleum product manufacturing industry	8.53E+00
052	Tile, stone and other building materials manufacturing industry	9.02E+00
053	Glass and glass product manufacturing industry	7.07E+00
054	Ceramic product manufacturing industry	5.62E+00
055	Refractory materials product manufacturing industry	5.97E+00
056	Graphite and other nonmetallic minerals product manufacturing industry	8.16E+00
059	Steel rolling processing industry	6.94E+00
062	Non-ferrous metal rolling processing industry	4.45E+00
063	Metal product industry	4.83E+00
064	Boiler and prime motor manufacturing industry	3.62E+00

065	Metal processing machinery manufacturing industry	3.77E+00
066	Hoisting transport equipment manufacturing industry	3.89E+00
067	Pump, valve, compressor and similar machinery manufacturing industry	4.11E+00
068	Other universal equipment manufacturing industry	4.09E+00
069	Mine, metallurgy, building's special equipment manufacturing industry	3.99E+00
070	Chemical industry, wood, nonmetal processing special equipment manufacturing industry	4.02E+00
072	Other special equipment manufacturing industry	3.79E+00
077	Motor manufacturing industry	3.54E+00
078	Power transmission and distribution and control equipment manufacturing industry	3.57E+00
079	Wire, cable, optical cable and electrical equipment manufacturing industry	3.84E+00
080	Home appliances and non-power implement manufacturing industry	3.36E+00
081	Other electrical machinery and equipment manufacturing industry	3.70E+00
082	Communication equipment manufacturing industry	2.81E+00
088	Instrument and meter manufacturing industry	2.99E+00
092	Electric power and heating power production and supply industry	1.26E+01
094	Water production and supply industry	3.60E+00
095	Building industry	4.88E+00
097	Road transport industry	2.45E+00
113	Real estate industry	5.30E-01

Table 5 Correspond sectors of the building materials, equipment, energy and labor[1]

Items	Sector No.	Items	Sector No.
Sandstone	010	Wire and cable	079
Cement	051	Crane	066
Wooden template	032	Valve, pump, heat pump	067
Water	094	Power transformation and distribution equipment	078
Building blocks, stone products	052	Air conditioner	080
UPVC/PE/PB pipes	049	Boiler	064
Glass	053	Labor (1)	095
Electric power, heating power	092	Labor (2)	113
Floor tiles, sanitary fittings and other ceramic products	054	Paint, preservative, adhesive	042
Reinforced bar, steel plate, section steel, wire rod, steel pipes	059	Bulldozer, excavator, road roller, mixing equipment	069

Note: Table 4 is emissions intensity in 2007. If emissions intensity of other years (after 2007) needs to be calculated, multiply currency purchasing power factor of the current year corresponding to 2007. 2008- 2011 currency purchasing power factors are as shown in Table 6.

Table 6 Annual purchasing power of money factor in China

Year	Purchasing Power Factor
2008	0.941
2009	0.948
2010	0.916
2011	0.867

Calculation Examples

[1] Labor (1) is the corresponding emission intensity during building construction, repair and dismantling. Labor (2) is the corresponding emission intensity of property management during operation.

Building information

This paper selects one residential building of Shanghai as example. This building was established in 2009, having 5-storey reinforced bar concrete structure and total building area of 2831.28m^2. Other specific information is as shown in Reference [25]. Raw Reference has utilized LCA method to measure and calculate the carbon emissions of this building's total life cycle, and this paper measures and calculates the GHG emissions with hybrid life cycle method.

Results and analysis of GHG emissions

Gross GHG emissions GWP of this building is 4512.13t, and annual emissions of unit area is 31.88kg, it is about 1.36 times (gross 3,223t, unit area year 22.8kg) as much as the original calculation result through comparison with the original result. The first reason is that the original calculation only considered CO2 emissions, without considering emissions of CH4 and NO2; and the second one is the calculation results arising from EIO model are generally higher that those of LCA calculation.

As shown in Fig. 2, according to the distribution of this building's total life cycle emissions, the building's operation stage contributed the most emissions, 87.3% of total emissions, the second is building materialization stage, accounting for 11.4%, and the least is building dismantling stage, only accounting for 1.3%. It can be found through analysis of direct and indirect emissions proportion in different stages that, the direct emissions proportion in building materialization[1] is only 4.9%, similar to the research result of Ji Junping[14] (97.1%), because upstream nonmetallic minerals production, metal rolling and electric power sectors generate GHG emissions in quantity, this also proves that, controlling emissions of upstream building materials production sector and improving utilization efficiency of building materials will have important significance for emission reduction in the process of materialization. In building operation stage, this building is hot in summer and cold in winter, without heating requirement in winter, and its indirect emissions are mainly from power utilization, with proportion of 89%, indicating that taking necessary building energy conservation measures and reducing energy consumption will cause direct impact on building operation stage. In building dismantling stage, this paper fails to consider construction waste recycling, so it is calculated with direct dismantling and burial method.

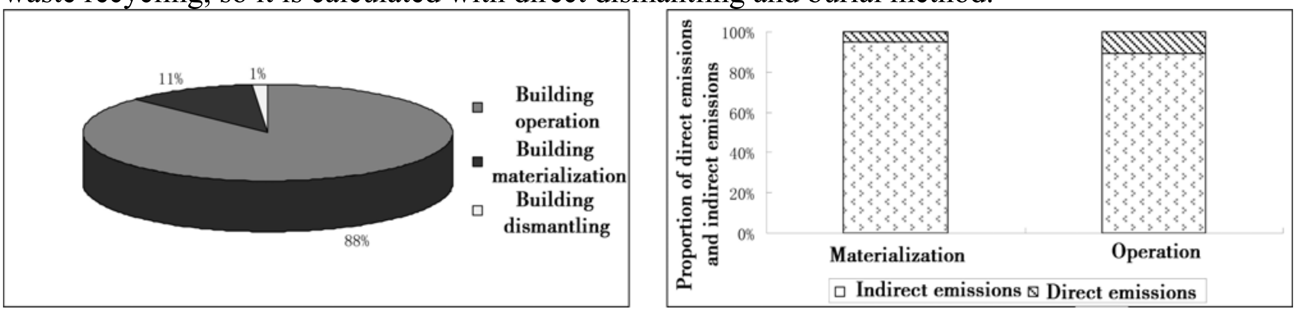

Fig. 2 Greenhouse Gas Emissions Distribution in Example

Conclusions

Buildings are the important source of GHG emissions, so it is of great significance to control the building's GHG emissions. This paper combines EIO and LCA methods and applies hybrid life cycle model to analyze and measure the GHG emissions of the building's total life cycle, and establish relevant mathematic model. This model has put the building's direct emissions and indirect emissions into consideration to calculate building emissions according to materialization, operation and dismantling stages. This model is able to systematically quantify the building GHG emissions, thus avoiding the disadvantages of the traditional LCA model, such as much data required, large quantity of calculation and truncation error, effectively utilizing the existing project price data and daily energy consumption data, and reducing input of labor and materials during accounting.

According to the analysis of the actual case conducted with this model, we can find that the key

[1]Because building material production and building industry belong to different sectors, this paper puts emissions of building materials during production in indirect emissions for calculation.

to the building GHG emissions is to control emissions in operation stage, especially reduce the building's energy consumption. Major control point in the building materialization stage is emission level of upstream materials production sectors. In the present stage, selecting reasonable building materials to improve the utilization efficiency of building materials can reduce the level of GHG emissions to certain extent. In the current stage, because dismantling stage only accounts for the relatively small proportion, its impact on the building's emissions can be temporarily ignored.

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