Ecological Footprint of Residential Building in Xining

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Abstract: The construction industry has a very significant environmental impact. Based on the theory of ecological footprint, this paper constructs a building life cycle assessment model, which takes Xining residential buildings as the research object, the ecological footprint of a residential building in Xining was calculated by using the advanced ecological footprint model – “provincial hectare method”. The aim is to understand the impact of buildings on the environment, and strive to resolve environmental pollution from the source. The results show that the ecological footprint of the building is 570.32 hm², which is 1.52 times its ecological carrying capacity. There is an ecological deficit. The ecological deficit should be reduced by improving the sustainable use of materials to promote the sustainable development of the construction industry.

1. Introduction
With the acceleration of urbanization and the speed of infrastructure construction, the construction industry has developed rapidly. The area of newly built houses in China each year is as high as 1.6 to 2 billion m²[1]. At the same time, environmental problems have also become increasingly serious. Studies have shown that the construction industry consumes 30% of raw materials, 42% of energy, 25% of water, and nearly 34% of direct, indirect air pollution, noise pollution, electromagnetic pollution, etc. Construction waste accounts for solid waste generated by human activities 40% [2]-[3]. The construction industry consumes a lot of resources, energy and generates a lot of environmental emissions. As everyone knows, Xining is an ecologically weak area. The negative impact of the construction industry on the environment is outstanding. It is imperative to resolve the contradiction between the rapid development of the construction industry and environmental degradation. At present, there are mainly two types of evaluation systems for the environmental impact of the construction industry at home and abroad. One is a frame-based evaluation system, such as BREEAM in the United Kingdom, LEED in the United States, and Green Building Evaluation Standard in China. Quantitative evaluation systems for life cycle assessment, such as ENVEST in the United Kingdom, BEES in the United States, Standard for Life Cycle Sustainable Assessment of Construction Engineering in China, etc[4]. However, there are the following problems: the frame-based evaluation system is mostly based on the expert scoring mechanism, with large artificial influence factors, and has a certain subjectivity. the determination of the weight system in the quantitative system based on life cycle assessment lacks standards, is highly controversial, and the evaluation system fails to establish a connection with the surrounding ecological environment. Ecological footprint is to provide human survival resources and absorb the total ecologically productive area of human-generated waste. According to research estimates by Stockholm Environment Institute, the environmental impact calculated by the ecological footprint component method is about 80% to 90% of the actual value [5],
and because of its simple calculation and easy understanding, it is widely used in tourism Industry, manufacturing, but in the field of construction industry, the ecological footprint is less applied. In order to quantitatively evaluate the environmental impact of buildings and promote the sustainable development of the construction industry, this paper divides buildings into pre-use, use and maintenance, demolition phases, and uses the ecological footprint analysis method to calculate the environmental impacts of buildings throughout their life cycle. The main purpose is to propose a detailed model to calculate the impact of the building on the environment, to achieve a quantitative assessment of the environmental impact on the life cycle of residential buildings, and to provide a reference for project decision making.

2. Method of ecological footprint

The theory of ecological footprint expresses all kinds of resources that the ecosystem provides to human uniformly with the biological productive area, according to the difference of productivity, the biological productive area is divided into six types: cropland, pasture, forest land, building land, fossil energy land and sea.

\[ Ef = N \cdot E_{f} = N \cdot r_{j} \cdot \sum_{i=1}^{n} (c_{i} / p_{i}) \]  

Where \( Ef \) is ecological footprint \((\text{hm}^2)\), \( N \) is number of population, \( E_{f} \) is per capita ecological footprint, \( j \) is type of ecologically productive land, \( i \) is type of consumption item, \( c_{i} \) is the per capita annual consumption of the \( i \)-th type of consumption item \((\text{t/person})\), \( p_{i} \) is the average annual productivity of \( i \) consumption items for ecologically productive land production \((\text{t/hm}^2)\), \( r_{j} \) is the equilibrium factor.

\[ r_{j} = \bar{p}_{i} / \bar{P} = (Q_{i} / s_{i}) / (\sum Q_{i} / \sum s_{i}) \]

where \( r_{j} \) is the equilibrium factor of type \( i \) bio-productive land \((\text{nhm}^2/\text{hm}^2)\), \( \bar{p}_{i} \) is the average productivity of type \( i \) land \( (*10^{3} \text{J}/\text{hm}^2)\), \( \bar{P} \) is the average productivity of Qinghai Land \( (*10^{3} \text{J}/\text{hm}^2)\). \( Q_{i} \) is the yield of type \( i \) land and \( s_{i} \) is the area of type \( i \) land. In 2015, the equilibrium coefficients of different land types in Qinghai Province are shown in Table 1.

| Table 1. equilibrium factor of different types of land in Qinghai Province (2015) |
|--------------------------------------------|
| Cropland | Forest | Pasture | Built Land | Sea | Fossil energy land |
| 0.71     | 0.01   | 1.19    | 0.71       | 0.005 | 0.01               |

The construction land in Qinghai mainly occupies cropland, so the equilibrium factor of the construction land uses the equilibrium factor of the cropland. Human mainly depend on forest to absorb CO\(_2\), so the equilibrium factor of fossil energy land adopts equilibrium factor of forest. The introduction of yield factor is to solve the problem that the productivity of the same type of land is different in different regions and climatic conditions, to establish a unified standard in different regions.

\[ y_{x}^{i} = \bar{p}_{x}^{i} / \bar{P}_{i} = (Q_{i} / s_{i}) / (Q_{i} / s_{i}) \]

Where \( y_{x}^{i} \) is yield factor of type \( i \) biological productive area in \( x \) region, \( \bar{p}_{x}^{i} \) is average productivity of type \( i \) land in \( x \) region \( (*10^{3} \text{J}/\text{hm}^2)\), \( \bar{P}_{i} \) is average productivity of type \( i \) land in Qinghai Province \( (*10^{3} \text{J}/\text{hm}^2)\), \( Q_{i} \) is the yield of type \( i \) land in \( x \) region; \( s_{i}^{x} \) is the area of type \( i \) land in \( x \) region, \( Q_{i} \) is the yield of type \( i \) land in Qinghai Province and \( s_{i} \) is the area of type \( i \) land in Qinghai Province. Table 2 shows the yield factors of different types of land in Xining City in 2015.

| Table 2. yield factor of different types of land in Xining (2015) |
|--------------------------------------------|
| Cropland | Forest | Pasture | Built Land | Sea | Fossil energy land |
| 7.63 | 3.52 | 1.09 | 7.63 | 0.35 | 3.52 |

The ecological carrying capacity of residential buildings is defined as the bio-productive area that can be provided by a certain area for residential building development. When the ecological footprint of residential building development in this area is larger than its corresponding ecological carrying
capacity, the ecological deficit indicates that the development of residential buildings in this area is in an unsustainable state and some measures should be taken. On the contrary, it shows that in the state of ecological surplus, this area residential development is in the stage of sustainable development.

\[
Ec = N \times ec = N \times (a_i \times r_i \times y_i)
\]

(4)

Where Ec is the regional ecological carrying capacity, N is the population, ec is the building land per capita ecological carrying capacity, \(a_i\) is the per capita biological production area, \(r_i\) is the equilibrium factor, \(y_i\) is the yield factor.

3. Ecological footprint evaluation model of Construction Project Life Cycle

The model evaluates residential buildings from the perspective of resource consumption. The boundaries can be divided into vertical and horizontal boundaries. Horizontal boundary is mainly divided into four parts: agriculture, industry, construction and occupants. The electricity and water consumed in use phase of building belong to the system. The manufacturing of furniture, appliances, decoration and other objects are outside the system boundaries of this study. Vertical boundary is the whole life cycle of the building, that is the cradle to the grave, the mining of building materials as a starting point and finish at the completion of the demolition of the building. For the division of the building’s entire life cycle, the research by Professor Zhang Zhihui is divided into the pre-use phase, the use and maintenance phase, the demolition and disposal phase [6]. Decision-making stage does not involve the consumption of resources, this article will not be considered, but good decisions can effectively reduce energy consumption, reduce ecological footprint. The research in this article can provide a reference for project decision-making. The whole life cycle ecological footprint of a building refers to the materials, energy and waste generated during the whole life process, it is expressed by six biological production areas. Finally, the equilibrium factors are used to convert various types of production area into provincial hectares as the unit of measurement land area.

\[
EF_{lc} = EF_{wu} + EF_{ope} + EF_{dem}
\]

(5)

Where \(EF_{lc}\) is the ecological footprint of the whole life cycle of a building; \(EF_{wu}\), \(EF_{ope}\) and \(EF_{dem}\) are the ecological footprints of the pre-use, use and maintenance, demolition and dispose phases of a building respectively.

3.1. Ecological footprint of pre-use phase

The ecological footprint in pre-use stage is the direct and indirect environmental impacts from the exploitation of raw materials to the use of the building, namely, the direct and indirect environmental impacts from the pre-use stage of the building, transportation of fuel to and from construction sites, municipal solid waste generated during working hours, materialization, transportation and production of building materials, machinery and equipment used in construction, and energy consumed in the use of machinery and equipment in this study, we consider only the fuel type, with electricity consumption considered separately. In addition, there is the amount of water consumed during construction and the land occupation caused by generated municipal solid waste [7]-[8].

(1) The ecological footprint of manpower mainly consists of three parts: the food consumption of construction workers on construction sites, the urban solid waste generated by workers during working hours and the ecological footprint caused by worker mobility.

\[
EF_{wf,fd} = (EF_m \times N_w \times N_{wd})/(h_m \times h_w)
\]

(6)

Where \(EF_{wf,fd}\) is ecological footprint of food (hm²/year), \(EF_m\) is a per-meal ecological footprint (hm²/year/meal) \(N_w\) is the number of workers on site and \(N_{wd}\) is the duration of the project, \(h_m\) is 8h meal \(h_w\) is a day’s work, usually 8h a day’s work.

\[
EF_{wf} = F/E_p \times r_j \quad E_p = A/E
\]

(7)

\[
EF_{wu} = \frac{EF_{f}}{\text{consumption}}
\]

(8)

Where \(EF_{wu}\) is the ecological footprint of food consumption, \(EF_{f}\) is the ecological footprint of food, and \(\text{consumption}\) is the number of workers on site and duration of the project.
Where $EF_{wfs}$ is ecological footprint of worker mobility (hm²/year), $F$ is fuel consumption (GJ), $Ep$ is energy productivity of fuel, $r_j$ is equilibrium factor of forest, $A$ is the absorption coefficient, $E$ is the emission coefficient.

$$EF_{wfs} = \sum CR_{xt} * G_i$$

(8)

Where $EF_{wfs}$ is the ecological footprint of municipal solid waste (hm²/year) for workers; $CR_{xt}$ is the conversion coefficient (hm²/year/t) ; and $G_i$ is the annual waste (T/worker/year) for each worker.

(2) The ecological footprint of building materials comes from consumable materials and transportation materials. There are two types of bioproductive area corresponding to them, one is woodland corresponding to wood, and the other is fossil energy land corresponding to other building materials except wood.

$$EF_{mat} = \sum_i Cm_i * Ese_{mi} / EP * r_j$$

(9)

Where $EF_{mat}$ is ecological footprint of construction materials except wood (hm²/year), $Cm_i$ is material consumption (kg), $EP$ is energy production (MJ/hm²/year), $Ese_{mi}$ is material energy (MJ/kg) and $r_j$ is equilibrium factor of land use for energy.

$$EF_{wf} = C_{wf} / Y_{wf} * r_j$$

(10)

Where $EF_{wf}$ is ecological footprint of wood consumption (hm²/year), $C_{wf}$ is the consumption of wood(m³/year),$Y_{wf}$ is the output of wood (m³/hm²/year),$r_j$ is the equilibrium factor of forest land.

$$EF_{tr} = \sum (c_{ma,i} * N_{rep} / T_{cap} * D_{ma}) * T_{con} * r_j$$

(11)

Where $EF_{tr}$ is ecological footprint of material transport (hm²/year),$c_{ma,i}$ is material consumption per repeat task $j$ ($t/rep$),$N_{rep}$ is repetition times of task $j$,$T_{cap}$ is truck capacity (t),$D_{ma}$ is average distance (km),$T_{con}$ is truck consumption (l/100km),$r_j$ is equilibrium factor of land use for fossil energy.

(3) The type of machine used and the total hours are determined based on the project quantity list, and the ecological footprint generated by the use of machine manufacturing at the construction site is not considered.

$$EF_{mac} = Cm_c * Ese_{mc} * N_{td} * r_j$$

(12)

Where $EF_{mac}$ is the ecological footprint of machinery (hm²/year), $Cm_c$ is the energy consumption per shift (kg),$Ese_{mc}$ is the machine’s corresponding ecological productive land area (hm²/kg), and $N_{td}$ is the number of shifts, $r_j$ is equilibrium factor of land use for fossil energy.

(4) The municipal solid waste generated during the construction phase is mainly divided into two types, one is soil, and the other is mixed municipal solid waste, in which the amount of soil accounts for more than 80% of the total.

$$CR_X = EFX / Ep * (1 - (%RX / 100)) * (%SEX / 100)) * r_j$$

(13)

Where $CR_X$ is municipal solid waste conversion (hm²/year/t),$Ex$ is energy intensity of waste material production (GJ/t),$Ep$ is energy productivity of waste (GJ/ hm²/year) , assuming energy productivity of fossil fuels, %RX is waste recovery rate , the excavated soil was reused 100% on site, and the recovery rate of mixed municipal solid waste was 70%.%SEX is percentage of energy saved from recycling,$r_j$ is equilibrium factor of cropland. Finally, the ecological footprint of construction waste can be calculated according to formula (9).

(5) Chinese electricity generation mainly includes hydropower, thermal power, and wind power. Hydropower and thermal power account for about 98% of the country’s total power generation.

$$Me_f = 10 * q_e e_w e_w n_w e_f / Ye$$

(14)

Where $Me_f$ is the ecological footprint of thermal power consumption, $q_e$ is the annual average power consumption, $r_e$ is the proportion of thermal power generation to total power generation, $v_e$ is the calorific value of standard coal per unit weight, $e_w$ is the standard coal consumption per unit power
generation, \( n_w \) is the carbon emission factor for coal, \( Y_E \) is productivity of fossil energy land, \( r_j \) is equilibrium factor of fossil energy land.

\[ M_{ew} = q_e * c_s * A * 10^6 \]  

Where \( M_{ew} \) is the ecological footprint of hydropower consumption, \( q_e \) is the annual electricity consumption, \( c_s \) is the proportion of hydropower consumption, \( A \) is the ecological footprint of unit hydropower consumption in China.

(6) Ecological footprint of water

\[ EF_{ww} = w / F_p \times r_j \]  

Where \( EF_{ww} \) is the ecological footprint of water consumption (hm²/year), \( w \) is the water consumption (m²), \( F_p \) is the forest productivity (m²/hm²/year), \( r_j \) is equilibrium factor of forest.

(7) Most of the infrastructure and built are located in areas of high agricultural quality, and the land that is directly used is considered to be productive and arable.

\[ EF_{wb} = s \times \eta_j \]  

Where \( EF_{wb} \) is construction land weight EF(hm²/year), \( s \) is consumed land surface area (hm²/year), \( \eta_j \) is equilibrium factor of construction land equal to equilibrium factor of cropland.

3.2. Ecological footprint of use and maintenance phase

The ecological footprint generated by the use and maintenance phase consists of two major parts, one part is the energy consumed by the ventilation, lighting, heating, air conditioning and other building equipment used by the building to maintain its own functions, as well as the water and electricity consumed in the course of use, the other part is the ecological footprint of the materials, machinery and manpower used in maintenance. The ecological footprint of the electricity, materials and manpower used in the maintenance phase is calculated in the same way as in the pre-use phase of the above introduction, note that fuel consumption for building ventilation, lighting, heating, and water ecological footprint are calculated using the same method as the power ecological footprint, because in the use of water and building ventilation, lighting, heating fuel mainly rely on electricity[9].

3.3. Ecological footprint of demolition and disposal phase

Construction and demolition waste is the result of unsustainable use of natural resources and energy in production processes, resulting in economic losses. China mainly relies on humans and machinery for demolition, so the ecological footprint of the demolition phase is divided into three parts: energy consumption of equipment and manpower, and land occupation by solid waste treatment [10].

\[ EF_{dem} = EF_{direct} + EF_{nuclear} + EF_{people} \quad EF_{direct} = A \times r_j \]  

Where \( EF_{dem} \) is ecological footprint for the demolition and disposal phase of a building, \( EF_{direct} \) is ecological footprint for the occupation of land by solid waste treatment, \( EF_{nuclear} \) is energy consumption of construction machinery for the demolition phase, \( EF_{people} \) ecological footprint for manpower, \( A \) is waste treatment area (m²), \( r_j \) is equilibrium factor of cropland. The calculation method of ecological footprint of manpower and machinery is the same as pre-use stage.

3.4. Ecological carrying capacity of construction

The traditional ecological carrying capacity refers to the ecological carrying capacity of a certain year, but the building ecological carrying capacity refers to the ecological carrying capacity of the building life cycle, which is mainly borne by the floor area of the building.

\[ Ec' = \sum T \times Ec' \quad \beta = C / A \quad Ec' = \beta \times ec \]  

Where \( Ec' \) is the ecological carrying capacity of the building, \( T \) is the life cycle of the building, \( ec' \) is the ecological carrying capacity of the building in a given year, \( C \) is the floor area of the building, \( A \) is the area, \( ec \) is the ecological carrying capacity of the building in a given year.
4. Case study
The research object is a residential building in Xining. The specific material consumption and energy consumption are shown in Table 3. The total waste generated during the dismantling phase is 5192.698t. Using the formula in the model, the ecological footprint of each stage of the building is shown in Table 4, and the ecological capacity of the residential building is 375.2hm².

Table 3. Consumption of various materials and annual energy consumption

| Name of building material | Material dosage (kg) | Annual energy consumption during operation |
|--------------------------|----------------------|--------------------------------------------|
| Steel                    | 361384               |                                            |
| Cement                   | 341080.2             | Water 5320m³                               |
| Wood                     | 340m3                |                                            |
| Sand                     | 1079824.7            |                                            |
| Glass                    | 4700                 | Electricity 216000kwh                      |
| Water                    | 391531.3 m³          |                                            |

Table 4. Ecological footprint of each stage of the building’s life cycle

| Life cycle stages                      | Ecological footprint (hm²) |
|----------------------------------------|-----------------------------|
| Pre-use phase                          | Worker 86.98 | 462.62 |
|                                        | Material 358.84 |        |
|                                        | Machinery 18.74 |        |
| Pre-use phase                          | Construction waste 6.0E-05 | 462.62 |
|                                        | building land 0.06 |        |
| Use and maintenance phase              | Use 105.70 | 105.70 |
| Demolition and disposal phase          | Demolition waste 0.002 | 0.002 |

5. Results and discussion
The results show that the ecological footprint of the building is 570.32 hm² and the ecological carrying capacity is 375.2 hm² which means the ecological footprint of the building is 1.52 times of the ecological carrying capacity, and there is ecological deficit. In addition, 81.4% of the total ecological footprint is in the pre-use stage and 18.6% in the operation and maintenance stage. In the pre-use stage of building, the proportion of material ecological footprint reached 77.4%, the proportion of specific materials as shown in figure 1, steel as the dominant material. Therefore, to control the ecological footprint, improve the use efficiency of building materials, reduce the consumption of building materials is an effective way to reduce the ecological footprint.

Figure 1. Ecological footprint of materials

6. Conclusion
The purpose of this article is to quantify the impact of the entire life cycle of a building on the environment. Based on the ecological footprint assumption, a model for calculating the entire life cycle ecological footprint of a building project is constructed. The three stages of the life cycle of a building in Xining were analyzed, and the environmental impact of the life cycle of residential buildings was quantitatively evaluated, which provided a reference basis for project decision-making and pointed out the direction for reducing the ecological footprint. For future research, we should
consider the impact of gas emissions during construction on the ecological environment, further improve the ecological sustainability assessment theory of construction projects, provide a basis for formulating ecological optimal solutions, and promote ecological sustainable development of construction projects.

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