Predicted model of ecological footprint based on PLCA

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Abstract. As the global ecological environment continues to increase, the sustainability research of construction projects has become a research hotspot at home and abroad. In order to achieve sustainable development of the construction industry, research on fabricated buildings is essential. Prefabricated building construction is the key to prefabricated construction, so the study of the sustainability of prefabricated components requires more attention. This paper defines the ecological footprint types of prefabricated components, and constructs a prefabricated ecological footprint estimation model based on Process Life Cycle Assessment (PLCA), taking concrete prefabricated composite panels as an example. An ecological footprint benchmark for the sustainability of prefabricated building components is provided by a comprehensive estimate of the resources, energy, and extent of CO₂ emissions from the prefabricated process life cycle.

1. Introduction

1.1. Ecological footprint
Ecological footprint, also known as ecological occupancy, is an analytical tool for the consumption of natural resources. It refers to the total area of ecologically productive land needed to produce the resources consumed by a certain population and to absorb the waste generated by these populations[1]. In the ecological footprint calculation, resources and energy consumption projects are converted into six land types: cultivated land, grassland, woodland, construction land, fossil energy land and waters. The research on macro-ecological footprint aims to provide guiding suggestions for national, regional and industrial development, and the research purpose of micro ecological footprint is to have more practical significance in proposing specific measures for the problem. The study of ecological footprint of buildings is a relatively mature field in the study of micro-ecological footprints. It is easy to understand, has high transparency, strong applicability, and is richer and more comprehensive than carbon emissions. Many scholars use it as a representative building in research. One of the indicators of ecological environmental impact. Before this, most scholars’ research on the ecological footprint of buildings mainly focused on the stage of building construction, operation and demolition. The sustainable development of buildings is expected to be achieved by reducing energy consumption during the operation phase. However, with the promotion of energy-saving technologies, the energy used in the production of buildings itself is actually increasing gradually, especially in the construction phase [2-3]. Therefore, it is necessary to reduce the resource consumption during the construction phase [4]. Prefabricated buildings are now considered as one of the strategies to reduce
energy consumption during the construction phase, minimizing the energy consumption of building components and reducing overall energy consumption, and better achieving sustainable building development [5].

At present, the research on the sustainability of prefabricated components is mainly based on the research of Life Cycle Assessment (LCA) carbon emissions, and the research on its ecological footprint is rarely involved. In order to more accurately and clearly understand the extent to which the prefabricated building has an impact on the ecological environment, it is necessary to treat the prefabricated component as a separate research object. This paper only measures the impact of the prefabricated component production process on the ecological environment, and accurately measures the ecological footprint of the prefabricated components from a more microscopic perspective, so as to better control its impact on the ecological environment and achieve sustainable development.

1.2. Life Cycle Assessment
Life Cycle Assessment (LCA) is one of the most widely used methods for assessing the environmental load and resource consumption of products, processes and service lifecycle processes. There are three main methods for LCA: one is Process LCA (PLCA); the other is the input-output LCA (IO LCA); and the third is the hybrid LCA (HLCA).

A process-based LCA (PLCA) quantifies the resource consumption of direct input and indirect input of the manufacturing process, and is suitable for products with specific production processes [6]. For the application of the construction industry, the energy consumption of building materials is calculated by specific production steps, which also makes it more difficult to collect data and may cause calculation errors due to incomplete information.

The input-output LCA (IO LCA) is based on material flow and measures the degree of consumption and environmental impact based on national or regional economic input-output tables. The data of this method is more easily obtained, and it is also susceptible to different national and regional differences, and the impact of public data is different [6]. Compared to PLCA, IO LCA is suitable for computing resource consumption at the macro level.

The hybrid LCA (HLCA) combines the advantages of PLCA and IO LCA. It uses PLCA to accurately divide the production process to improve the accuracy of IO LCA, expand the computational boundary [7], and reduce data fluctuations, errors, etc. due to geographical differences. However, it is more complicated than PLCA calculations.

By comparing the above three methods and combining the research content of this paper, this paper chooses the PLCA method to establish the ecological footprint measurement model of prefabricated components. In view of the fact that this paper only considers the ecological footprint of prefabricated components and the prefabricated component production process is relatively simple. Although PLCA has the disadvantages of time-consuming and difficult data acquisition, the prefabricated component production process is relatively simple, which can alleviate this determination, and PLCA can more accurately measure the resource consumption of each production process.

2. Establishment of Predicting Model Ecological Footprint Calculation Model

2.1. Prefabricated component production process
At present, the production methods of domestic prefabricated components are mainly long-line pedestal production, fixed die table production, and assembly line production. The production of long-line pedestal is mainly suitable for the production of prestressed components, such as SP board, double T board, etc.

The production of fixed die table is mainly suitable for special-shaped components, such as stairs, balconies, air-conditioning panels, etc., which are special, variable and complex concrete structures.

Pipeline production, the position of the workers is relatively fixed, can achieve higher automation and intelligence, mainly suitable for simple components, such as truss reinforced laminated panels, double-sided laminated wall panels, wall panels, etc.
2.2. Calculation boundary
When calculating the ecological footprint, the calculation boundary should be identified first. This paper measures the ecological footprint of prefabricated components, including artificial ecological footprint, material ecological footprint and mechanical ecological footprint.

Artificial ecological footprint: refers to the ecological productive land area occupied by various household items consumed by production workers in the production process of prefabricated components. Among them, food is the most important part, and humans ingest energy from food for prefabricated component production activities.

Material ecological footprint: refers to the ecological productive land area occupied by CO2 emitted during the exploitation of raw materials, the consumption of resources in the production process and the consumption of energy. Mainly consider the main materials such as steel and concrete.

Mechanical ecological footprint: refers to the various resources, energy and ecological productive land area occupied by machinery in the production process of prefabricated components.

2.3. Model establishment
According to the ecological footprint calculation boundary of the prefabricated component production process, the ecological footprint EFPC in the prefabricated component production process mainly consists of artificial ecological footprint EFp, material ecological footprint EFm and mechanical ecological footprint EFr, as shown in calculation method (1)–(7).

\[EF_{PC} = EF_{m} + EF_{p} + EF_{r}\]  
\[EF_{p} = \sum_{w=1}^{W} n_{wp} f_{p}\]  
\[EF_{m} = \sum_{m=1}^{M} \sum_{w=1}^{W} n_{wm} \left( f_{m} + f_{CO2} e_{m} \mu_{m} \right)\]  
\[f_{m} = S_{mi}/O_{m} \times \lambda_{mi}\]  
\[EF_{r} = \sum_{w=1}^{W} \sum_{r=1}^{R} n_{wr} \left( f_{r} + f_{CO2} \alpha_{rc} n_{rc} \right)\]  
\[f_{rc} = S_{rc}/O_{rc}\]  
\[f_{r} = f_{rc} \times \lambda_{rc} \times n_{rc}\]

EFp refers to the ecological footprint of the production of prefabricated components. \( n_{wp} \) represents the labor consumption in w work, and \( f_{p} \) refers to the artificial ecological footprint factor.

EFm is the ecological footprint consumed by raw materials, w represents various jobs; \( n_{wm} \) represents the consumption of the m-th material in the work of w; \( f_{m} \) refers to the ecological footprint factor of the m-th material. The material is mainly a solid consumable material consumed by the PC component. \( f_{CO2} \) refers to the ecological footprint factor of CO2 emitted during the absorption of energy consumption; \( e_{m} \) refers to the energy contained in the i-th material; \( \mu_{m} \) refers to the carbon conversion factor consumed in the mining, processing and production of the i-th material. \( O_{m} \) refers to the national annual output of material m, \( S_{mi} \) refers to the area of ecological production type land corresponding to material m; \( \lambda_{mi} \) refers to the equilibrium factor of the ecological production type of land corresponding to material m.

EFr is a mechanical ecological footprint; \( n_{wr} \) indicates the consumption of mechanical r in work w; \( f_{r} \) is the ecological footprint factor of mechanical r; \( f_{rc} \) indicates the energy footprint of the energy consumed by the machine r; \( S_{rc} \) refers to the area of ecological productive land corresponding to the energy consumed by the machine r. Here, it mainly refers to the area of fossil energy. \( O_{rc} \) indicates the national annual production of energy consumed by machinery r; \( \lambda_{rc} \) represents the eco–productive land balance factor corresponding to the energy consumed by the machine r, and here mainly refers to the equilibrium factor of the fossil energy source; \( \alpha_{rc} \) refers to the carbon dioxide emission factor of the energy consumed by the machine r; \( n_{rc} \) indicates the amount of energy consumed by the machine r.

2.4. Reference value of key parameters
The key parameters of the ecological footprint measurement model are mainly the unit ecological
productive area and equilibrium factor, as well as the artificial ecological footprint factor, the material ecological footprint factor, the mechanical ecological footprint factor; in addition, the material contains energy \( e_m \), material carbon conversion factor \( \mu_m \), carbon dioxide emission factor for mechanical energy consumption \( \alpha_{rc} \) and many more.

According to the data provided by the Statistical Yearbook of the National Bureau of Statistics [8], the land area and output of various types in the country in 2017 are calculated. The ecological production land balance factor is calculated by Equation (8), See Table 1-2.

| Table 1 | China's national land area and its output in 2017. |
|---------|-----------------------------------------------|
| Arable land | 14918.73 | Woodland | 25290.81 | Grassland | 21935.92 | Waters | 30117.21 | Construction land | 3909.51 |
| Yield (×10^4 t) | 103935.30 | 30430.06 | 9752.42 | 6445.30 |

\[
\lambda_i = \frac{S_i}{\sum_{i=1}^{n} S_i / \sum_{i=1}^{n} \sigma_i} \quad (8)
\]

\( \lambda_i \) indicates the equilibrium factor of the area of ecological productive land I; \( O_i \) indicates the national area of land type i; \( S_i \) indicates the yield of land type I; \( n \) indicates the total number of land types (cultivated land, woodland, grassland, etc.).

| Table 2 | China's national ecological productive land balance factor in 2017. |
|---------|-----------------------------------------------|
| Arable land | 4.26 | Woodland | 0.74 | Grassland | 0.27 | Waters | 0.13 | Construction land | 4.26 | Fossil energy land | 0.74 |

According to the above equilibrium factor, the artificial ecological footprint factor, material ecological footprint factor and mechanical ecological footprint factor required for this paper can be calculated.

The artificial ecological footprint factor mainly considers the food consumption of the construction workers, because the energy of human labor is mainly provided by food. According to the “Chinese Dietary Guidelines”, the main ecological food types and demand of the construction workers are used to obtain the unit ecological productive land area of the food, so that the artificial ecological footprint factor is calculated to be 0.001191544ha/day (8 hours per day). Working day calculation).

Material ecological footprint factor According to the 2.4 formula and reference [9], the ecological footprint factor of the main material of this paper is obtained, as shown in Table 3.

| Table 3 | Material ecological footprint factor. |
|---------|-----------------------------------------------|
| Material name | National annual output | Unit ecological productivity land area | Ecological productivity land type | Material ecological footprint factor |
| Steel | 104642.05×10^4 t | 0.000037361ha/kg | Construction land | 0.00015915786ha/kg |
| Cement | 233084.06×10^4 t | 0.000016773ha/kg | Construction land | 0.00006977568ha/kg |
| Sand | 600344.2×10^4 t | 0.00003ha/kg | Waters | 0.0000065ha/kg |
| Gravel | 100491.2501×10^4 t | 0.000148458ha/kg | Arable land | 0.00063243108ha/kg |
| Water | 28761.2×10^4m³ | 0.000001044ha/kg | Waters | 0.00000013572ha/kg |

The mechanical ecological footprint factor is mainly expressed by the ecological footprint of the energy consumed (see Table 4). According to the calculations of Equations 2.6 and 2.7, the mechanical ecological footprint factor is determined according to the specific research content and then calculated.

| Table 4 | Energy ecological footprint factor. |
|---------|-----------------------------------------------|
| Energy name | National annual output | Unit ecological productivity land area | Ecological productivity land type | Energy ecological footprint factor |
| Gasoline | 1935046.6×10^4MJ | 0.000000131ha/MJ | Fossil energy land | 0.00000099694ha/MJ |
| Diesel | 24956430×10^4MJ | 0.000000101ha/MJ | Fossil energy land | 0.00000007474ha/MJ |
The reference values for materials, energy carbon conversion factors, and embedded energy are derived from references [10–12], see Tables 5 and 6.

Table 5. Material contains energy and its carbon conversion factor.

| Material name | Unit material contains energy (MJ/kg) | Carbon conversion factor (kg/MJ) |
|---------------|---------------------------------------|----------------------------------|
| Steel         | 26.52                                 | 0.0894                           |
| Cement        | 5.5                                   |                                  |
| Sand          | 0.6                                   | 0.00004013ha/kwh                |
| Gravel        | 0.2                                   | Fossil energy land               |

Table 6. Energy carbon dioxide emission factor.

| Energy name   | Carbon dioxide emission factor (kg/unit) | Unit |
|---------------|------------------------------------------|------|
| Gasoline      | 2.0306                                   | kg   |
| Diesel        | 2.1710                                   | kg   |
| Thermal power | 0.9533                                   | kWh  |

3. Case study

In this paper, a 2120×3800×60mm PC laminate is taken as an example and produced by pipeline production. The production process of PC laminated board includes: cleaning the die table; spraying the release agent; scribing; installing the mold; installing the embedded parts; tying the steel bars; quality inspection; concrete pouring; leveling, plastering; initial setting and pulling; curing; Labeling; lifting 13 procedures. The above process includes materials, resources, fossil burning consumption, and these consumptions are expressed by ecological footprint, including material ecological footprint, artificial ecological footprint, and mechanical ecological footprint. The production process and ecological footprint of PC laminates are shown in Figure 1.

![Figure 1. PC laminate production process and source of ecological footprint.](image)

*Comment: Art: Artificial ecological footprint  Mec: Mechanical ecological footprint  Mat:Material ecological footprint

According to the PC component ecological footprint estimation model, the ecological footprint of each process of PC laminates and the ecological footprint of PC laminates are obtained. The ecological footprint of PC laminates in this paper only considers the main raw materials. The calculation results
are shown in Tables 7 and 8.

| Process                          | Ecological footprint type | Consumption | Unit | Ecological footprint factor (ha/unit) | Ecological footprint (ha) |
|----------------------------------|---------------------------|-------------|------|--------------------------------------|---------------------------|
| Cleaning the mold                | Cleaning machine          | Mec         | 0.4  | kWh                                  | 0.000029702               | 0.000042638               |
| Spraying release agent           |                           | HL          | 0.4167 | LD                                   | 0.001191544               | 0.000496516               |
| Cross-line                       |                           | HL          | 0.01875 | LD                                   | 0.001191544               | 0.00022342                |
| Arrangement of mold              |                           | HL          | 0.15  | kWh                                  | 0.000029702               | 0.00015989                |
| Arrangement of embedded part     |                           | HL          | 0.06875 | LD                                   | 0.001191544               | 0.000992949               |
| Quality inspection hidden part   |                           | HL          | 0.05625 | LD                                   | 0.001191544               | 0.00081919                |
| Arrangement of steel             | Lifting machine           | Mec         | 0.05  | kWh                                  | 0.000029702               | 0.00005330                |
|                                  |                           | HL          | 0.0625 | LD                                   | 0.001191544               | 0.000074472               |
|                                  | Rebar Mat                 | 81.8        | kg    |                                      | 0.000159158               | 0.028662204               |
|                                  | Steel Mat                 | 0.1273      | kg    |                                      | 0.000159158               | 0.000044605               |
| Leveling and smearing            |                           | HL          | 0.05625 | LD                                   | 0.001191544               | 0.00067024                |
| Surface galling                  | Pulling machine           | Mec         | 4.93333 | kWh                                  | 0.000029702               | 0.000525870               |
|                                  |                           | HL          | 0.0166667 | kWh                              | 0.001191544               | 0.00019859                |
| Curing                           | Curing kiln               | Mec         | 12    | kWh                                  | 0.000029702               | 0.001279144               |
|                                  |                           | HL          | 0.025  | LD                                   | 0.001191544               | 0.00029789                |
| Vibration                        | Lifting machine           | Mec         | 0.53333 | kWh                                  | 0.000029702               | 0.000056851               |
|                                  |                           | HL          | 0.0625 | LD                                   | 0.001191544               | 0.000074472               |
| Hoisting and transport           | Lifting machine           | Mec         | 0.53333 | kWh                                  | 0.000029702               | 0.000056851               |
|                                  | Transport vehicle         | Mec         | 1.25  | kWh                                  | 0.000029702               | 0.000133244               |
|                                  |                           | HL          | 0.04791667 | LD                     | 0.001191544               | 0.000057095               |

*Comment: HL: Human labor; LD: Labor day.

| Ecological footprint type          | Ecological footprint (ha) | Proportion |
|-----------------------------------|---------------------------|------------|
| Artificial ecological footprint   | 0.0020082835              | 0.45%      |
According to the calculation results, the PC laminate with a size of 2120×3800×60mm and a volume of 0.49m3 has an ecological footprint of 0.4501052ha, and most of the ecological footprint comes from building materials, accounting for 98.90% of the electricity consumed by the machine. The ecological footprint only accounts for 0.66%, and the artificial ecological footprint only accounts for 0.45%. It can be seen that the sustainable development of PC components can be realized by reducing the resource consumption of materials.

4. Conclusion
This paper constructs a biological footprint measurement model of prefabricated components based on PLCA, which includes the artificial ecological footprint, material ecological footprint and mechanical ecological footprint measurement model of prefabricated components. The estimation model proposed in this paper can be used to comprehensively evaluate the energy, resources and the impact of CO$_2$ on the ecological environment of prefabricated components. Based on this model, the ecological footprint database of prefabricated components can be established to provide basic data for the research of the ecological footprint of fabricated buildings. The scope of application of ecological footprints in buildings has played a very positive role in promoting the sustainable development of fabricated buildings.

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