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Eco-footprint-based life-cycle eco-efficiency assessment of building projects

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ABSTRACT

The prominent conflict between today's rapidly growing building projects and the deteriorating natural environment demands proper assessment of the ecological efficiency of a project in its life cycle, and this problem is addressed in this paper. First, to express the environmental impact of the project throughout its life cycle, the concept of life-cycle eco-footprint of a building project is defined, and corresponding computational models are proposed. The former scope of application of eco-footprint mainly in the construction phase of a building project is thus expanded. Moreover, as a building has the functional values of accommodating people and providing space for activities, two comprehensive eco-efficiency indices based on life-cycle eco-footprint are developed: per capita annual efficiency and space efficiency, which are used to assess the efficiency of the eco-footprint consumed by the project throughout its life cycle and determine if the eco-footprint consumed in realizing the abovementioned functional values is ecologically sustainable. The proposed method is then applied to analyzing the eco-footprint and eco-efficiency in each phase of the life cycle of an exhibition hall in Wuhan, China; moreover, based on the analysis result, measures are proposed to improve the eco-efficiency and reduce the life-cycle eco-footprint of the project. The new method proposed in this paper is expected to play an important role in minimizing the environmental impact of building projects and achieving sustainable development in their life cycle.

1. Introduction

Survey shows that building industry consumes about 40% of global energy, and emits about 30% of carbon dioxide (Change Intergovernmental Panel on Climate, 2001). How to make the development of building projects sustainable by the environment has become a focus of international attention. China has a very large building industry, whose improper consumption of energy and resource, large amount of waste production, and carbon dioxide emission has made unprecedented negative impact on the environment (Zhang et al., 2008). In China, buildings consume 37% of the total energy use, and buildings with high energy consumption have occupied 380 billion square meters and account for 30% of the total built-up land nationwide. Buildings also account for 32% of all water use in China. Compared to developed countries, the average steel products consumed for every square meter of built-up area is higher by about 10–25%; in mixing every cubic meter of concrete, about 80 kg extra concrete and 30% of extra water is consumed. Buildings produce about 40% of the total amount of waste and emit equal percentage of carbon dioxide (Wu, 2012). By 2020, the built-up area in China will increase by about 80%, and the conflict between rapid development of buildings and the deteriorating environment needs to be addressed (Wu, 2011), so that ecologically sustainable development of building projects may be achieved.

In recent years, energy consumption and carbon emission have drawn the attention of investigators in China and abroad. For the operation of buildings, some scholars have developed computational methods (Neto and Fiorelli, 2008) and predictive methods of estimating energy consumption (Gonzalez and Zamarreno, 2005), and effective reduction of energy consumption are identified by evaluating the variation of energy consumption in different plans (Yang et al., 2012; Zhao et al., 2009). Others also studied the variation of energy consumption in the life cycle of a building in different plans (Ramesh et al., 2012; Utama and Gheewala, 2008), and energy consumption and carbon emission in different phases of the life cycle (Ouyang et al., 2011; Monahan and Powell, 2011; Gustavsson et al., 2010; Junnila et al., 2006); proposed methods of reducing carbon emissions (Gonzalez and Navarro, 2006; Hong et al., 2012; Kneifel, 2010; Rinne and Syri, 2013), models for computing carbon efficiency, and methods of increasing carbon efficiency (Li et al., 2013). Although energy consumption and carbon emissions are important indices of assessing the environmental impact of building projects, other factors such as material consumption, water resource consumption, and solid waste production also have impacts on the environment, so energy consummation and carbon

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emissions are not enough in a comprehensive assessment. In this paper, the ecological footprint throughout the life cycle of building projects is used as a collective index for comprehensively assessing the impact of energy and resource consumed, and carbon and solid waste produced in each phase of the life cycle on the environment.

Ecological footprint was proposed by Mathis Wackernagel in the early 1990's as an index for assessing ecological sustainability (Chambers et al., 2004). Eco-footprint methodology represents the demand of product and service projects on the biosphere in the form of land area required to produce the resources consumed by these projects and to absorb the waste produced by them (Bin and Parker, 2012). Widely used on personal, regional, national, and global levels (Alderson et al., 2012; Ewing et al., 2012; Kissinger, 2013; Valentina et al., 2008), eco-footprint is a simple, effective, and relatively comprehensive index (Bin and Parker, 2012; Li et al., 2010; Solis-Guzman et al., 2013) for assessing ecological sustainability; however, it has not been widely used in the assessment of ecological sustainability and ecological efficiency of building projects, except for a limited number of studies. Based on the WBCSD ecological efficiency model (World Business Council Sustainable Development, 2000). Li et al. (2010) developed a model for assessing the ecological efficiency of the development of urban residential buildings. In such a model, the built-up area is taken as the product/service value of the project, and the eco-footprint in the construction phase as environmental impact. Solís-Guzmán et al. (2013) also investigated detailed computational models for the eco-footprint of in the construction phase residential buildings in Spain, contributing to the application of eco-footprint in assessing the sustainability of buildings. However, both references only considered the eco-footprint during construction. Bin and Parker (2012) developed an eco-footprint model based on life-cycle analysis for assessing the sustainability of residential buildings, but computational methods for each phase of life cycle are absent; additionally, the eco-footprint of water resource consumed and solid waste produced throughout the life-cycle of project were excluded.

Therefore, two major deficiencies are found in current research: (1) only the eco-footprint during construction was addressed; (2) current eco-footprint models does not include either the eco-footprint of water resource consumed, or carbon dioxide emitted, or solid waste produced in all phases of a building project. In this paper, the life cycle is separated into 4 phases: preparation, materialization, operation, and demolition and waste disposal, and a set of models are proposed for systematically computing the eco-footprint of energy and resource consumed, carbon dioxide emitted, and solid waste produced in each phase of the life-cycle of a building project.

Additionally, studies on ecological efficiency assessment of building projects based on life-cycle eco-footprint are lacking. In realizing its functional values of providing accommodation for people and space for activities, a building project has impact on the environment and consumes eco-footprint which should meet the requirement of sustainable development. In support of an improved method of assessing the sustainable development of a building project, in this paper, two eco-efficiency assessment indices are proposed: per capita annual efficiency and space efficiency of the eco-footprint consumed by the project throughout its life cycle. The proposed method may provide guidelines for project decision-makers and related participants to make development-sustainable plans during the initial preparation phase and reduce the project's environmental impact, promoting sustainable development of the building project. The proposed method is also applied to analyzing the eco-footprint and eco-efficiency in each phase of the life cycle of an exhibition hall in Wuhan, China, and measures are then proposed for further improving the eco-efficiency and reducing the eco-footprint of the project.

2. Methodology

2.1. Life-cycle eco-footprint of a building project

In this paper, the eco-footprint during the life cycle of a building project EF_{tot} is a new concept defined to improve the deficiencies in currently available methods. The principle of computing EF_{tot} is as follows: (1) represent the amount of the resource and energy to be consumed, the solid waste to be produced, and the CO_2 to be emitted in each phase of the life cycle of the project using the area of fossil energy land, cropland, pasture land, forest land, built-up land or marine and inland water; (2) using equivalence factors, the land area of these different types of biologically productive (bioproductive) land are uniformly measured in units of "national hectare (nha)" (Wu, 2011) and then summed to obtain EF_{tot}. In this paper, "nha" is taken as the measuring unit, instead of the former commonly used unit of "global hectare (gha)", since "nha" can better represent national eco-footprint.

EF_{tot} includes the eco-footprint in 4 phases: preparation, materialization, operation, and demolition and waste disposal. It is used to comprehensively assess the project's impact on the natural environment, and calculated with Eq. (1):

$$EF_{tot} = EF_{pre} + EF_{con} + EF_{ope} + EF_{dem} \tag{1}$$

in which EF_{pre}, EF_{con}, EF_{ope}, and EF_{dem} represent the eco-footprint (nha) in preparation (including planning, design, and survey), materialization (including manufacture of materials and project construction), operation, and demolition and waste disposal respectively.

Jiang (2011) and Li (2012) showed that resource and energy consumption and carbon emission in the preparation and the demolition and waste disposal phases constitute a small portion in the life cycle, so the eco-footprint model of the two phases are converted with correlation coefficients from the model of the materialization phase.

2.1.1. Eco-footprint in the preparation phase EF_{pre}

EF_{pre} mainly comes from the eco-footprint of energy and resource consumed and CO_2 emitted by transportation, office equipment, lighting, air conditioners and domestic water, and is derived based on the eco-footprint in the materialization phase, as shown in Eq. (2):

$$EF_{pre} = \ell_{pre} \times EF_{con} \tag{2}$$

in which, ℓ_{pre} represents the transformation coefficient based on the eco-footprint in the materialization phase, with suggested value of 1.1% (Jiang, 2011; Li, 2012).

2.1.2. Eco-footprint in the materialization phase EF_{con}

EF_{con} represents the eco-footprint in the materialization phase of the building project, and is calculated with Eq. (3):

$$EF_{con} = EF_{mat} + EF_{act} + EF_{bui} \tag{3}$$

in which EF_{mat}, EF_{act}, and EF_{bui} represent the eco-footprint (nha) of manufacture of materials, construction activities, and built-up land respectively.

EF_{mat} is calculated with Eq. (4), and it mainly comes from (1) the eco-footprint of the consumed raw materials EF_{mr} (nha) which is calculated with Eqs. (5) and (2)) the eco-footprint of energy consumed and CO_2 emitted in exploiting, transporting and manufacturing the raw materials into building materials EF_{mp} (nha), which is calculated with Eq. (7). Different from other studies, Eq. (4) includes not only the eco-footprint of energy consumed and CO_2