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Decision-making tools for evaluation the impact on the eco-footprint and eco-environmental quality of green building development policy

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ABSTRACT

Building projects consume large amount of energy and resources, and emit solid waste and CO_2 harmful to the eco-environment. In order to study the eco-environmental impact of green building development policies, a "Green Building Eco-environment (GBE)" model is constructed with the method of System Dynamics and implemented using the Vensim software. The model is used to simulate and evaluate the current state and future trend of variation of the eco-environmental impact of green building development in Wuhan during the years 2008–2050 under current green building development policies. Some policy factors are then adjusted in the simulation to determine the optimal green building development policies, under which the quality of the regional ecological environment in Wuhan would be improved most economically.

1. Introduction

Green building is developed to alleviate the conflict between the rapid development of buildings and the deteriorating ecological environment (eco-environment). Building projects consume large amount of energy and resources, and emit solid waste and CO_2 harmful to the eco-environment, so the eco-environmental impact of green building development needs more detailed and quantitative understanding.

The degree of destruction of the eco-environment by a building project may be evaluated with "Building Eco-footprint" (Bin & Parker, 2012; Teng & Wu, 2014). an index based on the concept of Ecological Footprint (Eco-footprint), which is a simple, effective, and widely used index proposed by Mathis Wackernagel in the early 1990s (Li et al., 2010; Bin & Parker, 2012; Solis-Guzman, Marrero, & Ramirez-De-Arellano, 2013; Lawrence & Robinson, 2014; Shrestha, 2010).

However, the interaction between green building development and the eco-environment system is dynamic and complex, which cannot be completely delineated by a single index. Moreover, other factors, such as the ecological carrying capacity, current green building development policies, and other indexes of the eco-environment, also play a role in the interaction. Therefore, developing a system dynamics model would be more suitable for analyzing the eco-environmental impact of green building development.

System Dynamics (SD) studies the complex relationships between multiple factors in a system from macro-perspective and offers an effective method of modeling and simulation (Forrester, 1958; Richmond, 1998; Wolstenholme, 1990; Richardson & Otto, 2008). Nowadays, the SD method has become a popular technique in the research of system dynamics modeling and simulation. For instance, Shih and Tseng (2014) constructed a system model for estimating the economic benefits of energy-saving measures, and this model is used to study the economic benefits of different renewable energies consumed by buildings; with the SD theory, Yan (2006) built a giant system model of sustainable development in Chifeng, which was used to evaluate and forecast the current state and trend of variation of sustainable development in Chifeng and provide suggestions for policy makers; Dong and Liu (2013) built a system model for studying the strategies of large-scale development of green building. The SD method has been applied successfully by many researchers in various settings such as the sustainable development of energy (Blumberga et al., 2014), urban planning for carbon dioxide emissions (Fong, Matsumoto, & Lun, 2009), the carrying capacity of water resources (Feng, Zhang, & Luo, 2008), and construction performance (Wan, Kumaraswamy, & Liu, 2013; Han, Love, & Pena-Mora, 2013).

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However, few scholars have treated green building and the eco-environment as a dynamic system, and there is a lack of direct report on system dynamics model for analyzing the eco-environmental impact of green building development. In this study, the SD method is used to construct a "Green Building Eco-environment (GBE)" model for simulating the current state and trend of variation of green building and ecological systems, and the impact of green building development on the eco-environment is analyzed. Such a model is expected to facilitate our understanding of the interaction between green building development and the eco-environment, and its pattern of variation. After this Green Building Eco-environment System Dynamics (GBE-SD) model is verified, the eco-environmental impact of green building development policies in Wuhan in 2008–2050 is simulated and analyzed, and then some policy factors are optimized with this model. Wuhan is one of the first branch of pilot cities in green building in China, and about 2.7% green buildings of China are located here, which makes Wuhan the best selection of this study.

2. Methodology

2.1. System Dynamics method

System Dynamics (SD) provides a method of system analysis and simulation that quantitatively represents complex dynamic behaviors inherent in real-world systems, such as nonlinearity, hierarchy, and time-lag, using feedback models (Forrester, 1958; Richmond, 1998; Wolstenholme, 1990; Richardson & Otto, 2008). This method requires low-level data accuracy, but can describe complex, dynamic, high-order, and highly non-liner relationships among the factors in a huge system (Liang, 2008; Wang, 2010; Yuan et al., 2011; Zhang et al., 2014), so it is good for macro-perspective evaluation and forecast.

There are five system dynamics software: Vensim, Professional DYNAMO, Stella, Ithink and Powersim. Compared to others, Vensim not only provides user-friendly interfaces for causal loop diagram design, stock-flow diagram construction, model quantification, result output visual display and policy test (Zhang et al., 2012), but also has wide application range and no fixed location. Therefore, the Vensim software provides an effective platform of implementing SD simulations.

Vensim offers 4 types of variable expressions for SD models (seen in Fig. 1): (1) Level variables (*L*), representing the variables whose values change and accumulate over time; (2) Rate variables (*R*), representing the amount of the variation of level variables each year; (3) Auxiliary variables (*A*), assisting the transformation between level variables and rate variables; (4) Constant variables (*C*), which remain the same value over time.

2.2. Scope of study

Green building interacts with the eco-environment in a dynamic and complex manner. This paper studies the ecological system affected by regional green building, in which "building" refers to "civil building"; the "region" is located in Wuhan, the capital of Hubei province in China, with an area of 8494 square kilometers.

This study focuses on six types of policy, including construction land saving, energy saving, material saving, water saving, CO_2 reduction and solid waste reduction policies. The whole policy presents the requirements of regional green building development. Take building CO_2 emission saving policy as an example, it represents the proportion of the required annual reduction of CO_2 emission to the amount emitted in the last year. The goal of the whole policy is to improve the eco-footprint and eco-environmental quality.

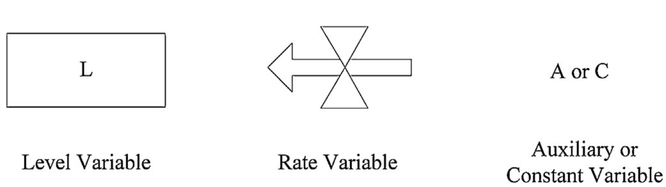

Fig. 1. Four types of variable expressions for SD models.

2.3. Process of study

This study is composed of constructing a GBE-SD model and policy optimization, and three main steps (seen in Fig. 2) are included in this process:

(1) Model construction and parameter quantification. Real-world observations and related data from Wuhan are used to find the influential factors in the GBE system, and the logical relationships among different factors are analyzed to design causal diagram and derive stock-flow model. A group of mathematical equations are obtained to quantitatively describe the relationships among different factors in the GBE system;
(2) Model validation. The SD model is verified with two methods: comparison with historical data and model validation by the Vensim software. If the model result deviates from test data in either approach, identify the causes and modify the model until the validation requests are satisfied and the result can reflect actual behaviors;
(3) Analyses of simulation results and policy optimization. Based on current green building development policies in Wuhan, the current state and trend of variation of the regional eco-environment are simulated and analyzed on the Vensim platform. Different policy plans are then simulated to find the optimal combination for sustainable development of green buildings in Wuhan with lower economical cost.

3. Model construction and validation

The construction of the GBE-SD model includes SD model design, parameter quantification, and model verification.

3.1. SD model design

3.1.1. Causal diagram design

Theoretically, green building has milder destruction to the eco-environment than traditional building; however, building construction and operation always consume energy, water, and materials, and also emit CO_2 and solid waste, inevitably causing eco-environmental deterioration. The degree of such deterioration can be quantitatively evaluated with regional building eco-footprint (Teng & Wu, 2014); this index is also used to determine the major influential factors in a Green Building Eco-environment (GBE) system.

The interaction between green building development and the eco-environment is complex, and a variety of factors need to be addressed simultaneously in the GBE system, such as those associated with the natural development rate of the eco-environment, energy, water, and materials consumptions, emission of CO_2 and solid waste, the ecological carrying capacity, eco-footprint, and policies. These factors are also interconnected with and restricted by each other, and most of them are dynamic variables over time. Such factors in a GBE system are shown in the causal diagram in Fig. 3.

Fig. 3 is an abstract and conceptual model of regional GBE system depicting the causal relationships between key factors. The "+" sign means positive causal loop, suggesting that the loop is