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Application of Life Cycle Assessment (LCA) and extenics theory for building energy conservation assessment

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ABSTRACT

Reduce energy consumption and environmental pollution is an important objective in energy sustainability. The building sector, one of the fastest growing in terms of energy consumption, accounts for over 40% of final energy. Building energy conservation will drive the application of new energy conservation technologies and strongly promote the development of sustainable building. In this paper, the extenics theory and life cycle assessment (LCA) are proposed in building energy conservation assessment. Analytic hierarchical process (AHP) method and 9-scale pair-wise comparison are adopted to determine the weights of the factors in different hierarchies. A building energy conservation assessment model combining LCA and the extenics theory is established. The matter-element and the dependent function are defined. Then the synthesis dependent degree and the final grade index are calculated. Thus the building energy conservation grade is obtained. An example is used to illustrate the proposed approach. The results provide guidance to assess building energy conservation performance and determine the energy conservation grade of buildings.

1. Introduction

Energy shortage and environmental pollution have become major technological, societal and political challenges facing the world [1,2]. With increasing concerns about ecological preservation since the late 1980s, building energy efficiency was seriously concerned [3,4]. The building sector, one of the fastest growing in terms of energy consumption, accounts for over 40% of final energy [5,6]. The building sector also contributes largely in the global environmental load of human activities. Saving energy activities in buildings requires cooperation from everyone including architects, engineers, interior designers and researchers [7]. Rational design and energy consumption control of buildings are more and more important in energy sustainability and they have become important strategies in sustainable development. The need for building energy conservation is based on the fact that it simultaneously reduces conventional fuel consumption, building energy cost, and global warming gas release to the atmosphere [8].

Building energy conservation assessment, extended to its design and construction, allows for a proper quantification of the building's energy implications, and hence provides the basis for appropriate planning in the sector [9,10]. It will help to reduce CO_2 emission and consumption of the fossil fuels and promote to utilize the renewable energy and the new energy conservation technology. Its rationality directly affects the veracity and standardization of the assessment.

Building energy conservation assessment should include aspects such as building form, envelope design, building equipment system design, energy and resources consumption, renewable energy, environmental impacts and so on. Thus building energy conservation assessment is a multi-variables problem.

Some studies have been carried through in building energy conservation assessment over the years. Rey *et al.* [7] proposed a new methodology called "Building Energy Analysis" (BEA) that allows implementation of Energy Performance of Buildings Directive (EPBD) on energy certification of the buildings. Patxi *et al.* [11] outlined a methodology to develop energy benchmarks and rating systems starting from the very first step of data collection of the building stock. Wang *et al.* [12] established a quantitative building energy efficiency assessment model combining AHP and attribute mathematics. Shi [13], Wu *et al.* [14], and Wu *et al.* [15] adopted AHP and fuzzy mathematic method in building energy conservation assessment. Lu [16], Ding *et al.* [17] and Yan [18] studied building energy conservation assessment by artificial neural network theory.

From above literatures, application of AHP method, artificial neural network theory, and fuzzy AHP (FAHP) method in the field of building energy conservation assessment has proliferated in recent years. These methods can determine ambiguous and uncertain

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characteristic number, but the energy conservation level was usually obtained by the maximum membership degree and it cannot completely reveal the energy conservation performance.

The extenics theory was first put forward by Prof. Cai Wen in 1983 [19]. It can describe both the mutual transform between "yes" and "no" and the degree that an object possesses certain character [20]. In extenics theory, the values of the dependent function are acquired from $(-\infty, +\infty)$. Thereby the dependent degree is able to reflect whether it belongs to a certain degree or not from positive and negative. Therefore more different information is open up from the evaluation results. Thus the extenics theory will make the evaluation results more precise and more profound.

In addition, at present, the energy conservation performance in the use stage is mainly paid attention. It is not all-around. Unlike general consumer goods, a building possesses a long life span consisting of its construction, operation & maintenance, and demolition and dismantling, consuming energy resources throughout its life cycle, and yielding environmental byproducts.

As the development of building energy conservation, LCA should be introduced, and the energy conservation performances and environmental impacts in all stages of the life cycle should be assessed. There is a clear interaction between all of the stages of a building's life: for example, if less is paid attention in the design phase (e.g. poor insulation), the investment and energy needed for use and maintenance will increase. Thus the introduction of LCA makes the assessment results more reasonable and all-around. In LCA, if a system can be identified with a beginning and an end, the characteristics of the system related to energy and environment can be investigated. Therefore reasonable decisions about the energy and environmental performances for a product or system can be made [21]. On the basis of such consideration, the application of LCA in building energy conservation will be a feasible and effective way. This kind of research, however, is not enough by far.

To the best of the authors' knowledge, no extenics theory application was found that deals with the assessment of building energy conservation or similar issues. The aim of this paper is twofold. One is to propose a life cycle assessment model in building energy conservation. The other is to evaluate building energy conservation using the extenics approach and provide a new scientific method for building energy conservation assessment.

The paper is organized as follows. The first section includes the introductory part; Section 2 introduces the methodology; Section 3 describes the assessment method combining LCA and extenics theory; Furthermore, a case is illustrated to assess the building energy conservation and obtain the energy conservation grade in Section 4; Section 5 contains results and discussion; Section 6 verifies the proposed method. Finally, conclusions are listed.

2. Methodology

2.1. Life cycle assessment of building energy conservation

At present, the energy conservation performances in the use stage of the building are mostly focused on. As the development of modern evaluating method, applying the LCA method in building energy conservation assessment has become a trend [22–25].

LCA is a powerful and internationally accepted system analysis tool that studies the environmental aspects and potential impacts of a product or service system throughout its life cycle (raw material extraction, manufacturing, distribution, use, end of life and waste recycling) [26–30]. The LCA methodology allows to assessing the potential environmental impacts of a product or service during its whole life cycle ("from the cradle to the grave") [31].

As products, buildings are special since they have a comparatively long life, they often have multiple functions, they contain many different components, they are normally unique (there are seldom many of the same kind), they are integrated with the infrastructure [32].

Given the complexities of the interaction between the built and the natural environment, LCA represents a comprehensive approach to examine the environmental impacts of the entire building. Buildings consume energy throughout their whole life cycles [33]. The LCA should consider not only the building materials and energy consumption in the construction and use stage, but also the production and transportation of the building materials, and even the material recyclability and waste management in the decommissioning stage. This implies that, in LCA, the assessment criterion extends both time and space domain. The energy conservation performances of all stages in the life cycle are assessed. Therefore the assessment results are more scientific and all-around.

2.2. Summary of extenics theory

2.2.1. Extenics theory

2.2.1.1. Introduction of the extenics theory. The extenics theory was originally put forward by Cai to solve contradictions and incompatibility problems in 1983 [19]. In this world, there are some problems that cannot be directly solved by given conditions, but the problems may become easier or solvable through some proper transformation.

In the objective world, all things are the entity of quality and quantity. And the objects (problems) are recognized and classified base on crisp set, fuzzy set [34] and extension set respectively. In the crisp set, an element either belongs to or does not belong to a set, so the range of the truth-values is $[0, 1]$, which can be used to solve a two-valued problem. The fuzzy set concerns not only whether an element belongs to the set but also to what degree it belongs. The range of the membership function is $[0, 1]$ in the fuzzy set. The extension set extends the fuzzy set from $[0, 1]$ to $[-\infty, +\infty]$. This means that an element belongs to any extension set to a different degree [35].

2.2.1.2. Extenics theory in building energy conservation assessment. The building is a complicated system. The model for building energy conservation assessment, which integrates energy consumption, sustainable development, and environmental protection, should run through the whole life cycle of the building. In different stages of the building, the energy conservation indexes are different. By the indexes in different stages, the final energy conservation performance can be regarded as the guideline for energy conservation assessment of the building. For the life cycle of the building is an embedded process, the indexes are more and more detailed. Thus the assessment for building energy conservation is not only general, but also a system with multi-layer and multi-structure. The indexes in each layer can be decomposed downward and can be also advanced upward. Therefore the energy conservation performances in different stages and different layers can be restricted with each other.

The idea of extension set in matter-element is accordant with that of identification problem. The dependent function describing the extension sets makes the identification method more subtile. By defining the assessment grades, the building energy conservation assessment model with multi-layer can be established by the matter-element method. The energy conservation level can be ranked into five grades, and the numerical value ranges of each grade are determined. The actual performance of each index is then substituted into each grade set. The assessment result of the index can be obtained by the dependent degree. And finally, the energy conservation level of the building can be obtained.