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Application of improved grey relational projection method to evaluate sustainable building envelope performance

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ABSTRACT

Buildings are energy gluttons. Improving thermal performance of building envelopes will reduce energy consumption in buildings. The development of advanced building envelope systems reducing energy losses is a critical research frontier. This study introduces a simple but reliable methodology for building envelope evaluation and optimization in the conceptual stage. An improved grey relational projection method is proposed to select the optimum building envelope alternative. A combination weighting method combining the subjective weighting method and the objective weighting method is adopted to calculate the weights of the factors and sub-factors. The relative projection values of the alternatives are calculated. And the optimum alternative is obtained. An example is given to demonstrate the proposed method. Finally the proposed method is verified. The results show that this method is simple and practical, and it has potential as a powerful tool in building envelope evaluation and optimization for building owners, manufacturers, designers, and evaluators.

1. Introduction

Energy shortage and natural environment deterioration have become global issues [1]. Buildings are energy gluttons and have a large impact on the global climate change and other energy-related environmental issues [2]. Building energy consumption accounts for approximately 40% of the global energy demands [3–6]. One of the main ways to diminish this consumption is to reduce the energy losses and have more energy-efficient building designs. Heat transfer through the building envelope is the principal component of building cooling/thermal loads, therefore energy is needed to compensate for thermal energy losses or gains that occur in building envelope systems [7].

Improving thermal performance of building envelopes will reduce energy consumption in buildings. A building envelope with poorly insulated walls, roofs, and foundations is typically characterized by up to 40% of total heat loss; draft could result in up to 25% of total heat loss; and low quality doors and windows could result in up to 30% of total heat loss [8]. The successful design of building envelopes system requires that special attention be paid in the conceptual stage. When several building envelope alternatives are generated, overall evaluation should be made in order to obtain the best solution. Building envelope evaluation is able to help overcome some significant market barriers and ensure cost effective energy efficiency opportunities incorporated into new buildings [9]. The development of advanced building envelope systems reducing energy losses is a critical research frontier.

Currently, in building envelope design stage, designers and researchers heavily rely on previous experiences or software such as energy simulation programs to determine appropriate values for envelope parameters and obtain the optimum building envelope alternative. Hugues et al. [10] created a computerized approach: the functional analysis to support integrated building envelope design and established a functional model of the building envelope design process. With the simulations of the buildings by the computer programme DEROB-LTH, Smeds and Wall [11] compared some typical constructions and system designs using best technology available. Yik et al. [12] presented the results of several studies on the influence of different envelope characteristics to the energy behavior of flats in high-rise residential buildings in Hong Kong by using the software HTB2. Yu et al. [13] used eQUEST software to analyze envelope design on energy saving of air conditioner in hot summer and cold winter zone in China.

Many sophisticated energy simulation programs (e.g., DOE, Energy Plus, Dest) are of great help to study the performance of building envelope system. However, for the models are intended for the analysis of a predetermined design solution, the process of searching for a better design solution is time-consuming and ineffective because of the inherent difficulty in exploring a large design space [1].

Only a few studies were conducted on multi-objective evaluation method. Hauglustaine and Azar [14] optimized the building envelopes using genetic algorithms with as many as 10 criteria

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related with code compliance, energy consumption, and costs. Bouchlaghem [15] presented a computer-based model for the design of building envelopes combining analytical and graphical methods to optimize the thermal performance of a building. Nerija et al. [16] proposed a methodology for the multivariant design and multiple criteria analysis of a building's life cycle and took into account criteria's quantitative and qualitative characteristics for determination of criteria weights. He et al. [17] presented the concept of a building envelope performance evaluation framework, which integrates existing simulation applications and evaluation criteria with multidisciplinary knowledge, state-of-the-art Information Technologies (IT), and Industry Foundation Classes (IFC).

The prime functions of the building envelope are to provide security, solar and thermal control, moisture control, indoor air quality control, access to daylight, and views to outside, cost effectiveness and aesthetics. A good envelope design should be the result of a systematic approach, checking all relevant elements with respect to energy-related, environmental, capitalized and physical qualities [18]. It is therefore necessary to apply an integrated approach to the process of optimizing building envelope design and evaluating the performance [19]. Although some related studies have attempted to adopt multi-objective evaluation model in building envelope design and evaluation, the efficient and effective method has yet to be developed. In the current work, the grey relational projection method is proposed in the optimization and evaluation of building envelopes.

Optimization and evaluation of building envelopes is composed of white information (have been understood), black information (have not been found) and grey information. The grey information is qualitative and the relationship between each evaluation index is mutually independent. Although the relationship is uncertain, it exists in reality and is called grey relation. Therefore, optimization and evaluation of building envelopes is a grey multi-objective decision problem.

Grey relational projection theory is an effective means analyzing the relationship between sequences with grey information. It has been applied in many fields [20–22]. Effort in analyzing building envelope evaluation by the grey relational projection method is lacking. Most of the grey relational projection methods are based on a single base point (the ideal alternative). The paper aims to propose a double base point (the positive ideal alternative and negative ideal alternative) grey relational projection method in building envelope evaluation.

When determining the weights of the evaluation indexes, the weights are normally determined by either the subjective or objective method in most multi-objective decision problems. In order to integrate the merits of both approaches, the paper proposes a combination weighting method to determine the weights of the factors and sub-factors. In order to ensure the consistency of the decision matrix, consistent matrix analysis method is adopted to determine the subjective weights. The technique for order preference by similarity to ideal solution (TOPSIS) is used to determine the objective weights.

The primary purpose of the research is to develop a methodology for the evaluation and optimization of building envelopes and select the optimum building envelope alternative in the conceptual stage. This is done with the aim of attracting some attention to the consequence of energy conservation on building envelopes and providing some criteria for building envelope design.

This paper is organized as follows. The first section includes the introductory part; Section 2 establishes the evaluation framework and indexes; Section 3 describes the improved grey relational projection method in building envelope evaluation and optimization. Section 4 illustrates a case to select the optimum building envelope alternative; Section 5 contains validity of the proposed method, and the last section concludes.

2. Building envelope evaluation framework and indexes

The building envelope comprises the floor, exterior walls and roof that separate the inside conditioned space from the outside or unconditioned space. The function of the envelope is to enclose the space in such a way that its environmental characteristics can be regulated within acceptable limits [23]. Before performing the evaluation, however, criteria for building envelope performance should be determined. With an emphasis on sustainable building envelope, the factors affected the building envelope performance are selected including thermal characteristics, building form, cost, innovation, reliability and environmental effects. The energy performance of building envelope is influenced by following factors:

(1) The heat transfer characters including walls, floors, windows, doors, roofs and the sunlight penetrating into the interior living or work spaces strongly influence the heating/cooling load of the building. Thus the heat transfer coefficients greatly affect the thermal insulation performance of the building envelopes. The smaller the heat transfer coefficient is, the smaller the capacity of heat transmission is. The heat transfer coefficient is a critical factor for energy consumption of the building.
(2) The energy performance may also be influenced by the building form. Building form coefficient is the ratio of the surface area to the volume. The smaller the form coefficient, the fewer the dissipate heat, which is beneficial to building energy conservation. Therefore, the form coefficient should be controlled at a small value. The maximum form coefficient and perfect form coefficient are proposed based on the form coefficient. The maximum form coefficient is the ratio of perimeter of a cross-section to its area in the building. It reflects the influence of the cross-section form to energy conservation performances of the building. The perfect form coefficient is the ratio of the maximum form coefficient to form coefficient. And it reflects the influence of building height to the energy conservation performances of the building. Additionally, the building orientation, floor-to-ceiling height, wall-to-window ratio and shading coefficient also greatly influence the energy conservation performance of the building envelopes.
(3) Costs are also considered in order to obtain effective design for the end user. The economy benefits can be broken down in two types of costs: initial construction costs and maintenance costs. For instance, initial construction costs may be reduced by selecting lower quality components, that will, however, result in increasing the maintenance costs [10].
(4) In order to encourage the designers and developers to adopt new technology and new materials in sustainable building envelope, innovation is also considered in the building envelope performance.
(5) The building envelope is regarded as a system enclosing and protecting the indoor environment from disturbing outdoor conditions, and the indoor environmental quality of a building has a significant impact on occupant health, comfort, and productivity. Therefore reliability of the building envelopes is taken into account [24]. Reliability contains safety, comfort and durability of the building envelopes.
(6) Quarrying, processing of various raw materials and manufacture of materials and structures as well as their transportation, building construction and maintenance are often harmful to the environment. Sustainable building envelope should be constructed of materials that minimized life-cycle environmental impacts such as global warming, resource depletion, and human toxicity. In order to minimize