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Cost-effective energy saving measures based on BIM technology: Case study at National Taiwan University

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ABSTRACT

This study utilized BIM technology (eQUEST) to conduct an energy consumption analysis and simulated re-design of the Civil Engineering Research Building at National Taiwan University. After obtaining a verifiably accurate simulation, energy-saving effects were investigated by altering the building's envelop design and analyzing the results. In addition, cost remains a crucial factor throughout the process in order to reflect the relationship between building expenses and energy efficiency during design scheme optimization. The results of this study can provide better and more comprehensive choices for building owners, designers, and developers in future.

1. Introduction

According to the United Nations Environment Programme (UNEP) [1], buildings are the largest worldwide consumers of energy. The impact of energy consumption is particularly significant in the usage phase, which can last several decades. Most of the energy used by any building is consumed during the usage (or operational) stage of the building's life-cycle. Researchers and developers have considered methods of energy consumption reduction for many years, however, reducing energy consumption almost always means increasing cost. For this reason, energy efficiency is not often a high priority for building owners. It is crucial to secure techniques for successfully optimizing designs while keeping them cost-effective, as doing so provides more options for building owners or designers in the design phase.

Building Information Modeling (BIM) is a relatively new technique that has been developed and applied in the engineering field. It is a data model that integrates all relevant information for engineering projects with three-dimensional digital technology. BIM is mainly used in the design phase, but also during the eventual construction and operation phases. Utilizing BIM significantly increases design efficiency, and reduces risk throughout the engineering and construction process. Many researchers have explored the possibility of using BIM to simulate energy consumption [2–6]. Persson et al. [7], in one such study, analyzed a low-energy building in Sweden using the dynamic energy response of buildings LTH (Derob-LTH) technique to find that windows have a considerable impact on the energy consumption and greenhouse gas emissions of residential buildings. Window size, specifically, was shown to affect the winter thermal loads and summer cooling loads of buildings, and Derob-LTH analysis successfully provided the most efficient size of south-facing windows for residential buildings.

There have been numerous studies published previously that relate to eQUEST application [8–10], specifically in terms of energy consumption simulation. Zhu [11], for example, used eQUEST simulation models to analyze the effect of various energy-saving measures on building energy consumption conditions. With office buildings in Hangzhou area as example, Hu et al. [12] compared the actual monthly power consumption of office buildings in Hangzhou against their consumption as-simulated by eQUEST, and found that eQUEST is indeed able to quickly and reliably predict the energy consumption of buildings. In a study by Kensek [13], compared actual monthly electricity usage results against results provided by eQUEST, DesignBuilder, and Vasari simulation, then simulated four alternative energy conservation schemes for three different climate conditions in California by targeting the building envelop;

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the primary goal of the study was to determine if the simulated retrofitting options produced similar trends in all three programs.

There have also been valuable studies on field energy consumption of building envelops. Nikoofard et al. [14], for example, evaluated the economic feasibility of window modifications using energy simulations built based on a Canadian hybrid residential end-use energy model, plus greenhouse gas emissions information. Their results showed that thermally improved windows can substantially reduce energy consumption and greenhouse gas emissions from the Canadian residential sector. In another study, Nikoofard [15] quantified the magnitude of the effect of site shading on the energy requirements of residential buildings in Canada, and found that external shading should indeed be given due consideration in energy simulations. Kim et al. [16] studied the impact of different exterior shading devices on air conditioning loads in residential buildings, demonstrating that exterior shading devices can effectively reduce air conditioning energy consumption. Liu et al. [17] found that retrofitted external building walls consistently make the largest contribution to ECER in high energy-consuming buildings compared to other parameters, followed by retrofitted external windows.

A cost-benefit analysis framework was proposed by Goodacre et al. [18] to assess the potential scale of the benefits of upgrading heating and hot water energy efficiency in English stock buildings. Ge et al. [19] studied the effects of clay-brick-powder on concrete mechanical properties, and applied their orthogonal experimental design to study the significance sequence of all influencing factors; the optimal proportions were determined based on experimental and orthogonal analysis. Kaklauskas et al. [20] developed a multivariant design and multiple criteria method for building refurbishment analysis that can be applied to determine the significance, priorities, and utility degree of building refurbishment alternatives to select the optimal variant. There have been several previous researchers who have studied the economic aspect of this technology. For example, Mehmet et al. [21] used an annualized Life-Cycle cost method for economic analysis. Which conducted performance experiments and economic analysis on a horizontal ground-source heat pump (GSHP) system. The GSHP system has been shown to offer unique economic advantages compared to the five most common conventional heating methods. Another study by Mehmet [22] featured a techno-economic comparison between the ground-coupled heat pump (GCHP) system and air-coupled heat pump (ACHP) system. The results indicated that system parameters have a substantial effect on performance, and that GCHP systems are preferable to ACHP systems for the purposes of cooling spaces economically.

2. Methodology

The BIM technique is relatively new and has been developed extensively in recent years. It is now commonly applied in the engineering field. BIM is best described as a data model built by integrating three-dimensional digital techniques with various manner of relevant information about a given engineering project. BIM is mainly used in the design stage, construction stage, and late operation and management stages. It can considerably improve efficiency and reduce risk throughout the entire constructional engineering process. In this study, eQUEST was applied to conduct an energy consumption simulation. The eQUEST energy consumption simulation model was established based on the Civil Engineering Research Building of Taiwan University, then the outer wall, roof, and extended length of sunshades were analyzed via the simulation (in regards to both energy efficiency and cost-effectiveness,) to determine the effects of different energy-saving design schemes.

Typically, to conduct a test with this large amount of test factors that must be considered simultaneously would be highly complex. The number of independent factors that must be accounted for makes it difficult to ensure a fully comprehensive test. Orthogonal testing is a highly efficient test method which solves the multi-factor test problem by applying an orthogonal table that is organized according to different parameters [23]. The orthogonal table contains representative horizontal parameter combinations determined after comprehensive testing to determine orthogonality, so the table can effectively be used to replace comprehensive tests through facilitating analysis of only the most important conditions. An orthogonal test design was applied in this study to find the optimal building design scheme among all combinations with fewer simulation iterations.

The economical index Net present value (NPV) is the difference between the present values of cash inflows and outflows. NPV was also utilized to analyze the economic feasibility of the design schemes, in addition to sensitivity analysis to determine the influence of cost variations on the index. It is important to note that there may have been some differences in the cost analysis results due to different brands and manufacturers of building materials, though the typical Taiwanese building structure was the main source of information.

3. Case-study at National Taiwan University

3.1. Characterization of the Civil Engineering Research Building

The Civil Engineering Research Building (Fig. 1), the newest teaching building in the Civil Engineering Department of National Taiwan University, was completed on June 23, 2008. It is located in No. 188, Section Three, Xinhai Road, Taipei City. The building includes a basement floor and nine above-ground floors (the second floor is a shock insulation floor,) and the total floor area is about 9886 m^2. The main structural sections of the building were constructed using a pre-casting method. The total cost of the building was about 8,133,641 USD. The majority of the department's testing equipment is still housed in the old Civil Engineering building, and the new building contains mostly classrooms and office space for professors and other department personnel.

The new building consumes a considerable amount of energy overall, and though it is convenient for professors and students, the financial burden of the building weighs rather large on the Civil Engineering Department. Energy consumption statistics (Table 1) of the Civil Engineering Research Building were gathered over the past three years to inform this study.

The data gathered for this study shows low power consumption due to the holiday season in February, during which time the building was more likely to be unoccupied. The peak season for power consumption was June to October, during which time the temperature is relatively high in Taiwan, so air conditioning consumption was relatively high.

The Energy Use Intensity (EUI) is the ratio of the total annual energy consumption to the total floor area (kWh/m^2 a). The EUI of the Civil Engineering Research Building is 121.86 kWh/m^2 a (Table 1) according to actual energy consumption, which is quite close to the maximum value, 123.4 kWh/m^2 a [25], of common buildings in each college of Taiwan University. This indicates that the building consumes energy at a significantly high level.

3.2. Taiwanese climate conditions and original design

The northern area of Taiwan features a subtropical climate, while the southern area has a tropical climate. Taiwan as a whole possesses a typical oceanic climate, with high-temperature and