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Sustainable building envelope design by considering energy cost and occupant satisfaction

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ABSTRACT

The built environment is a major contributor to the world's carbon dioxide emissions, with a considerable amount of energy being consumed in buildings due to heating, ventilation and air-conditioning, space illumination, use of electrical appliances, etc., to facilitate various anthropogenic activities. The development of sustainable buildings seeks to ameliorate this situation mainly by reducing energy consumption. Sustainable building design, however, is a complicated process involving a large number of design variables, each with a range of feasible values. There are also multiple, often conflicting, objectives involved such as the life cycle costs and occupant satisfaction. One approach to dealing with this is through the use of optimization models. In this paper, a new multi-objective optimization model is developed for sustainable building design by considering the design objectives of cost and energy consumption minimization and occupant comfort level maximization. In a case study demonstration, it is shown that the model can derive a set of suitable design solutions in terms of life cycle cost, energy consumption and indoor environmental quality so as to help the client and design team gain a better understanding of the design space and trade-off patterns between different design objectives. The model can be very useful in the conceptual design stages to determine appropriate operational settings to achieve the optimal building performance in terms of minimizing energy consumption and maximizing occupant comfort level.

Introduction

Climate change caused by global warming is said to be one of the most important challenges facing society today, with a major contributor being excessive greenhouse gas (GHG) release into the environment. Carbon dioxide (CO_2) emissions are a particular problem (Masters, 1998) and an attempt to reduce atmospheric CO_2 concentration is inevitable worldwide (Scheffer et al., 2006). In pursuit of this, a cut in energy consumption is one of the most effective ways to achieve significant emission reduction in the immediate future. A way to reduce emissions is by switching to clean energy sources as this can minimize the CO_2 emitted from the oxidation of carbon embodied in fossil fuels. Meanwhile, however, primary energy consumption and CO_2 emissions grew by 49% and 43% respectively from 1984 to 2004 (IEA, 2006) and 81% of the world's total primary energy supply in 2008 was generated by fossil fuel (IEA, 2010) with no evidence of any reduction since that time. Indeed, the escalated demand for energy, especially in developing countries due to increasing industrialization, rapid urbanization and rise in living standards, is only aggravating the situation (Dakwale et al., 2011).

The built environment is a major culprit with a considerable amount of energy being consumed in buildings due to heating, ventilation and air-conditioning (HVAC), space illumination, use of electrical appliances, etc., to facilitate various anthropogenic activities. Studies indicate that the energy consumed by buildings were 39% in the United Kingdom, 37% in the European Union (Perez-Lombard et al., 2008), 40% in the United States (USDOE, 2010), 31% in Japan and 40% in Hong Kong (Juan et al., 2010). The main reasons for high building energy consumption include an increase in population, greater reliance on building services equipment, amelioration of comfort level of indoor environment, and increase in time spent inside buildings (Perez-Lombard et al., 2008).

As a major energy consumer, buildings are also one of the most significant CO_2 emitters. Studies have shown that over a third of the world's CO_2 emissions emanate from the combustion of fossil fuels in order to satisfy the energy demand of buildings (Filippin, 2000; Levermore, 2008). Therefore, buildings have a significant role to play in lowering CO_2 emissions. Improving the energy efficiency of buildings not only does this, but can also help preserve non-renewable energy sources (Lee & Yik, 2004). Over the years, sustainable building has gained increasing attention and popularity from stakeholders in the

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construction industry such as architects, engineers, developers, contractors and government. Sustainable building is designed, constructed, operated, renovated and disposed of in accordance with ecological principles for the purposes of minimizing the environmental impact of the built environment and promoting occupant health and resource efficiency (Kibert, 2003). In addition to benefitting the environment and occupants, sustainable buildings can also produce substantial economic benefits by reducing operating expenses, enhancing building marketability and market value, improving the productivity of occupants and thus the revenue-generating ability of corporate tenants of office buildings, minimizing potential liability due to poor indoor environment, and optimizing life cycle economic performance (USGBC, 2010; USEPA, 2012).

In many sustainable building guidelines and evaluation methods, the design phase is the most comprehensively emphasized and addressed phase of the life cycle (Bunz et al., 2006). Although some forms of minor energy conservation could be achieved via relatively simple and individual measures during the operational phase, significant reduction in energy consumption is made possible only if design solutions are generated and fully assessed during the design stage. The most effective point of incorporating sustainable features is in the early design stage (Wang et al., 2005). For instance, a typical feature of sustainable building design is good insulation of the building envelope to lower heat loss and thus decrease the energy demand for heating and cooling.

However, sustainable building design is a complicated process involving a large number of design variables, each with a range of feasible values. Seen this way, a design solution is basically a result of choosing a value for each design variable and combining them together. This creates a very broad space of all possible design solutions. A simple example is a sustainable building design problem involving five design variables: north south, east and west wall window types, and exterior wall insulation thickness. Assume that the windows on each façade can be chosen from 10 different types and the insulation thickness takes discrete values ranging from 10 mm to 170 mm in 10 mm steps, which amounts to 17 feasible values for insulation thickness. The design space therefore consists of 170,000 ($10^4 \times 17$) possible solutions.

Another aspect in sustainable building design is its multiple, and often conflicting, objectives—the simultaneous minimization of cost and environmental impact for example. This involves a trade-off in which the aim is to locate a set of diversely distributed Pareto-optimal solutions rather than single best solution as occurs in single objective optimization.

Acting as a boundary separating indoor and outdoor environment, the building envelope plays a critical role in determining the energy performance of a building. The building envelope consists of various elements including exterior walls, roofs, doors, windows, skylights, and walls and floors in contact with the ground (EMSD, 2007b). Building operational settings, such as lighting power density, air temperature, relative humidity, air velocity, and outdoor air exchange rate, determine the occupants' comfort level of indoor environmental quality (IEQ) as well as affecting the building's energy performance. Although such settings belong to the building's operational stage, deciding on their appropriate values must be considered during the design stage as, together with other physical building configurations and external climate conditions, they determine energy performance as a complete system. For example, to achieve the same level of thermal comfort, if the building envelope has higher thermal resistance, the cooling temperature setting can be increased accordingly, which will also reduce energy consumption and energy cost.

One approach to dealing with such issues is through the use of optimization models. Although rarely used in building design practice, these powerful tools have the potential to identify better design solutions and provide a more comprehensive knowledge of the whole design space. Quite a number of optimization models for sustainable building design have been developed in past research, but they are limited in either not including consideration of occupant comfort level or using only thermal comfort to partially represent occupant comfort level. In this paper, a new multi-objective optimization model is developed for sustainable design of office buildings in Hong Kong, a Special Administrative Region of China, by considering the design objectives of cost and energy consumption minimization and occupant comfort level maximization. In a demonstration on a hypothetical case study, it is shown that the model could be a useful tool for designers at the conceptual design stage to derive a set of suitable design solutions and help gain a better understanding of the design space and trade-off patterns between different design objectives.

Optimization of sustainable building design

Many sustainable building design optimization models have been developed considering only one objective. The optimization model developed by Saporito et al. (2001), for example, minimizes just the energy consumption for heating requirement. This utilizes computer thermal simulations to understand the dynamic interaction of different parameters and the lattice method for global optimization to uniformly search the highly multi-dimensional design space. Similarly, Al-Homoud (1997) and Coley & Schukat (2002) consider energy consumption only but expand the coverage of energy consumption to include both the heating and cooling requirement. Al-Homoud (1997) applies a computer-based detailed hourly energy simulation model for evaluating energy performance and a direct search method for optimization. Coley & Schukat (2002) couple the genetic algorithm (GA), a population-based optimization technique, to a simplified dynamic energy model with characteristic equations solved analytically in order to identify a large number of distinctly different low-energy design solutions. Lighting energy is included in addition to heating and cooling energy in evaluating the single design objective of energy performance in the model developed by Caldas & Norford (2002) for optimizing the placing and sizing of windows in an office building. Energy behavior is assessed using a sophisticated BEPS program (DOE2.1E) and GA is employed to guide the solution generation and search process. However, considering energy performance alone tends to produce high-cost design solutions. For instance, when optimizing building envelope configurations, the final design solution can involve the extensive, but financially infeasible, use of wall insulation. Generally speaking, therefore, although single objective models are able to pinpoint the best design solution with respect to the designated design objective, they cannot be put into use in practice as multiple design objectives are usually considered simultaneously in sustainable building design. Multi-objective models can more accurately reflect real life situations and are therefore more suitable.

Financial impact and environmental impact are the two commonly adopted design objectives in existing studies. In the multi-objective optimization model developed by Shi (2011), EnergyPlus, a sophisticated and widely used BEPS software tool, was integrated into modeFRONTIER, an optimization suite that contains a series of preprogrammed optimization algorithms. This was done with the goal to minimize the energy demand for space conditioning and insulation usage of office buildings in Southeast China. With only one insulation material, insulation usage is essentially equivalent to initial cost. A multi-objective genetic algorithm (MOGA) which is based on concept of Pareto-optimality was used in the study. Wang (2005) developed a simulation-based optimization system aimed at minimizing the life cycle cost (LCC) and life cycle environmental impact of a building. Life cycle environmental impact was evaluated using the indicator 'expanded cumulative energy consumption', calculated by summing the cumulative energy consumption in resource inputs and the abatement energy consumption due to waste emissions. The model was later applied in other studies (Wang et al., 2005; Wang, 2005) to optimize the floor shape and building envelope with the same set of design objectives. Likewise, Hamdy