Energy and Buildings 105 (2015) 139–153

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Building information modeling based building design optimization for sustainability

Sha Liu[a,*], Xianhai Meng[b], Chiming Tam[c]

[a] Department of Construction Management, Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, 116024 Liaoning, China
[b] School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, United Kingdom
[c] Division of Building Science and Technology, City University of Hong Kong, Hong Kong

ARTICLE INFO

*Article history:*
Received 8 January 2015
Received in revised form 11 May 2015
Accepted 14 June 2015
Available online 22 June 2015

*Keywords:*
BIM
Sustainable building
Building performance
PSO

ABSTRACT

Environmental problems, especially climate change, have become a serious global issue waiting for people to solve. In the construction industry, the concept of sustainable building is developing to reduce greenhouse gas emissions. In this study, a building information modeling (BIM) based building design optimization method is proposed to facilitate designers to optimize their designs and improve buildings' sustainability. A revised particle swarm optimization (PSO) algorithm is applied to search for the trade-off between life cycle costs (LCC) and life cycle carbon emissions (LCCE) of building designs. In order to validate the effectiveness and efficiency of this method, a case study of an office building is conducted in Hong Kong. The result of the case study shows that this method can enlarge the searching space for optimal design solutions and shorten the processing time for optimal design results, which is really helpful for designers to deliver an economic and environmental-friendly design scheme.



## 1. Introduction

Nowadays, the construction industry has become the third largest contributor of greenhouse gas emissions to the environment. Over 70% of the greenhouse gases are emitted from buildings [1]. Buildings also consume 70% of the energy in the U.S. Considering that climate change is getting worse, to reduce the emission loads of greenhouse gases, especially carbon emissions, of buildings becomes a top priority of the construction industry. On the other hand, tighter budgets and higher customer expectations have brought more pressure on project participants than ever before to control the LCC [2]. In this situation, methods which can improve the sustainability of a building while minimizing the LCC have drawn increasing attention in recent years. One of the useful methods is developing sustainable buildings.

Making good design decisions at the initial stage plays an important role in realizing sustainable buildings. An investigation by Rebitzer [3] indicated that although design itself does not induce many environmental impacts, it determines nearly 70% of the environmental impacts over the whole lifetime of a building. Not only can energy be saved by applying sustainable buildings, LCC of buildings can also be reduced. Kats [4] made a statistical analysis of green building costs and financial benefits in the U.S. It showed that comparing with the conventional buildings, a sustainable building with 20-year lifetime has the benefit of \$50–66/ft$^2$. Obviously, the better designs are made, the more economic and environmental-friendly projects will be. In recent years, BIM has become a popular approach used for sustainable building design. It simulates a construction project in the virtually visible environment. All the related information, including geometry, spatial relationships, geographic information, and quantities and properties of building elements, is saved in its model [5]. Therefore, BIM provides an ability to do the simulation for verifying the performance of design schemes. The use of BIM enables designers to improve their designs and select the optimal one.

This study aims to develop a BIM based multi-objective optimization model, facilitating designers to identify and choose the optimal carbon emission and cost trade-off design scheme for their clients.

*Abbreviations:* BIM, building information modeling; PSO, particle swarm optimization; LCC, life cycle cost; LCCE, life cycle carbon emission; HVAC, heating ventilating and air conditioning; DF, daylight factor; DA, daylight autonomy; COP, coefficient of performance; AED, annual energy demand; CEF, carbon emission factor; WBS, work breakdown structure.

* Corresponding author.
*E-mail addresses:* liusha626@outlook.com (S. Liu), x.meng@qub.ac.uk (X. Meng), bctam@cityu.edu.hk (C. Tam).

http://dx.doi.org/10.1016/j.enbuild.2015.06.037
0378-7788/

## 2. Building design methods

### 2.1. Development of sustainable building design methods

The theme of sustainable building is not to deplete resources, disturb ecosystems, or disrupt natural life rhythms during design, construction, operation, maintenance and demolition of a building. Since it is inevitable to carry out human activities with some negative influence on the environment and building itself, the adoption of sustainable buildings tends to cut down as many negative impacts as possible. Design is a central element of sustainable building practice. Since 1990s, sustainable building design methods have been increasingly accepted by designers, engineers and researchers in the construction industry. Generally, sustainable building design methods fall into three major categories.

Initially, rules and guidelines are used by people to examine and weigh the sustainability of designs. The empirical rules or guidelines are generalized statements, tables or diagrams that can guide decision-making for good design [6]. These principles can be easily applied and do not require many complex techniques or time-consuming procedures. Butera [7] compared resources and energy consumption structures of cities in developing and developed countries, and suggested that in order to improve the efficiency of building performance, sustainable design solutions should be differentiated in developing and developed countries. Tam et al. [8] proposed a system called "green construction assessment" to improve the environmental performance of the construction process in Hong Kong, in which different weightings of management performance indicators and operational performance indicators are summarized for designers and project managers as references to refine their own projects. Besides sharing knowledge and experience, taking a small model to provide data, knowledge, and experience for the industry and society was identified by Seyfang [9] as a good way to enhance building sustainability. Currently, the commonly used guideline is green building rating system. Since the Building Research Establishment Environmental Assessment Method (BREEAM) was first established in UK in 1992, many countries and territories have formed their own standards, for example, Leadership in Energy and Environmental Design (LEED) in the U.S., and Hong Kong Building Environmental Assessment Method (HK-BEAM). These standards are useful to evaluate the performance of a completed building. However, how to design a sustainable building and enable it to reach the design criteria has never been introduced by any building environmental assessment methods.

The increasing complexity of building designs with the development of building structures, materials, equipment indicates that only simple rules and guidelines cannot fulfil the requirements of current projects. In order to obtain more accurate data, many related elements, such as climate information, interactions among building subsystems and the architectures around, should be considered as well. Therefore, trial-and-error methods are applied to predict the performance of specific designs. Many studies attempt to reduce carbon emissions and energy consumptions by selecting proper building materials. For example, González and Navarro [44] calculated the carbon emission and embodied energy of some alternative materials in the same unit, and the ones with lowest values are picked out to compose new designs. Comparing with the original designs, LCCE of the new ones can be reduced up to 30%. However, González and Navarro [44] did not take the costs of materials into consideration. Besides building materials, some other factors are also studied. In the envelope design method proposed by Cheung et al. [10], six important design factors: insulation, thermal mass, glazing type, window size, color of external wall and external shading devices, are tested one by one. The values that lead to the least energy consumption of the factors are combined together to compose a new design. This method can save 31.4% of annual required cooling energy. Studies on lighting performance can also use trial-and-error methods. For example, Reinhart et al. [11] selected four types of windows to test the illumination level through them. The four windows have the same size but different glazing types, sunshade locations, and blinds locations and sizes. The merits and demerits of each type of windows are obtained by comparing the values of dynamic daylighting metrics. Although trial-and-error methods have been applied to extract the relationships among essential factors, energy consumption and carbon emission of buildings, there are still some shortcomings that cannot be ignored. Firstly, since designers have to repeat the calculation steps until they get the one satisfying all the preset criteria, large workloads are required when using trial-and-error methods. Secondly, this kind of methods can only deal with one design at a time; and continuous factors cannot be processed. The limitations cause many important factors being ignored and the search space being narrowed down. Thirdly, large workloads lead to long processing time. Due to time limit, designers usually miss the best solutions. Therefore, it is difficult to obtain the optimal design by trial-and-error methods.

In order to solve the problems in the former mentioned methods, optimization design methods are generated. Optimization methods aim at searching for optimal solutions with respect to some predefined performance criteria [6]. By applying an optimization method, the result can lead to both an improved solution and a broader knowledge about design space [12]. Various kinds of optimization strategies have been proposed for building design improvement. Burger [13] used level set methods for the optimization of building shape design and reconstruction. Choudhary et al. [14] applied analytical target cascading, a multi-level engineering design optimization framework, to decompose energy analysis problems of a building into hierarchical levels. Since these methods heavily rely on some mathematical equations, the precision and reliability of their results are waiting for improvement. For this reason, simulation tools have been introduced into optimization design methods. In the investigation conducted by Wetter and Polak [55], BuiltOpt, a detailed building energy and daylight simulation program, was utilized to analyze the energy performance of buildings. Since multi-objective problems are met mostly in the real world, the artificial intelligence approach, which is popularly used in many other areas, has been applied for the improvement of sustainable building design. As a search heuristic that mimics the process of natural evolution, genetic algorithms (GA) have become a widespread optimization method. Many studies attempt to optimize the designs of building structure and envelope by means of GA so as to get the trade-off between cost and energy consumption of buildings ([15,16,56]). Considering that it takes time for the potential solutions to converge during optimization process, Magnier and Haghighat [17] exploited artificial neural network to characterize building behavior before using GA. As a result, the operation time can be reduced and the energy can be saved by up to 13%. GA is not the only effective way for sustainable building design; other multi-objective optimization methods are also competent for this work. In the strategy proposed by Rapone and Saro [18], PSO was taken to refine the curtain wall design of an office building with the aim of carbon emission reduction. Its results illustrated that this method is effective and universal adaptive. For all the optimization design methods, there are generally two common grounds: (1) for sake of boosting the searching speed for optimal solutions and improving the accuracy of results, simulation tools are deployed to interact with optimization algorithms; (2) discrete and continuous factors are all counted and the design space is enlarged, which enhance the reliability of the design schemes.