Energy and Buildings 87 (2015) 45–56

Contents lists available at ScienceDirect

Energy and Buildings

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

Improving building energy efficiency by multiobjective neighborhood field optimization

Zhou Wu*, Xiaohua Xia, Bo Wang

Department of Electrical Electronic Computer Engineering, University of Pretoria, South Africa

A R T I C L E I N F O

Article history:
Received 5 September 2014
Received in revised form 29 October 2014
Accepted 31 October 2014
Available online 11 November 2014

Keywords:
Energy efficiency
Building retrofit
Optimal maintenance
Multiobjective neighborhood field optimization

A B S T R A C T

For some existing buildings with out-of-date facilities, energy efficiency retrofit is a promising method to reduce energy consumption of buildings with small amount of investment. Among many choices of alternative efficient interventions, different strategies to select them are closely related with retrofit cost, energy saving and net present value (NPV), which are conflicted with each other. A multiobjective energy efficiency retrofit problem has been modeled to cover these essential objectives. The multiobjective neighborhood field optimization (MONFO) algorithm is utilized to solve the proposed model for finding optimal retrofit strategies. Besides retrofit strategies, maintenance strategies of repairing or replacing failed interventions are also evaluated and incorporated in the proposed model. Results in case studies indicate that MONFO is a suitable algorithm to obtain accurate and diverse Pareto optimal solutions for energy efficiency retrofit, and that optimization of maintenance strategy can improve the overall performance of project compared with empirical maintenance strategy.

1. Introduction

Due to globally increasing energy consumption, fossil fuel resources suffer from risks of over exploration and possible distinction in the near future. Meanwhile carbon and pollutant emissions caused by burning of fossil fuel have been growing over the last decade with great threat to environment. To control fossil fuel consumption and carbon emissions, it is necessary to decelerate the increasing rate of energy demand and reduce it if possible. Energy efficiency improvements of existing buildings and regulations for newly designed buildings are proposed as the most popular way to achieve reduction of energy consumption, as the building section with long life cycle contributes approximately 40% of world energy consumption [1–3]. The building section consumes energy for providing services such as space heating and cooling, water heating, and lighting. As well known, retrofitting existing buildings cost much less than newly constructing energy efficient building, so building retrofit is currently the most feasible and practical method to reduce energy demand in the building section.

As innovative technologies and energy conservation measures are nowadays widely applied in building services, energy saving is never an unreachable goal of building retrofit. Even though energy efficiency retrofit introduces additional embodied economic and environmental impacts, it is proven as a sound activity because the economic and environmental payback period could be less than 3 years [2]. During the past decades, many governments and international organizations have put significant emphasis on energy efficiency improvement for existing buildings [4]. In the United States, the federal government has given much financial support in building retrofit. In Australia, the Commercial Building Disclosure (CBD) programme has been proposed to promote energy efficiency information public for large commercial office buildings, and sufficient budget has been invested to retrofit government buildings. In Italy, energy consumption of public buildings and utilities has been evaluated in Tuscany to find the most effective and feasible way of saving energy [5].

In building retrofit projects, the main and also difficult issue is to identify those solutions that are the most effective and reliable ones over the lifetime of buildings [6–8]. Because there are a great number of alternative measures available for retrofitting each building component or service. The strategy of selecting measures within a variety of proposed alternatives can be optimally designed to compensate environmental, financial and social factors and to achieve energy efficiency improvement while satisfying each stakeholder's requirements and other practical constraints [9]. For a building retrofit project, decision makers (DM) need design a specific retrofit strategy to decide types of employed alternative measures and the number of alternative measures in each

* Corresponding author. Tel.: +274204341; fax: +27123625000.
E-mail addresses: wuzhsky@gmail.com (Z. Wu), xxia@up.ac.za (X. Xia), wb8517@gmail.com (B. Wang).

http://dx.doi.org/10.1016/j.enbuild.2014.10.079

type before start of project. Several benefits, such as energy efficiency improvement, property value increase and other technical, environmental and social concerns, can be usually achieved in the optimal design of retrofit strategies [10–12]. Among these benefits, energy efficiency improvement is the most practical and economic one, based on which many retrofitting projects have been initiated. In practise, building retrofit for improving energy efficiency has involved several conflicting objectives that cannot be optimized simultaneously [13]. For example, energy saving and retrofit investment are contradicting as normally energy-effective measures are not cost-effective and cost-effective measures are neither energy-effective. Therefore, the so-called building energy efficiency retrofit problem s a multiobjective optimization problem with multiple conflicting objectives subject to several constraints, such as building characteristics, energy saving target and payback period. The scope of this paper is to discuss how to improve energy efficiency by building retrofit, so the building retrofit problem mentioned in the following parts is defined specifically as the energy efficiency retrofit problem.

Trade-off solutions among conflicting objectives necessarily cover all possible scenarios of building retrofit for decision makers. Methods of designing these scenarios can be categorized into two kinds, i.e., empirical methods and multi-criteria (MC) methods. For the empirical method, some representative scenarios can be developed by professional building energy experts based on their knowledge and experience [14]. Information, such as characteristics and location of building, must be considered in designing these scenarios. Using energy simulation tools (e.g., Energy Plus [15] and TRNSYS [16]), practical impacts of these scenarios are evaluated and one favorite scenario is then chosen as the building retrofit strategy. However, it is difficult for experts to find an optimal strategy by such empirical trial-and-error design. In the multi-criteria (MC) method, with respect of Pareto optimality some best trade-off scenarios can be provided to decision makers for references, which are diversely distributed in the whole feasible space. In Gero et al. [17], the MC model was used in the process of building design for exploring trade-offs between thermal performance and other criteria such as capital cost and usable space. In Kaklauskas et al. [18], a multivariate design method based on the MC analysis is developed for building retrofit to determine the significance, priorities and utility degree of alternative measures. In Juan et al. [19], multiobjective genetic algorithms are applied to decision making systems that offer optimal refurbishment actions that trade off cost and quality. Some other MC-based approaches for building retrofit projects can be found from [1,6,20–22].

In most of these MC-based approaches, the initial investment of retrofitting is often considered in the economic analysis. As an important part of life-cycle cost analysis (LCCA), the maintenance cost [8] over the whole project period has been neglected in these approaches. Their weakness is the same that the optimal solution with respect to the initial investment may be cost-ineffective over the long term, because the cheap alternative measures installed may suffer more frequent failures and bring more expensive maintenance cost. The scope of maintenance includes activities required to operate and maintain facilities and their supporting infrastructure in a satisfactory condition to meet their intended function. For example, necessary maintenance of building envelope (such as windows and walls) will require extra investment cost, but energy savings caused by insulation improvement may bring higher investment benefits even though no alternative measures is installed. In practice, due to fatigues and failures energy efficiency of alternative facilities largely deteriorates if no maintenance will be conducted. A well-scheduled maintenance plan (or called strategy) can cost-effectively guarantee sustainable performance of energy savings and monetary profits. In this paper, the LCCA is used to evaluate costs associated with the initial retrofit and the following maintenance, in which maintenance cost has been optimized to achieve great energy saving and payback in the proposed multiobjective building retrofit model.

For each type of existing facilities, several different choices of measures with the same function should be considered in the optimal retrofit strategy. If only one single type of alternative measures is chosen to retrofit existing facilities, the retrofit strategy cannot be globally optimal for large and multi-functional buildings under the LCCA [6,21,13]. Based on our previous work [22], multiple choices of alternative measures are included in the proposed multiobjective model, in which the number of alternative measures for each category is optimized in the retrofit and maintenance strategies. Furthermore, another task of this paper is to answer a common question of decision makers, say, how to generate all representative scenarios for satisfying different preferences of stakeholders. To fulfil this task, multiobjective neighborhood field optimization (MONFO) algorithm proposed in [23] has been used to find Pareto optimal solutions of the building retrofit problem. Unlike the weighted sum method [21,22] in which only one optimal solution can be found for certain predefined weights, MONFO is applied to generate a diverse set of optimal solutions trading off all objectives. According to stakeholders' preferences, decision makers can choose one optimal solution that mostly satisfies these preferences. If stakeholders change their preferences, decision makers could choose another satisfactory solution from the Pareto set obtained by MONFO.

The contributions of this paper mainly include three aspects. Firstly, maintenance plan is evaluated in the proposed multiobjective building retrofit model. Unlike [21,22] without maintenance optimization, in this paper the maintenance plan as well as the retrofit strategy has been considered as variables of optimization in the LCCA. The proposed model can generalize both situations with or without optimal maintenance, which have been studied in the simulation section. Secondly, several conflicting objectives, i.e., retrofit cost, energy saving and NPV, are considered in the multiobjective model with multiple choices of alternative interventions. Thirdly, MONFO is a promising multiobjective optimization algorithm to ensure accuracy and diversity of the obtained Pareto solutions. In one single run of MONFO, comprehensive information of all possible retrofit scenarios will be provided to decision makers.

The paper is organized as follows. The multiobjective building retrofit problems are modeled in Section 2. Section 3 describes MONFO algorithm and the procedure to solve the target problem. Some numerical simulation of a building retrofit project is performed in Section 4. The paper is concluded in the last section.

2. Multiobjective energy efficiency retrofit problems

In building energy efficiency retrofit projects, there is more than one choice of alternative intervention to replace an existing facility. Both intervention type and number of interventions in each chosen type will be determined by decision makers. These numbers are called decision variable of retrofit strategy in the building retrofit problem. Before retrofitting, auditing target buildings is required for obtaining required data of existing facilities. Assume that existing facilities can be classed into K types. For the kth type of existing facilities to be retrofitted, let $J_k (k = 1, 2, \ldots, K)$ denote the types of alternative interventions. The number of alternative interventions in each type among J_k can be denoted as a vector $\mathrm{n}_\mathrm{k} = (n_k^1, n_k^2, \ldots, n_k^{J_k})$, in which n_k^j denotes the number of alternatives of the jth type for retrofitting the kth type of existing facilities. Then the retrofit strategy can be generalized as $\mathbf{x} = (\mathbf{n}_1, \mathbf{n}_2, \ldots, \mathbf{n}_K)$ with $\sum_{k=1}^{K} J_k$ dimensions.

The objectives of building retrofit may include to minimize retrofit cost and payback period, and to maximize energy saving