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A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings

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ABSTRACT

The building sector contributes a large proportion of the world's total final energy consumption. As a result, considerable attention has been paid to energy efficiency in the building sector. At the current stage, building retrofitting is the most feasible and cost-effective method to improve building energy efficiency. This paper presents a multi-objective optimization model for life-cycle cost analysis and retrofitting planning of buildings. A net present value (NPV) based economic analysis taking life-cycle cost into account is introduced to formulate the objective functions. In addition, a combination of multiple alternative measures for each retrofitting intervention is considered in determining the optimal solution. The presented model aims at maximizing both energy savings and economic benefits during a selected time frame. It allows decision makers to make best use of the available budget. A differential evolution (DE) algorithm is proposed to solve this optimization problem. The result of the case study illustrates the effectiveness of the multi-objective optimization model to support the planning of energy-efficient and cost-effective building retrofitting projects.

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1. Introduction

The building sector is nowadays drawing considerable attention in the energy area, being responsible for about 40% of the total energy consumption in the European Union (EU) and 32% in the world [1]. The practice of green buildings can reduce the growth of future energy demands. However, improving the energy efficiency in existing buildings is not similar to that in a brand new green building. Building retrofitting is currently the most feasible method to reduce the present energy demands in existing buildings.[1]

During the building retrofitting, energy conservation measures (ECMs) are taken on the current facilities. The development of technologies allows more and more available ECMs to improve the energy performance, whereas the selection of proper measures needs to satisfy several different requirements. Decision makers should take energy, economic, social and other factors into account to strike the best balance between stakeholders' and occupants' requirements [2]. The obtained optimal solution is usually a trade-off between these energy and non-energy related factors. Therefore a key problem of building retrofitting is the identification of the proper measures for the project using different criteria based on specific requirements.

Over the last decade, the multi-criteria (MC) model has often been used to evaluate a building retrofitting project. The criteria mainly focus on the energy efficiency, the capital cost and other comfort factors, such as the usable space for the occupants in the building [3], the air quality and the thermal comfort [4]. Some MC-based approaches for the evaluation of retrofitting projects can be found from [5–8]. During the design phase of a retrofitting project, MC are also adopted. Energy saving and capital cost are the most considered criteria for optimal building retrofitting planning [9,10]. As the requirements within these criteria are often contradictory, the planning process is essentially a multi-objective optimization problem subject to several constraints.

According to a recent review [11], there is a clear growth in the popularity of multi-objective optimization for sustainable building design. Recent research [12] especially discusses a multi-objective optimization model for building retrofitting investment decision. The objectives of the model are to maximize the energy savings and minimize the payback period for the given initial investment. By using the model in [12], a cost-effective retrofitting plan with a budget constraint can be obtained. However, in [12], the optimal solution is restricted only to a single preselected retrofitting measure per type of intervention. In practical projects, more alternatives can be provided for each type of intervention. The decision maker has to select the proper measures, even a combination of

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[1] A Guide to Energy Management in Public Buildings, 2008, http://old.gbcsa.org.za/system/data/uploads/resource/101_res.pdf.

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several measures from all available options for the same intervention. Such a selection is difficult to make prior to the multi-objective optimization. A more feasible method is to simultaneously consider all available alternatives during the optimization. The selection of proper measures thus becomes a part of the optimization.

When evaluating several alternatives, one must not only consider the initial cost of an alternative, as one alternative could appear cost-effective at the installation stage but also more expensive to maintain during the operation than other alternatives. Such alternative would in fact not be a cost-effective option over the long term. To evaluate the long-term cost-effectiveness of building retrofitting investments, life-cycle cost analysis (LCCA) should be applied. LCCA is an advanced technique especially for assessing the total cost of facility ownership. The life-cycle cost (LCC) is associated with the estimation of future cash flow. The LCC of an asset is defined as *the total cost throughout its life including planning, design, acquisition, support and any other costs directly attributable to owning or using the asset*.[2] For the building retrofitting investments, LCCA, a widely used technique for building retrofitting, can be applied to estimate the overall cost of the alternatives during the life-cycle of the building and evaluate the cost-effectiveness. Kaynakli [13] used LCCA to determine the optimal thickness of the insulation material in a building envelope for best cost-effectiveness. Menassa [14] presented a method to determine the investment of building retrofitting projects by taking into account different uncertainties associated with life-cycle cost and perceived benefits of this investment.

The simple payback period (SPP) was chosen to assess the economic viability in [12]. A variety of typical economic analysis methods can be used to evaluate the cost-effectiveness of building retrofitting investments, such as net present value (NPV), internal rate of return (IRR), overall rate of return (ORR), benefit–cost ratio (BCR), discounted payback period (DPP) and SPP [15,16]. When the future cash flow is taken into account, NPV is identified as the most widely used technique for optimal building energy assessment [17]. The NPV method, rather than the other economic analysis methods, translates the future cash flow into the present value of money, provides an explicit method to evaluate the overall value of a project. If the NPV of a prospective project within a chosen time frame is non-negative, the project is considered profitable. Verbeeck and Hens [18] as well as Petersen and Svendsen [19] used the NPV method to compare the economic viability of different retrofitting measures.

This paper builds on and extends the study of [12] by presenting a multi-objective optimization model with life-cycle cost analysis for building retrofitting planning. The optimization model involves both selecting proper retrofitting measures from a range of available alternatives per type of intervention and determining the quantities of retrofitted facilities using the chosen retrofitting measures. The model aims at minimizing energy consumption, reducing the payback period and maximizing economic benefits with the lowest possible life-cycle cost. The payback period is defined as the earliest possible time after which the NPV of this project remains non-negative. The economic viability is assessed by the NPV method. Life-cycle cost indicates the economic sustainability of the project and minimal life-cycle cost is emphasized in the model to guarantee long-term cost-effectiveness.

The presented model considers combinations of multiple alternative retrofitting measures in a building. There are many possible combinations, and the evaluation of alternatives often involves non-linear objective functions, as shown in [9,10,12]. With the development of computational powers and algorithms, it is possible to address problems that were previously infeasible [11]. The evolutionary algorithm (EA), a kind of generic population-based meta-heuristic optimization algorithm, is generally applied to address building energy optimization problems. As a typical EA, genetic algorithms (GAs) are widely used in optimal building retrofitting studies, such as [20] and [12]. However, when using GAs to solve a new optimization problem, the encoding becomes difficult and the convergence speed is slow. As one of the improvements of the classical EAs, differential evolution (DE) algorithms are simple and efficient heuristic methods first proposed by [21]. According to [21] and [22], DE generally outperforms GAs and many other algorithms on many numerical benchmark problems, including unimodal as well as multimodal functions, functions with correlated and uncorrelated variables, and a single problem with plateaus. Comparing to the other EAs, DE is robust, converges faster, and easy to implement. Consequently, a DE algorithm is adopted to solve the optimization problem presented in this paper. As a case study, a practical building retrofitting project is used to test and verify the feasibility and advantages of the proposed approach.

The remainder of this paper consists of four sections. Section 2 gives the formulation of the multi-objective optimization model. Section 3 introduces the DE algorithm to solve the optimization problem. Section 4 provides results and analysis. Section 5 draws conclusions and discusses future research.

Table 1
A sample retrofitting plan.

Facilities	Alternatives	Quantities
Lighting	Lighting intervention 1	20
	Lighting intervention 2	0
	Lighting intervention 3	35
Geyser	Geyser intervention 1	25
Air-Con	Air-Con intervention 1	0
	Air-Con intervention 2	30

2. Multi-objective optimization model

2.1. Decision variables

A building retrofitting plan consists of a set of retrofitting actions, which represents what and how retrofitting measures are implemented. The retrofitting action is characterized by three components: the existing facility to be retrofitted, the alternative interventions of new technological interventions and the quantities of items corresponding to the chosen interventions, as demonstrated in Table 1.

Assume that there are I types of facilities to be retrofitted, each corresponds to J_i types of alternative interventions. Let x_i^j denote the number of selected items from the ith type of facility with the jth alternative intervention, namely alternative intervention (i, j). For $i = 1, 2, \ldots, I$, let $X_i = (x_i^1, x_i^2, \ldots, x_i^{J_i})$, and $X = (X_1, X_2, \ldots, X_I)$. X is the decision variable which characterizes a retrofitting plan.

2.2. Multi-objectives formulation

Three objective functions are involved in the model. They are formulated as Eqs. (1)-(3):

$$f_1(X) = \mathrm{ES}, \quad (1)$$

$$f_2(X) = \mathrm{NPV}, \quad (2)$$

$$f_3(X) = T_p, \quad (3)$$

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[2] NSW Treasury, Life Cycle Costing Guideline, http://www.treasury.nsw.gov.au/_data/assets/pdf_file/0005/5099/life_cycle_costings.pdf.

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