Energy and Buildings 65 (2013) 10–18

Contents lists available at ScienceDirect

Energy and Buildings

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

Sequential equi-marginal optimization method for ranking strategies for thermal building renovation

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ARTICLE INFO

Article history:
Received 15 December 2012
Received in revised form 21 April 2013
Accepted 12 May 2013

Keywords:
Building optimization
Building renovation
Sequential search method
Building performance
Equi-marginal principle
Marginal utility optimization
Life cycle cost

ABSTRACT

Planners of building renovation projects prefer to evaluate recommended renovation strategies in terms of the benefits of the money invested. This study proposes a sequential building optimization method that requires only one optimization run to rank the recommended renovation strategies and parameters within a range of initial budget limits for building renovation projects. The proposed optimization method builds on the equi-marginal optimization method derived from consumer behavior research in microeconomics. By using this method, decision makers can evaluate financial long-term benefits of an investment and can see the diminishing marginal return, resulting in defining the most feasible budget limits. It provides the marginal benefit for each recommended renovation strategy in a cost benefit diagram. The proposed method differs from the already existing sequential optimization methods in the way the algorithm finds the optimal solution in each iteration and does not need expert knowledge for its application. The evaluation criterion is the life cycle cost (LCC). The sequential optimization algorithm uses thermal simulation software. For case studies with different budget limits and climate conditions, an existing building in the cool climate of Ann Arbor, Michigan is taken for reference. Results show that the optimization method provides reliable results leading to recommendations for renovation strategies that are ranked according to their marginal utility by investment. The ability of the user to see marginal utility by investment will improve economic decision making.

1. Introduction

The effect of greenhouse gas emissions on the global climate is one of the main problems of the century. Various economic avenues to reduce greenhouse gas emissions have been studied and researchers agree that the largest economic potential to reduce greenhouse gas emissions can be achieved in the existing built environments [1]. The built environment accounts for 30–40% of the industrialized society's total energy demand and approximately 44% of the total material use, as well as roughly 30% of the total CO_2 emission [2]. Huge reductions in energy demand can be achieved through building renovation [3].

Building renovation projects commonly must meet budget limits, and the building planners' goal is to find an optimal balance between investment and long-term life cycle costs (LCC). The optimal solution for the life cycle cost may be too high an investment [4]. When budget limits are being defined in the planning process, it is an advantage for the decision makers to be able to see the marginal long-term benefits for each potential financial investment increment [5,6] and to see marginal long-term benefits under different budget limits.

Planners and decision makers also want to know the marginal improvement of recommended renovation strategies rather than having only one optimal solution [7]. It would be even more valuable if planners could know the significance, priority, and utility benefit of recommended renovation strategies [8]. In addition, for the best decision-making, recommended parameter settings such as window type, thickness of insulation, and other improvements should be ranked for their economic efficiency. In this way planners can balance the most economical trade offs between the investment cost and the life cycle cost. An effective way to meet the outlined demands is to illustrate the investment cost as a function of the life cycle cost in a cost benefit diagram with precise results given at each budget increment. The diagram also demonstrates the diminishing marginal benefit as budget limit increases.

Building renovation projects are multi-variable problems that include a large number of possible combinations of parameter settings. It is often not clear which part of the building envelope or technical system is most effective to renew, improve, or replace. To assist in planning processes, thermal simulation programs like

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0378-7788/$ – see front matter
http://dx.doi.org/10.1016/j.enbuild.2013.05.028

TRNSYS [9], Doe-2 [10], or EnergyPlus [11] are used to perform parametric studies.

The parametric study often used in planning processes involves changing one parameter while leaving others constant. These studies can potentially miss important interactive effects [12]. One way to find a global optimal solution is to use enumerative search methods where each possible parameter setting is combined with each other. Because of the large number of combinations, this optimization process is computationally expensive and would take too much time. A more promising solution is to use a building optimization algorithm coupled with a simulation program to find an optimal solution [13].

The objective of this study is to propose a sequential building optimization method that provides a ranking of recommended renovation strategies and parameters within a range of initial budgets for building renovation projects. The proposed optimization method is based on the equi-marginal optimization method adapted from consumer behavior research in microeconomics. The proposed method differs from the already introduced sequential optimization methods in the way the algorithm finds the optimal solution for each iteration. Furthermore, the proposed method requires only one run for a range of budget limits. The goal is to provide an optimization algorithm that can be used by architects and planners with basic knowledge in thermal building simulation but without any expert knowledge, which is not the case with most existing sequential optimization methods.

The evaluation criterion in this study is the life cycle cost including the net present value (NPV). A building that is optimized only in terms of its operation cost is most likely not very cost effective because additional investment cost would overwhelm any savings in operation cost. Therefore, a balance must be found between increases in investment cost and savings in operation cost. Life cycle cost analysis (LCC) is a method for assessing the total investment cost over an anticipated lifetime. The net present value (NPV) of the LCC calculates the probable future energy price changes and inflation rates to the initial cost. LCC analysis has been used and proven as performance criteria in several studies [14,15].

For a case study in a climate with a heating season [16], a student dormitory building on the campus of the University of Michigan in Ann Arbor, Michigan was selected. The case study specifies all relevant characteristics for renovation of the building envelope. In the case study, four renovation strategies are evaluated: (1) replacement of the windows (2) addition of insulation to the roof, (3) wall, and (4) floor.

The outline of this paper is as follows: first, an overview is provided in Section 2. Then, the methodology of optimization algorithms and evaluation criteria is explained in Section 3. Section 4 provides the calculation results for a case study. Section 5 provides a discussion of the robustness of the equi-marginal optimization method. Finally, Section 6 summarizes the conclusions.

2. Overview and background

Building optimization approaches taken toward achieving the objectives outlined in Section 1 can be classified as discrete and continuous parameter optimization methods. Continuous parameter methods like the simplex method [17], the pattern search algorithm [18], the harmony search algorithm [19], and the multi-directional search algorithm [20] based on numerical optimization have been introduced for building optimization [21]. However, Choudhary found that numerical building optimization algorithms based on simulations have non-smooth functions and can fail to find the optimum solution [22]. Furthermore, these methods are limited because continuous parameters are almost non-existent in building renovation. Instead, optimization methods using discrete parameters, like the genetic algorithm [23], particle swarm [24,25], and sequential search methods are more suitable for building renovation such as this one.

The genetic algorithm (GA) is a probabilistic search technique to find optimal solutions for discrete parameters. Within each iteration of the algorithm, a different path toward an optimal solution is found and the end result may vary [24,26]. Experiments have demonstrated that this algorithm does not always result in good solutions [27]. Furthermore, because of the way it finds optimal solutions, this algorithm does not rank the recommended building renovation strategies and parameter settings.

The particle swarm method has also been used successfully for building optimization. However, the method has been found to be relatively computationally intensive [26] and it does not rank the marginal benefit of the recommend parameter settings for building renovation.

The term “sequential search algorithm” has been applied in this study to an optimization method that iteratively improves the building performance. In each iteration step, the most effective solution is found by comparing the results of previously defined strategies and parameter settings. The optimal strategy in the search space is found according to its marginal benefit and recorded in each iteration step. Because of this sequential approach, this algorithm has a significant advantage over optimization algorithms that provide only the optimal solution in that it ranks the recommended strategies and also provides the marginal benefit.

A difference in the sequential optimization process used for building simulation compared to the problems in microeconomics or mathematics is that the starting values, such as energy demand or life cycle cost, will change dynamically in each iteration step in relation to reductions in operation energy demand in each successive step. Only top-down sequential approaches can be used because forecasting the results in future iterations is not possible. Thus, there is a risk that large improving strategies can be overlooked in earlier iteration steps.

Christensen at al [28,29] introduced the software tool BEopt based on a sequential search algorithm. BEopt uses the DOE 2 and TRNSYS as a simulation environment. As in most forms of sequential search algorithms or greedy algorithm (Section 3.1.2), the chosen strategy is then removed from the parameter search space for future evaluation. The developer of BEopt modified the algorithm to overcome the problem of overlooking large improvement strategies and negative interactions between strategies. BEopt keeps track of solutions in previous iterations and compares them with the current solution. Interactions between parameter settings must be identified by the user before using the algorithm where technical expertise is necessary [26]. The particular strength of BEopt is to find the optimal combination for zero net energy buildings [30] in terms of operation cost and, thus, does not impose a budget limit constraint for building renovation projects. Of note, no literature was found that describes a sequential search algorithm that illustrates the marginal benefit of strategies under different budget limit constraints for building renovation.

To address problems with any one method, researchers have developed hybrid optimization methods that combine two or more methods [22,3]. However, Choudhary has found that hybrid methods need expert analysis from researchers or engineers of different levels of complexity [22], and, in general, hybrid methods are not designed to rank recommended strategies and parameter settings.