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Variability of optimal solutions for building components based on comprehensive life cycle cost analysis

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ABSTRACT

Building energy contributes to a significant fraction of the total energy cost during all processes of its life span. Buildings are dynamic, non-linear systems with a large number of components that strongly influence total building energy consumption. Therefore, it is challenging to find an optimal combination of building components to minimize the building life cycle cost (LCC). This paper proposes a framework of building systems optimization designed to minimize life cycle cost by combining optimization algorithms and a comprehensive building life cycle cost model. A case study based on an office building demonstrates that annual energy costs and initial construction costs are major contributors to the whole building life cycle cost. A case study of an office building shows that when the building lifespan is greater than 30 years, the cumulative annual energy consumption cost is projected to be higher than the initial construction cost. Finally, optimal component combinations vary with different lengths of a building's life span. For instance, wood window frames become the optimal component for less energy and maintenance cost when the building lifespan changes from 14 to 60 years.

1. Introduction

Building energy contributes to a significant fraction of the total national energy cost during a building's lifetime. In developed countries, building energy consumption represents 20–40% of total national energy use and this percentage is above the industry and transportation figures in EU and the US. The growing trend in building energy consumption will continue during the coming years due to building floor area expansion and associated energy needs [1]. Buildings have relatively long life spans. In the U.S., the median lifetime of commercial buildings is 50–65 years [2]. In addition, buildings are dynamic, non-linear systems with a large number of components that strongly affect building energy consumption. This complicates optimizing total building energy consumption. Several specific components that contribute strongly to total building life cycle cost (LCC), most notably building enclosure and mechanical systems [3].

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the lifecycle of a product [4]. Following the definition and guidance in the International Organization for Standardization (ISO) 14040 [5], building life cycle includes construction, annual operation and maintenance, and demolition. The cash flow during these phases contains construction capital cost, transportation cost, annual operating energy consumption, maintenance cost, and demolition cost.

2. Literature review

2.1. Building life cycle analysis

A large number of LCA tools have been developed for designers and researchers to analyze life cycle cost, such as BEES, ATHENA EcoCalculator, ATHENA Impact Estimator, and SimaPro [6]. The existing LCA tools are designed for different levels of flexibility and detail. However, as shown in Table 1, every existing LCA tool is missing one or more analysis aspects of building life cycle analysis. Therefore, this study proposes a comprehensive methodology that covers all the phases of the building life cycle.

The data used in the existing LCA tools are mostly based on built-in life cycle inventory databases. However, building energy consumption is not only determined by building materials, but also by building profile and location. The proposed methodology combines a dynamic building energy simulation for annual operating energy consumption and a built-in database containing information regarding other costs. The building energy simulation will consider envelope profile, mechanical system type, and building location.

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Table 1
Life cycle assessment tools.

LCA tools		BEES	ATHENA EcoCalculator	ATHENA impact estimator	SimaPro	Proposed methodology
Development organization		EPA (US)	ATHENA (Canada)	ATHENA (Canada)	PRé Consultants (Netherlands)	–
Analysis level		Material	Assembly	Building	Variable	Building
Program complexity		Low	Low	Medium	High	Depend on users
Analysis aspect	Capital cost	Y	N	Y	Y	Y
	Operational energy	Y	N	N	Y	Y
	Transportation	Y	N	N	Y	Y
	Maintenance	N	N	Y	N	Y
	Demolition	N	N	N	N	Y
	Life cycle economic cost	Y	N	Y	Y	Y

2.2. Building optimization methods

A large number of research projects have developed methodologies for building optimization. In the following literature review, they are divided into two categories: simple method and advanced optimization method.

2.2.1. Simple method

Simple methods are the straightforward methodologies based on derivation and simple iteration.

2.2.1.1. Derivation. There are many optimization problems in the field of building energy. Simple optimization projects usually focus on only one component of building. Hasan [7] selected the insulation thickness as the optimization parameter. This optimization method is based on a life cycle cost analysis, which is a function of degree days and wall thermal resistance. The optimum insulation thickness is obtained by minimizing the total cost. Hence, the derivative of total life cycle cost (Ct) with respect to insulation thickness (X) is set equal to zero, obtaining the optimum insulation thickness (X_{op}). Dombaycl et al. [8] used a similar method to optimize insulation-thickness of the external wall for five different energy-sources (coal, natural gas, LPG, fuel oil, and electricity), and two different insulation materials (expanded polystyrene and rock wool).

This is the most straightforward way to obtain the optimum. This method is effective in simple problems that have one or two optimized parameters with countable options and one objective. If one function cannot define the problem objective, the derivation method is not adequate to achieve the optimum. The optimization problem needs more advanced methods when the objective is too complex to describe as a function of variables.

2.2.1.2. Simple iteration. Another simple method is based on iteration. A choice between two options is made at each step of the iteration according to a comparison of the energy consumption results. In every iteration, the option of variables gives a better solution of the objective, and the optimal variable is chosen for the next iteration. In 1989, Gustafsson and Karlsson developed an OPtimal Energy Retrofit Advisory (OPERA) to implement the optimal retrofit combination for multi-family buildings [9]. The process, showed in Fig. 1, starts with calculation of LCC for the existing building, followed by several iterative comparisons and choices.

In this case, the aim of the retrofit is to decrease the existing LCC. The model focuses on envelope and ventilation retrofits: attic floor insulation, floor insulation, external wall insulation, glazing type, weather-stripping, and exhaust-air heat pumps. The method requires significant computational resources that increase exponentially with the number of the optimized parameters in one problem. Therefore, when the problem becomes more complex with many parameters, the efficiency of this method to make an optimal decision could decrease.

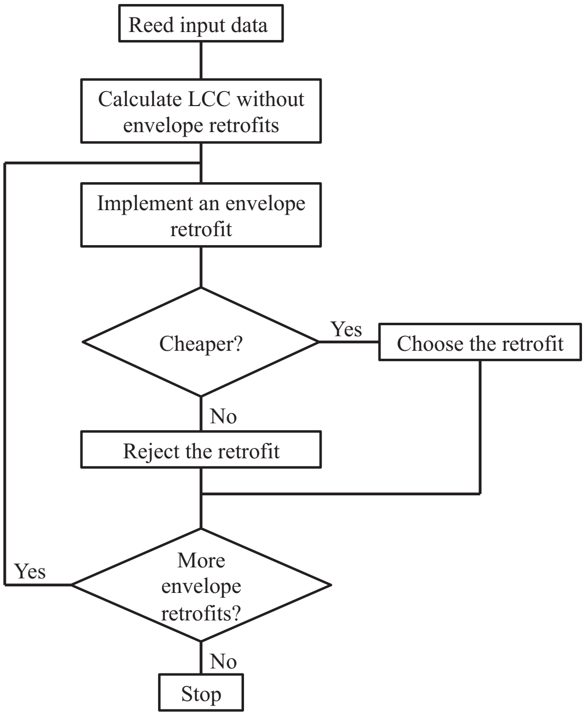

Fig. 1. Flow chart of iteration.

2.2.2. Advanced optimization methods

The limitations of the simple methods have encouraged more advanced methods to solve building energy optimization problems, such as neural network sequential search and genetic algorithms.

2.2.2.1. Neural network. A study to optimize office building shape is accomplished by Ouarghi and Krati [10]. In this study, the objective is minimizing annual building energy cost. The building shape is described by its relative compactness, with a cube as the reference building. Relative compactness is defined as the ratio of the building volume to its surface area. The study used a Bayesian neural network to optimize building energy performance, trained by results from simulations using the DOE-2 engine.

The neural network is a reliable method in optimization problems, but requires training to guarantee reliability. Furthermore, simulation of the real project is needed for the training since the network must learn to react realistically. Unfortunately, in design projects, decisions must be made within a certain time frame, which means there is rarely sufficient time and material to train the network.