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Multi-objective optimization of building envelope design for life cycle environmental performance

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ABSTRACT

The building envelope incorporates significant amount of construction materials and is a key determinant of the embodied energy and environmental impacts in buildings. It is also a mediator between indoor and outdoor environmental conditions and has significant impacts on operational energy use in many types of buildings.

The present article utilizes a multi-objective optimization algorithm to explore optimum building envelope design with respect to energy use and life cycle contribution to the impacts on the environment in a low-rise office building in Seattle, Washington. Design inputs of interest include insulation material, window type, window frame material, wall thermal resistance, and south and north window-to-wall ratios (WWR). The simulation tool eQuest 3.65 is used to assess the operational energy use, while Life Cycle Assessment (LCA) methodology and Athena IE are used to estimate the environmental impacts. Also, a hybrid artificial neural network and genetic algorithm approach is used as the optimization technique. The environmental impact categories of interest within the LCA include: global warming, acidification, eutrophication, smog formation, and ozone depletion. The results reveal that the optimum design scenario incorporates fiberglass-framed triple-glazed window, about 60% south WWR, 10% north WWR, and R-17 insulation.

1. Introduction

The contribution of buildings to the overall environmental impacts of human activities has been well-documented [14,11]. According to the US Energy Information Administration [11], 19% of the world's primary energy is consumed in the US. The major consumers of the total energy in the US, as the EIA data reveals, include commercial buildings (18.5%), residential buildings (22%), industrial sector (32%), and transportation (27.5%). Buildings also contribute 40 percent to carbon dioxide emissions in the states EIA, 2012 and about 66% to generation of non-industrial solid-waste [14].

Life Cycle Assessment (LCA) methodology has gained increasing popularity in recent years to assess how buildings or their components contribute to the negative impacts on the environment over their entire life cycle. Considering the entire stages; i.e., cradle to grave, in LCA offers a more informed basis for decision-making, compared to other methodologies that focus on operation phase of life cycle only and rely on metrics such as operational energy use. LCA studies typically address all stages of a building's life cycle and cover one or more of six impact categories. LCA methodology's principles, requirements and guidelines are prescribed by ISO 14040 [21], and ISO 14044 [22]. In 2011, the European Committee for Standardization developed EN 15978 [12] as the standard for using LCA in assessment of the environmental performance of buildings. In addition, International Standards Organization (ISO) provides metrics and requirements for determining the carbon footprint of buildings through [23].

Many studies use LCA in assessing the environmental impacts of buildings. For instance, Kosareo and Ries [26] compare intensive and extensive green roofs versus conventional roofs with regard to their impacts on ozone depletion, global warming, acidification and eutrophication. Pulselli et al. [29] use energy analysis and emergy evaluation methods to assess environmental costs and benefits of three different types of envelopes (an air cavity wall, a plus-insulated wall and a ventilated wall). Azari and Kim [4] focus on

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Table 1
An overview of some LCA literature.

Reference	Subject of LCA			LCA stages					Impact Categories						
	Construction Materials	Building Envelope, Components, and Systems	Buildings	Material Extraction	Manufacturing	Construction	Operation & Maintenance	Demolition & Recovery	Other	Human Toxicity	Smog Formation	Global Warming	Energy Use	Eutrophication	Acidification
[1]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[3]		✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
[4]	✓	✓		✓	✓	✓	✓			✓		✓		✓	✓
[10]	✓	✓		✓	✓	✓	✓	✓				✓			
[24]	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
[25]	✓		✓	✓	✓	✓	✓	✓	✓						
[26]		✓		✓	✓	✓	✓	✓	✓			✓		✓	✓
[28]		✓		✓	✓	✓	✓	✓	✓	✓		✓			
[29]		✓		✓	✓	✓	✓	✓	✓				✓		
[31]		✓		✓	✓	✓	✓					✓	✓		
[32]	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
[33]	✓		✓	✓	✓	✓	✓	✓	✓				✓		
[34]		✓	✓	✓	✓	✓	✓	✓	✓				✓		
[35]		✓	✓	✓	✓	✓	✓	✓	✓				✓		

curtain walls and apply a computational process-based environmental life cycle assessment (LCA) to compare the effect of change in mullion materials on curtain wall's environmental impacts. Azari [3] conducts a parametric LCA analysis to examine how the change of design input values in a limited number of building envelope configurations would impact the environment.

Dodoo et al. [10] is an example of studies that focus on building structures. The study uses the consequential-based LCA to compare three versions of timber structures; i.e., cross-laminated timber, beam-and-column and modular structures. In an LCA study of an office building, Junnila and Horvath [24] conduct a complete life-cycle analysis on an office building with a service life of 50 years and investigate its impacts with regard to acidification, eutrophication, climate change, etc. They later extend this study and compare the impacts of office buildings in the US and Europe [25]. In Australian context, Treloar et al. [33] and Treloar et al. [34] study the embodied energy of construction materials (2001a) in a building and, in another project, measure the embodied energy in several office buildings and study the effect of height and number of floors on changes in embodied energy. In another study, Yohanis and Norton Yohanis and Norton (2002) study the variations in life-cycle embodied and operational energy as well as capital cost as a result of change in building parameters."

Finally, Tingley et al. [32] is a study at the scale of construction materials in which LCA is used to compare three different insulation materials when applied in a typical dwelling. A snapshot of a selected number of LCA studies in the field of built environment is shown in Table 1.

One limitation in many comparative LCA studies is the limited number of variables and combinations, out of all possibilities, that are studied. This in turn results in incomprehensive conclusions with regard to optimized LCA. Because of the significant resources that would be needed to analyze all possible scenarios in a comprehensive LCA study, computational optimization techniques are utilized to address the challenge. To consider all possible combinations of design inputs and values, an optimization problem is started with identification of design inputs and proceeds with determining risks and constraints, finding the objective function, setting the minimum and maximum thresholds on design inputs, choosing an optimization algorithm, and eventually obtaining the results; i.e., the optimum solution to optimization problem [9].

The present article tries to use an intelligent optimization algorithm to explore optimum building envelope design combination in a low-rise office building from operational energy use and environmental life-cycle impacts perspectives. The design inputs of interest include wall thermal resistance (R-value), insulation material, glazing type, window-to-wall ratio (WWR) in north and south facades, and frame material. Using these variables, we attempt to find the design combination that yields the lowest operational energy use and the least environmental impact. To achieve the objective, an integrated energy and environmental life-cycle assessment methodology is used to quantify the environmental impacts associated with each design combination. The results are then used in a hybrid artificial neural network and genetic algorithm-based approach to identify the optimum design combination.

2. Methods

A two-phase research methodology was pursued as illustrated in Fig. 1. The first phase is LCA methodology followed by optimization efforts.