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A review on optimization methods applied in energy-efficient building geometry and envelope design

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ABSTRACT

Building envelope parameters and geometric configurations can considerably influence the building energy performance. However, determining the best trade-offs of different building shape and envelope configurations to yield near-optimal design alternatives with respect to their energy performance is not a straight-forward task. Consequently, different methods have been utilized to optimize building envelope parameters and geometric configurations to achieve better energy performance. The objective of this paper is to provide an extensive review of the optimization methods and their application in energy-efficient architectural building design to better identify the potentials and applicability of different optimization methods. This paper reviews the optimization research, where building envelope parameters and geometric configurations are considered remarkably as the optimization independent variable(s) and building energy consumption/demand is included as an objective in the optimization process. The associated derivative-free and derivative-based optimization methods and their application in energy-efficient building design are included in this review. In addition, decision-making approaches are discussed for multi-objective optimizations. Current optimization tools are demonstrated. Finally, crucial considerations, including limitations and suggestions for the related future studies are concluded.

1. Introduction

Energy management policies have been trying to deal with the issues associated with energy all around the world. Either the main context is the energy bottleneck, such as the energy crises in the 1970s, or environmental issues, such as climate change concerns, there have been strategies and plans proposed to tackle the related issues with energy management strategies. The proposed long-term and short-term plans are in accordance with the sustainability framework [1].

A considerable portion of the total energy consumption is related to building sector [2]. Pérez-Lombard et al. [3] identified the increase in energy consumption of residential and commercial sectors that reached 20–40% of total global energy usage, where half of the building energy consumption is dedicated to Heating, Ventilation, and Air Conditioning (HVAC) systems. Therefore, energy-efficiency in building design is one of the main focuses of regional, national, and international energy policies [3]; especially, the energy-efficiency in HVAC systems, lighting, and miscellaneous electric loads and other end-uses that have the highest delivered energy intensity in both residential and commercial sectors [4].

Thermal performance of buildings is related to three main categories: micro-climate of the environment of the building, building physics, and required thermal comfort inside the building [5]. Among these categories, building physics, specifically building envelope parameters, can impact the building energy performance and comfort to a considerable extent. Building skin typically consists of opaque, transparent, or the combination of opaque and transparent components and influences the heating, cooling, and lighting energy consumption in a building by properties such as material conduction, solar energy transmitted through the window, shading characteristics, visible

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Abbreviations: ACO, Ant Colony Optimization; ANN, Artificial Neural Networks; ATC, Analytical Target Cascading; CMA-ES/HDE, Hybrid Covariance Matrix Adaptation Evolution Strategy Algorithm (CMA-ES) and Hybrid Differential Evolution; Coordinate Search, Coordinate Search algorithm; Discrete Armijo gradient, Discrete Armijo Gradient algorithm; DM, Decision Maker; ENSES, Elitist Non-dominated Sorting Evolution Strategy; evMOGA, Multi-objective evolutionary algorithm based on the concept of epsilon dominance; FO, Full Optimization; GA, Genetic Algorithm; HJ, Hooke–Jeeves algorithm; HM, Harmony Memory; HMCR, Harmony Memory Considering Rate; HS, Harmony Search; HVAC, Heating, Ventilation, and Air Conditioning; LCC, Life-Cycle Cost; MODA, Multi-Objective Dragonfly Algorithm; MOGA-II, Multi Objective Genetic Algorithm II; MOPSO, Multi-Objective Particle Swarm Optimization; Nelder and Mead, Simplex algorithm of Nelder and Mead with the extension of O'Neill; PAR, Pitch Adjusting Rate; pNSGA-II, Non-Dominated Sorting Genetic Algorithm with a Passive Archive; PR_GA, Two-phase optimization using the Genetic Algorithm; PSO, Particle Swarm Optimization; PSO on a mesh, PSO that searches on a mesh; PSO/HJ, Hybrid Particle Swarm Optimization and Hooke and Jeeves algorithm; SA, Simulated Annealing; sGA, Simple Genetic Algorithm; spMODE-II, Multi-objective differential evolution algorithm; SS, Sequential Search; WWR, Window-to-Wall Ratio

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transmittance, effective aperture etc. [6–9]. Glazing systems can enable the utilization of daylight [10], as well as the direct solar energy gain [11,12] while opaque exterior walls can benefit indirect gain [13–15]. Furthermore, geometrical configurations of a building, such as shape factor, length-to-width ratio, window-to-floor ratio, and Window-to-Wall Ratio (WWR) [16] can impact building energy load. Therefore, HVAC systems and lighting loads are essentially influenced by building envelope. Consequently, previous research have focused on optimizing building envelope components. For example, the optimum insulation thickness, as an influential parameter of the building on its energy use, demand, life-cycle analysis etc. have been the focus of different studies [17–22]. The objectives of these research cover different metrics, including the annual energy use, demand, life-cycle analysis etc. [23–40].

In general, the energy-efficient design of building envelope components and building geometry can potentially reduce the non-renewable portion of the total building energy consumption by taking advantage of the renewable energy resources such as sunlight, wind, etc., which are continually replenished. Passive and active strategies that use different renewable energy resources can be adopted in building envelope and geometry design. Selecting appropriate renewable energy resources in a building requires considering different factors such as the available renewable energy, associated implementation and maintenance costs, incentives, local regulations, and the characteristics of the energy profile [41]. While some of these factors are related to the implementation of the active strategies, others are common between passive and active strategies. In fact, building envelope components, as the parts of a building forming the primary thermal barrier between interior and exterior, influence the building energy consumption and comfort significantly even without implementing active applications. The inherent impact of the building envelope on the building energy consumption emphasizes the advantages of using the renewable energy resources either with passive or active strategies.

One of the main renewable energy resources applied in buildings is the receiving energy from the sun. For example, passive solar heated buildings utilize the solar thermal energy. Thermal properties of thermal storage walls in building envelope can then play a crucial role in building energy consumption pattern and peak shaving [14]. Furthermore, the visible portion of the energy received from the sun can impact the daylight performance in a building and offset lighting loads, which also alter cooling and heating loads [10]. Besides passive strategies, solar renewable energy can be utilized in building envelope using active technologies. Building-integrated photovoltaic is an example that uses solar energy to generate electricity and can be used in building envelope (e.g. rooftop shingles, building façade, or the glazing systems). The other application of the solar energy in buildings is the solar hot water systems. Solar hot water systems can be integrated into the building design to collect the heat from the sun and deliver it for the hot water usage. Building integrated solar thermal shading system that uses small-sized solar thermal panels is an application of utilizing solar energy to generate hot water while reducing solar heat gain and controlling glare [42]. Solar ventilation preheating systems, a low cost and efficient strategy that has no storage requirement, is also another application of using the energy received from the sun as a renewable energy resource that can be used in preheating ventilation air [41].

The other application of renewable energy resources in the building envelope is the wind. Wind velocity influences the heat transfer through the building envelope. In addition, besides buoyancy-driven ventilation, wind-driven ventilation systems, mainly categorized into single-sided or cross ventilation systems, are effective strategies to leverage wind energy to reduce building energy consumption and improve comfort and indoor environmental quality, including the hygrothermal performance that comprises of the transport and storage of heat and moisture [43]. Furthermore, in naturally ventilated double-skin facades, the cavity airflow can impact building energy performance and comfort [44].

In general, the architectural design aims to achieve the best set of performances while considering the applicability and constraints. As stated by Gero et al. [5], three categories are defined based on the approach of using the information related to the performance of an architectural design in the design process. *Design → performance* approach predicts the performance of a design based on the design variables, *performance → design* is exploring design alternatives with higher performances with changing design variables and observing the results, and *performance → performance* relationship deals with the trade-off of conflicting objectives in different performance criteria [5]. Although there are different methods to analyze building thermal and daylighting performance, including detailed simulation software, many of them offer evaluative rather than prescriptive result [45]. Therefore, trade-offs and optimization of architectural design, specifically building envelope optimization, with respect to the energy use of the building still need further investigation.

Furthermore, Architectural design can be categorized as an ill-defined problem, which in many aspects does not have a clear path for the solutions as well as clear criteria for straight-forward evaluation and trade-off as it involves parameters that cannot be quantified easily. Therefore, computer-aided design has been developed and implemented in many aspects of architectural design. Gero [46] identifies three influential events for the advent of the use of computers in architectural design, including the space layout planning (e.g. as in Souder and Clark hospital space layout planning in 1963 and 1964 [47,48]), computer graphics in the representation and manipulation of the virtual models for buildings (e.g. in Sutherland publication of the “Sketchpad” system in 1963 [49]), and the Notes on the Synthesis of Form publication of the Alexander [50]. With the technical changes and the availability of the hardware and software, the use of computers in architectural design become more pronounced in both research centers and industry. Currently, the utilization of the computer in parametric architectural design [51] and generative and algorithmic design [52] is increasingly deployed in the architectural and multi-disciplinary design process.

There are different applications developed for optimization in architectural design. Optimization platforms that can be coupled with building energy simulation tools are examples that assist building designers to search for the near-optimal design alternatives to achieve high-performance building designs. There are also different systems proposed for building optimization. An example of the systems that proposes the intelligent assistance of computer-aided design-based system to find better solutions is intelligent computer-aided design system [53], which includes six knowledge-based systems working as domain experts. Although there are different methods and tools proposed for building energy optimization, special considerations should be deliberated for different cases.

The objective of this study is to illustrate the state-of-the-art of the energy-efficient building shape and envelope design optimization and demonstrate the related considerations. Providing the extensive review of the building shape and envelope optimizations can reveal the efficiencies and applicability of different generic optimization algorithms in architectural building design as well as the potential considerations for the future studies.

1.1. Previous reviews

Previous related reviews have discussed materials related to this review. Evins [54] reviewed the application of computational optimization methods in building design with particular focus on residential and retrofit. Nguyen et al. [55] reviewed simulation-based optimization methods applied to building with the main focus on handling discontinuous multi-modal building optimization problems. Machairas et al. [56] studied optimization algorithms in building design. Shi et al. [57] reviewed building energy efficient design optimization from the architectural standpoint. Huang and Niu [58] reviewed the optimization of building envelope design of the last 30 years. Tian [59] reviewed