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Performance indices and evaluation of algorithms in building energy efficient design optimization

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ABSTRACT

Building energy efficient design optimization is an emerging technique that is increasingly being used to design buildings with better overall performance and a particular emphasis on energy efficiency. To achieve building energy efficient design optimization, algorithms are vital to generate new designs and thus drive the design optimization process. Therefore, the performance of algorithms is crucial to achieving effective energy efficient design techniques. This study evaluates algorithms used for building energy efficient design optimization. A set of performance indices, namely, stability, robustness, validity, speed, coverage, and locality, is proposed to evaluate the overall performance of algorithms. A benchmark building and a design optimization problem are also developed. Hooke–Jeeves algorithm, Multi-Objective Genetic Algorithm II, and Multi-Objective Particle Swarm Optimization algorithm are evaluated by using the proposed performance indices and benchmark design problem. Results indicate that no algorithm performs best in all six areas. Therefore, when facing an energy efficient design problem, the algorithm must be carefully selected based on the nature of the problem and the performance indices that matter the most.

1. Introduction

1.1. Background

Resource crisis, climate change, and other environmental challenges have led to a paradigm shift toward a more energy efficient society. As the building sector accounts for 30%–40% of the society's total energy demand, approximately 44% of the total material use, and 30% of the total CO_2 emission [1], building designs targeting energy efficient design have shown their merit as the most economically beneficial strategy for energy saving and pollution reduction.

Energy efficient design optimization for buildings is a new technique that relies on optimization algorithms to generate new designs based on simulation results and predefined design objectives. Compared with the conventional “trial-and-error” design methodology, which is largely dependent on designers' knowledge and experience, this new technique is more efficient, more powerful, and more likely to achieve optimal or near-optimal design solutions. The energy efficient design optimization technique for buildings is becoming an active research field. It is widely used in the optimization of building envelope, HVAC systems, energy generation, and earthquake safety [2–5].

The general procedure of the energy efficient design optimization technique is illustrated in Fig. 1 [43]. It consists of multiple steps, with the ones operated by the designer marked in green and the ones operated by the computer marked in pink. The optimization and energy simulation engines drive the design process. Optimization algorithms play a key role because they generate new designs based on user-defined design objectives and energy simulation results. Therefore, the performance of optimization algorithms is vital for the effectiveness and efficiency of the building energy efficient design and optimization workflow.

The demands of a search method aimed at working efficiently on a specific optimization problem have led to various optimization algorithms. The commonly used algorithms in the energy efficient design optimization for buildings can be grouped into three categories, namely evolutionary algorithms, derivative-free search algorithms, and hybrid algorithms [6]. Each category contains a variety of algorithms.

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Nomenclature

n	number of optimization tests conducted by an algorithm
Y_i	objective function value of the optimal solution obtained in the ith test
M	mean of objective function values of optimal solutions obtained in all tests
SD	standard deviation of objective function values of optimal solutions obtained in all tests
X'	optimal solution obtained by an algorithm in the first optimization run
X^*	true optimal solution
$f(X)$	objective function
m	number of independent variables
l_k	lower bound of the kth variable
u_k	upper bound of the kth variable
$d(X^*,X')$	normalized Euclidean distance between the optimal solution obtained by an algorithm and the true optimum
$g(f(X^*),f(X'))$	relative distance in the objective function values between the optimal solution obtained by an algorithm and the true optimum
t	total number of solutions searched by an algorithm
h_{kj}	value of the kth variable corresponding to the jth solution
M_k	mean of the kth variable values of all searched solutions
SD_k	standard deviation of the kth variable values of all searched solutions
COV	coverage of an algorithm
X_b	first solution of the region approximates to the global optimum
β	a constant that is personally defined to determine the region approximate to the global optimum
OA	average amplitude oscillation of the objective function

Evolutionary algorithms are used most frequently in building performance optimization, examples being the Genetic Algorithm (GA) and its modified versions, namely Multi-Objective Genetic Algorithm (MOGA) [7], Multi-Objective Genetic Algorithm II (MOGA-II) [8], and Non-dominated Sorting Genetic Algorithm II (NSGA-II) [9]. Particle swarm optimization (PSO), simulated annealing (SA), and ant colony optimization are some other evolutionary algorithms that are generally popular but rarely found in research works that focus on the optimization of building design.

A well-known derivative-free optimization algorithm family is the direct search method [10], which includes Hooke–Jeeves algorithm, coordinate search, exhaustive search, mesh adaptive search, etc. The Hooke–Jeeves algorithm seems to be the most popular one employed in building optimization [4].

Hybrid algorithms are combinations of different algorithms. The typical procedure is to use a global search algorithm to find a near-optimal solution, and then utilize the result as a starting point for a local optimizer. An example of this operation is implemented in GenOpt [11], where the PSO algorithm starts a global searching for the optimal solution. When the PSO finishes, the Hooke–Jeeves algorithm continues the searching process to refine the result.

1.2. Literature review

Existing literature on the performance of optimization algorithms is mostly from non-architectural fields, including mathematics, computer science, and operations research. Suganthan et al. [12] proposed 25 benchmark functions and 5 algorithm evaluation criteria, namely, success rate, convergence graphs, algorithm complexity, parameters, and encoding. Elbeltagi et al. [13] compared five evolutionary algorithms (i.e., GA, memetic algorithm, PSO, ant-colony system, and shuffled frog leaping) in terms of processing time, convergence speed, and quality of results, in solving continuous and discrete benchmark functions.

However, the effectiveness and efficiency of optimization algorithms used in building energy efficient design optimization are not adequately addressed. Although the volume of literature focused on building energy efficient design optimization has increased rapidly during the last two decades [2], most of the studies apply optimization algorithms to specific design problems without delving into their performance. Few relevant research works are reviewed below.

Wetter and Wright [14] assessed eight algorithms (i.e., coordinate search algorithm, HJ algorithm, PSO, PSO that searches on a mesh, hybrid PSO-HJ algorithm, simple GA, Simplex algorithm of Nelder and Mead, and discrete Armijo gradient algorithm) for their performance in minimizing annual energy consumption and simulation numbers. They found that the hybrid algorithm achieved the biggest cost reduction with a higher number of simulations than the simple GA, which consistently came close to the best minimum. In particular, Simplex algorithm and discrete Armijo

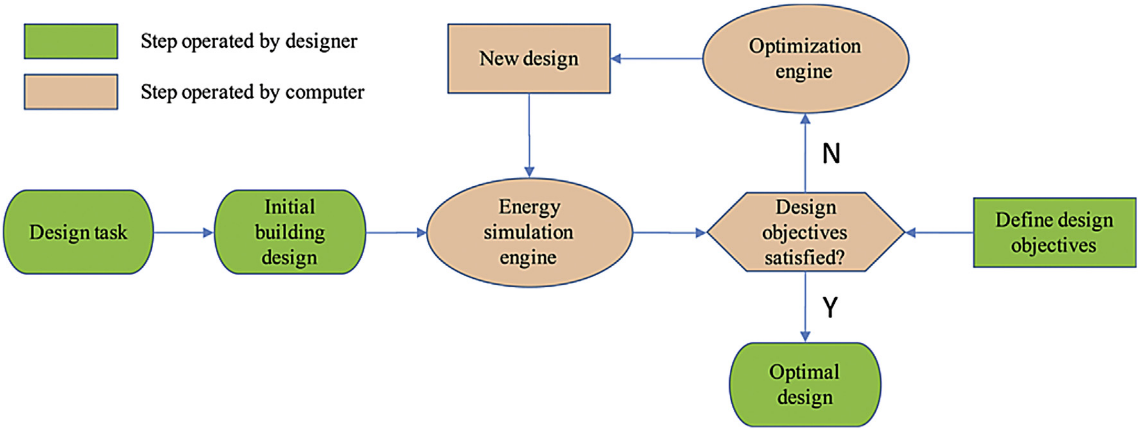

Fig. 1. General procedure of the energy efficient design optimization technique for buildings.