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Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO)

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HIGHLIGHTS

- A methodology is presented for building energy performance optimization.
- EnergyPlus is used as the building energy simulation program.
- Multi-objective particle swarm optimization is used as the optimization approach.
- The method is applied to a single zone case study in four climatic regions of Iran.
- Building specifications are optimized to minimize its annual energy consumption.

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ABSTRACT

This paper proposes an efficient methodology for the simulation-based multi-objective optimization problems, which addresses important limitations for the optimization of the building energy performance. In this work, a mono- and multi-objective particle swarm optimization (MOPSO) algorithm is coupled with EnergyPlus building energy simulation software to find a set of non-dominated solutions to enhance the building energy performance. To evaluate the capability and effectiveness of the approach, the developed method is applied to a single room model, and the effect of building architectural parameters including, the building orientation, the shading overhang specifications, the window size, and the glazing and the wall material properties on the building energy consumption are studied in four major climatic regions of Iran. In the optimization section, mono-criterion and multi-criteria optimization analyses of the annual cooling, heating, and lighting electricity consumption are examined to understand interactions between the objective functions and to minimize the annual total building energy demand. The achieved optimum solutions from the multi-objective optimization process are also reported as Pareto optimal fronts. Finally, the result of multi-criteria minimization is compared with the mono-criterion ones. The results of the triple-objective optimization problem point out that for our typical model, the annual cooling electricity decreases about 19.8–33.3%; while the annual heating and lighting ones increase 1.7–4.8% and 0.5–2.6%, respectively, in comparison to the baseline model for four diverse climatic regions of Iran. In addition, the optimum design leads to 1.6–11.3% diminution of the total annual building electricity demand. The proposed optimization method shows a powerful and useful tool that can save time while searching for the optimal solutions with conflicting objective functions; therefore facilitate decision making in early phases of a building design in order to enhance its energy efficiency.

1. Introduction

Energy is one of the most important resources used by the modern society and is the core of the economic and social activities in the industrialized countries. In recent years, there has been an enormous increase in the global energy demand due to industrial development and population growth. In the context of the European Union efforts to reduce the growing energy expenditure, it is widely recognized that the building sector has an important role, accounting about 40% of the total energy consumption and 36% of

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Nomenclature

COP	coefficient of performance
C_1	cognitive learning factor
C_2	social learning factor
CMI	current motion influence
$F(\vec{x})$	objective function vector
F_{ws}	composite function
$f_i(x)^{min}$	minimum value of the ith objective function
$f_i(x)^{max}$	maximum value of the ith objective function
Gbest	global best position
$\vec{g}(\vec{x})$	inequality constraints vector
$\vec{h}(\vec{x})$	equality constraints vector
k	number of objective functions
λ_i	weighting coefficient
m	number of inequality constraints
n	number of decision variables
Pbest	personal best position
PMI	particle memory influence
q	number of equality constraints
r	random element
S	feasible criterion space
SI	swarm influence
t	time
$v_i(t)$	velocity of ith particle
w	weighted inertia
$x_i(t)$	position of ith particle
$\vec{x}$	decision variables vector
X	feasible decision space

the carbon dioxide emission [1]. In addition, most of the energy used in buildings and construction sectors is produced from fossil fuels, making them the largest emitter of greenhouse gases on the planet. According to the U.S. Energy Information Administration, energy consumption in buildings is dominated almost 57% by heating, ventilation and air conditioning (HVAC), and lighting [2]. As a result, buildings energy efficiency improvement has become an international big deal for designers and researchers given a high potential for building modifications [3] by incorporating whole building energy analyses [4] rather than analyzing a building as a set of disconnected parts [5]. Whole building design can help architects and engineers to determine the amount of cooling, heating, and lighting loads in order to analyze the characteristics and energy performance of buildings. Good energy performance of buildings is generally obtained by selecting more comprehensive and executive decisions to decrease the energy demand. Building designers often use whole building energy simulation programs such as DOE-2, EnergyPlus, ESP-r, eQUEST and TRNSYS to analyze the thermal and energy behaviors of buildings. In order to evaluate the energy performance of a building, many effective and important design parameters must be taken into account. Architectural parameters are very important in reducing the building energy consumption; but are difficult to be tackled because of the complicated and nonlinear interactions of the processes [6]. An approach known as "parametric study" may be used to investigate the building performance. According to this method, the input of each decision variable is changed to understand its effect on the design objective functions while all other building parameters are kept fixed. This technique can be repeated iteratively with other variables. Although studies are a useful method to explore alternative design options and to establish parameter dependencies of the solutions [7], it may be too time consuming and practically impossible due to the large number of combinations. By coupling an appropriate optimization procedure with a whole building energy simulation tool, it is possible to analyze and to optimize buildings characteristics in less time [8].

Over the past years, considerable research works have been directed toward simulation-based optimization of building energy consumption with the overall aim of understanding the most appropriate building parameters and architectural configurations to promote its energy efficiency. Nguyen et al. [9] reviewed the simulation-based optimization methods applied to the building performance analysis and Bandara and Attalage [6] discussed the applicability of the optimization methodologies in the building performance optimization. Brown et al. [10] developed an online building optimization tool to minimize the energy use in a cost effective manner and to evaluate the distributed energy generation alternatives. Chantrelle et al. [11] presented a multi-criteria tool (MultiOpt) based on the NSGA-II genetic algorithm coupled with TRNSYS to optimize the buildings renovation. In a similar work, Tuhus-Dubrow and Krarti [12] developed a genetic algorithm optimization tool coupled with DOE-2 applied to optimize a building shape and envelope features. Saporito et al. [13] performed a multi-parameter study to investigate the heating energy use in the office buildings using a thermal simulation code, named APACHE. In another research, Shan [14] provided a methodology to optimize the building facade with respect to triple objectives of cooling, heating, and lighting electricity demand to achieve the minimum annual energy cost. Kusiak et al. [15] presented a data-driven approach for optimization of a heating, ventilation, and air conditioning (HVAC) system in an office building using a strength multi-objective particle swarm algorithm. In addition, Znouda et al. [16] presented an optimization program that couples genetic algorithm with a simplified tool for building thermal evaluation (CHEOPS) with the purpose of minimizing the buildings energy consumption. Karmellos et al. [17] developed a methodology and a software tool for optimum prioritization of energy efficiency measures based on the primary energy consumption and the initial investment cost criteria in buildings. Moreover, Yu et al. [18] presented a novel multi-objective genetic algorithm model using NSGA-II to optimize the energy efficiency and thermal comfort in buildings. Magnier and Haghighat [19] used TRNSYS simulations, the multi-objective genetic algorithm, and the artificial neural network to optimize the building design. In another work, Wright et al. [20] investigated the application of a multi-objective genetic algorithm search method in the identification of the optimum payoff characteristic between the energy cost of a building and the occupant thermal discomfort. In addition, Lu et al. [21] presented a comparison study on two design optimization methods for renewable energy systems in buildings, including a single objective genetic algorithm and a multi-objectives non-dominated sorting genetic algorithm (NSGA-II). Recently, Hamdy et al. [22] proposed a modified multi-objective optimization approach based on the genetic algorithm coupled with IDA ICE building performance simulation program to minimize the carbon dioxide equivalent emissions and the investment cost of a two-story house and its HVAC system. Karaguzel et al. [23] integrated the whole building energy simulation program, EnergyPlus, with GenOpt tool to minimize the life cycle cost of a reference commercial office building model.

Echenagucia et al. [24] proposed an integrative approach for the early stages of building design by means of genetic algorithm, with