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A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance

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ABSTRACT

The recast version of the Energy Performance of Buildings Directive (2010/31/EU) proposes a comparative methodology aimed at defining the energy performance of buildings "with a view to achieving cost-optimal levels". Really, how can the cost-optimal technologies be detected? Moreover, how can the most proper packages of energy efficiency measures be chosen in order to obtain the cost-optimality? This paper would provide answers to these questions, by proposing a new methodology for the evaluation of the cost-optimality, by means of the multi-objective optimization of energy performance of buildings and indoor thermal comfort. The optimization procedure is developed by means of the coupling between MatLab and EnergyPlus, by implementing a genetic algorithm, and it allows the evaluation of profitable and feasible packages of energy efficiency measures applied to buildings. Then, following the adoption of these packages, the global cost over the lifecycle of the building is calculated, in order to identify the cost-optimal solution. After the presentation of the methodology, the developed method is proposed for the optimization of the energy retrofit of an existing building. Furthermore, the method can be applied also for new architectures, by considering reference buildings.

1. Introduction

The building sector is very energy-intensive, by requiring, at the EU level, around the 32% of final energy demand and almost the 40% of primary energy request. In this scenario, the recast version of the Energy Performance of Buildings Directive 2010/31/EU [1] proposes a general framework for evaluating the energy performance of buildings, by introducing a comparative methodology "with a view to achieving cost-optimal levels" [2]. More in detail, the cost-optimal analysis should identify packages of energy efficiency measures (EEMs) which minimize the global cost, by taking into account the entire lifecycle of a building. This kind of analysis cannot be applied to each single building, and, therefore, a set of reference buildings (RBs) must be defined [3] in order to represent the national stock, as already done in the past, even if with different aims [4,5]. Within this context, a new question is under discussion at the scientific community involved in the topic of the building energy modeling, and this concerns the modalities for performing the cost-optimal study in order to have rigorous outcomes. Surely, suitable optimization methods, based on the energy simulations and aimed at tailored and reliable evaluations of the energy performance of buildings, are a possible answer [6]. The designers often adopt building performance simulation (BPS) tools for analyzing the energy behaviors of buildings, as well as for achieving specific scopes, like – for instance – the reduction of the energy request or the improvement of indoor comfort [7]. In order to improve the energy performance of buildings, one of the first developed approaches has been the 'parametric simulation method'. This approach makes variable, within a proper range, some design parameters, in order to see their effects on some objective functions, while other variables are constant. Under the point of view of computation, this method is very expensive and not completely reliable because of the non-linear interactions among the design variables. Therefore, starting from the 1990s, numerical optimizations and/or simulation-based optimizations [8] are adopted more and more frequently, also thanks to the very rapid diffusion of the computer science. A numerical optimization methodology can be defined as an iterative procedure that provides

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Nomenclature

A	conditioned building area (m^2)
a	absorption coefficient of solar radiation (–)
B	budget (€)
BPS	building performance simulation (–)
Bz	recommended package according to the utopia point criterion for the budget of z00,000 € (–)
Bz'	recommended package according to the comfort criterion for the budget of z00000 € (–)
C_i	investment cost associated with the ith decision variable (€)
c_e	elite count (–)
DH	percentage of annual discomfort hours (%)
DH_{max}	maximum value of DH, using the minimum comfort level criterion (%)
dh	annual discomfort hours (h)
$E_{cooling}$	annual primary energy for space cooling (kW h/a)
$E_{heating}$	annual primary energy for space heating (kW h/a)
EEM	energy Efficiency Measure (–)
EER	energy efficiency ratio of a chiller at rated conditions (W_{TH}/W_{EL})
EP	annual primary energy per unit floor area (kW h/m^2 a)
e	tolerance in the average change of the spread of Pareto front (–)
$\underline{\mathbf{F}}$	vector of objective functions (–)
f_c	crossover fraction (–)
f_m	mutation probability (–)
GA	genetic algorithm (–)
g_{max}	maximum number of generation (–)
h	annual occupied hours (h)
N	number of decision variables (–)
n_b	number of budgets (–)
n_i	number of bits encoding the ith decision variable (–)
RB	reference building (–)
s	population size (–)
T_{heat}	set point temperature of indoor air during the heating season (°C)
T_{cool}	set point temperature of indoor air during the cooling season (°C)
t	thickness (m)
U	overall heat transfer coefficient (thermal transmittance) (W/m^2 K)
$\underline{\mathbf{x}}$	vector of decision variables (–)

Greek symbols

η	nominal efficiency of the hot water boiler (–)
τ	generations' index (–)

Subscripts and abbreviations

BB	base building (–)
r	referred to the roof (–)
v	referred to the vertical opaque walls (–)
w	referred to the windows (–)

progressive improvements of the solution until the achievement of a sub-optimal configuration (the 'actual optimal' is normally unknown) [9–11]. In the last years, many studies focused on the combination of BPS tools and optimization programs, in order to improve the optimization algorithms, above all for reducing the required computational time and CPU resources. Presently, several algorithms are available, typically classified like local or global methods, heuristic or meta-heuristic methods, derivative-based or derivative-free methods, deterministic or stochastic methods, single-objective or multi-objective algorithms and many more. The research community involved in the topic of building energy performance often prefers the use of derivative-free optimization routines [12], because a continuous or differentiable objective function does not exist and the gradient information, even if obtained numerically from the model, is not accurate in many cases. With reference to the derivative-free methods, genetic algorithms (GAs) are the most widespread. Indeed, these concern a class of mathematical optimization approaches which reproduce the natural biological evolution, as long as the processes of inheritance, selection, mutation and crossover provide an optimal population after a number of iterations (generations). Genetic algorithms have had a good diffusion in the building simulation community, because these can manage black box functions as those provided by BPS tools. Moreover, these methods have a quite low probability of converging to local minima, without ensuring the optimal solution, but producing a good solution (sub-optimal), close to the optimal one, in a reasonable time. Furthermore, with reference to the building sector, GAs allow multi-objective optimizations that are more appropriate compared to the single-objective ones. Indeed, conflicting goals are often required at the same time. Therefore, high performance buildings require a holistic and integrated team approach [13]. Even with well-coordinated researches, it is difficult to find a meeting point that allows the optimal solution for all necessities. Thus, the multi-objective optimization is generally required in building applications. The main purpose is to identify the so-called 'Pareto front', and thus the set of non-dominated solutions. With reference to the building efficiency, in order to avoid too complex problems, the researchers usually define only two objective functions, and thus carbon dioxide equivalent emissions and investment cost [14], carbon dioxide equivalent emissions and life cycle cost [15], energy demand and thermal comfort [16–19]. In few cases, some studies propose three objectives, and thus energy demand, carbon dioxide equivalent emissions, investment cost [20], or energy demand, thermal comfort and investment cost [21].

This manuscript proposes a new methodology for performing the cost-optimal analysis of EEMs, suitable to be applied to new or existing buildings. The study is based on the multi-objective optimization of energy demand and thermal comfort. The optimization procedure implements a GA and is based on the combination of EnergyPlus [22] and MatLab [23]. As shown in the next sections, after the presentation of the coupling strategy, the methodology is used for the evaluation of the cost-optimal solution in the design of the refurbishment of an existing building located in the Italian city of Naples, and thus in Mediterranean climate.

2. Methodology

The new approach, based on the multi-objective optimization, is proposed for the evaluation of the cost-optimal solution with reference to the energy refurbishment of existing buildings. Analogously, the proposed methodology is suitable also to be applied to new buildings, by considering RBs. The method combines EnergyPlus and MatLab. EnergyPlus has been chosen as BPS tool for two main reasons: (a) on one hand, this program allows reliable modeling of both building and HVAC systems, and, secondly, (b) it works with text-based inputs and outputs, and these facilitate the interaction with optimization algorithms. According to [8], EnergyPlus is probably the most widely "whole building energy simulation program" [22] used for the research in matter of building optimization. A number of studies testify its reliability in predicting energy performance of buildings and facilities. Obviously, a proper definition of the models and expertise in the assignment of all boundary conditions (starting from the selection of the solution algorithms of