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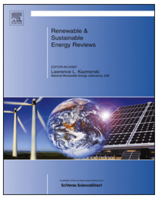

Algorithms for optimization of building design: A review

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ABSTRACT

Building design is quite a complicated task with the design team trying to counterbalance various antagonistic parameters, which in turn are subject to various constraints. Due to this complexity, performance simulation tools are employed and as a consequence, optimization methods have just started being used, mainly as a decision aid. There are examples, amongst the architectural community, where probabilistic evolutionary algorithms or other derivative-free methods have been used with various decision variables and objective goals. This paper is a review of the methods and tools used for the building design optimization in an effort to explore the reasoning behind their selection, to present their abilities and performance issues and to identify the key characteristics of their future versions.

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1. Introduction

Building performance simulation tools have been widely used by the research community, but only during the last decade, did they begin to be used in the architectural design process. There are many reasons for this delay, starting from the difficulty of using these tools, the acquisition of necessary skills, their associated costs, the uncertainty in the results and the general impression that the designer is restricted by the limitations of the tools.

Nowadays, a large number of simulation tools do exist with user friendly interfaces and a plethora of available training material. With their use, design teams, after defining a number

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of decision parameters, can explore new designs which were not accessible through the traditional approach. For example, current legislative changes in Europe have led to the revision of national building energy codes in order to include a more advanced computational approach. Therefore, in most cases, compliance with codes is the driving force behind their use, this fact does not guarantee the optimization of building energy consumption. Thus far, studies concerning the impact of various parameters on building design have relied on parametric analyses which in turn were based on detailed building simulations. The latter are computationally expensive and using a brute force technique to evaluate all possible solutions is not a viable process. It was the need, therefore, to explore the solution space more efficiently and fast that gave rise to the adoption of optimization techniques. It has to be mentioned that the transfer of a real world design problem into the mathematical domain has limitations and that the commonly used optimization algorithms applied to building design problems cannot ensure that the optimal solution will be found. Nevertheless, better building performance may be obtained compared to common practice where no optimization is used. Therefore, the understanding of optimization method's strengths and weaknesses is crucial in order for them to be used effectively in related design problems.

Optimization is the procedure of finding the minimum or maximum value of a function by choosing a number of variables subject to a number of constraints. The optimization function is called cost or fitness or objective function and is usually calculated using simulation tools. Because of code features, the results may be non-linear and have discontinuities, making necessary the use of special optimization methods that don't require the computation of the derivatives of the function. Optimization methods can be applied to a number of different building design problems such as massing, orientation, façade design, thermal comfort, daylighting, life cycle analysis, structural design analysis, energy and of course cost. The structural design (i.e. selection of beam/columns cross section) and building controls (operation/scheduling) optimization are not part of the present review. However, in some of the reviewed cases optimization of both building design and setpoint scheduling or more advanced multi-disciplinary optimization was applied.

The review is separated into four major sections exploring different viewpoints of the subject. The first section deals with the optimization algorithms which have been utilized in building design problems. The next one presents the optimization tools and some of their characteristics. The third section lays out three building performance evaluation methods that affect the optimization approach differently and discusses the strengths and weaknesses of each method. The forth section reviews the optimization targets exploring the objective functions and the design variables commonly used for building design problems. Finally, future perspectives on the use of building design optimization are presented.

2. Optimization algorithms

Generally, an optimization problem can be represented in mathematical form as:

$$\min_{x \in \boldsymbol{X}} f(x)$$

where $x \in \boldsymbol{X}$ is the vector of the design variables, $f : X \to \mathbb{R}$ is the cost or the objective function, and $\boldsymbol{X} \subset \mathbb{R}^n$ is the constrain set.

When there is more than one objective function for optimization then a multi-criteria or a multi-objective optimization problem arises. This is common in building design problems and these functions are often contradictory. Typically, there are two popular approaches for multi-objective optimization problems. The first one uses a weighted sum function where each of the objectives is normalized and summed up with their associated weight factors to get only one cost function. Typical optimization algorithms can be used to solve it but the information on how the different sub-objectives interfere with each other cannot be extracted. Testing different weight factors causes an increase in the number of optimization problems, which in turn, demands longer processing times.

The other popular approach for multi-objective optimization is proposed by Pareto [1]. A solution is Pareto optimal or non-dominated when there isn't any other feasible solution that improves one objective without deteriorating at least another one. The multi-objective algorithms result in a set of non-dominated solutions which is called Pareto frontier. When the problem consists of two objectives, the Pareto frontier can be represented as a curve. Fig. 1 presents a typical example of Pareto frontier for a minimization problem with two objectives.

The above mentioned multi-objective approaches have both advantages and disadvantages. As Cao et al. [2] indicate, the algorithms that provide Pareto solutions focus on exploiting the diversity of the solutions, but often present issues of inadequate efficiency and effectiveness. The weighted sum methods are more efficient and easier to implement, but require prior knowledge and they don't provide information on the compromise between the objectives.

The selection of the optimization algorithm depends on the problem that needs to be solved. There are some situations where an analytical solution of the objective function can be obtained, as Adamski [3] and Marks [4] proposed. They mathematically describe the shape of a building and solve it with numerical methods, finding the true optimal. When the solution space is relatively small and the calculation of the objective function is fast, the entire space can be searched to find the true optimal. Such examples are presented by D'Cruz and Radford [5] who used a simple building model and Pareto optimal Dynamic Programming to optimize thermal load, daylight, planning efficiency and capital cost. Jedrzejuk and Marks in [6,7] described the building design problem mathematically and solved it numerically, by applying the CAMOS computer system. Castro-Lacouture et al. [8] used a mixed integer optimization model to select materials that maximize green building LEED credits. Michalek et al. [9] used CFSQP, a C implementation of Feasible Sequential Quadratic Programming to solve their building geometric layout problem. Chakrabarty [10] used non-linear programming in his proposed HudCAD tool for optimization of housing and urban development projects. Petersen and Svendsen [11] presented a simplified economic optimization method from an early stage near-optimum economic design. Stavrakakis et al. [12] used sequential quadratic programming

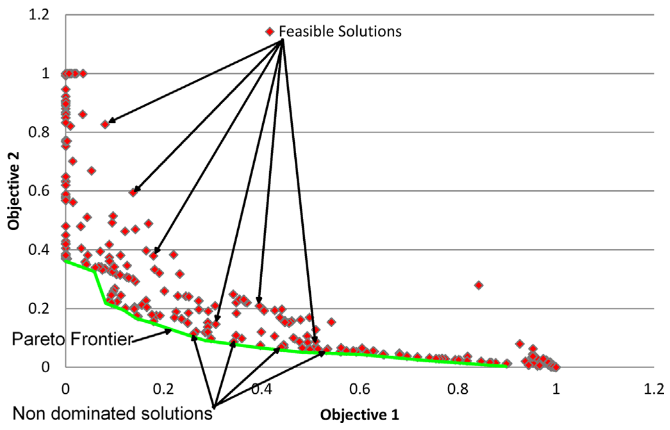

Fig. 1. An example of Pareto frontier.
Source: Prototype.