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Comparative study of multiple criteria decision making methods for building design

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ABSTRACT

In this paper, multiple criteria decision making methods are studied in the context of building design. The approach is to compare the functionality and the results provided by different methods on three test problems that represent various design situations. The number of criteria in the test problems are two, three and four. Multicriteria optimization is applied to generate the alternatives, among which a preferred solution is to be searched by the decision making methods. Six methods have been selected for comparison: the weighted sum method, the weighted product method, VIKOR, TOPSIS, PROMETHEE II, and a procedure based on the PEG-theorem. The numerical study on the test problems indicate that in most cases, the methods provide different solutions. The PEG-procedure tends to find a well-balanced solution, where none of the criteria is emphasized. While the "best" MCDM method is not discovered in the study, information about the performance of the methods in building design problems is presented.

1. Introduction

1.1. Background

Construction management decisions typically involve several conflicting aspects that need to be considered. These decision-making situations can be formulated as multicriteria optimization problems, where the different aspects of a building project constitute the conflicting criteria that are optimized simultaneously. It is widely recognized that most of the total cost and the performance of the building is determined by the decisions made in the conceptual design phase. Therefore, applying multicriteria optimization in this early phase can lead to considerable savings in the building project, see, for example, [1–3] for recent research and applications.

In the literature, a multitude of methods for computing Pareto optimal designs that represent the compromise solutions between the criteria, is available. As a result of multicriteria optimization, a set of Pareto optimal solutions is obtained. However, usually a single or few designs has to be chosen for further inspection and development. In the context of building design, this decision-making task can be very difficult, since due to the multidisciplinary nature of the design problem, several non-commensurable criteria exist and often there are many Pareto optima to choose from. Multiple criteria decision making (MCDM) methods provide a valuable tool for supporting the choice of the preferred Pareto optimum. Together with multicriteria optimization, the MCDM methods unite the different disciplines involved in the design process in order to yield a compromise solution with a solid computational background.

Since the 1970s, literature on multiple criteria decision making has been increasing tremendously [4]. Based on their properties, problems and solution approaches can be categorized in various ways (see, for example, [5–7]). For the purposes of this paper, we call multicriteria optimization the process of generating the alternatives (Pareto optima), and multiple criteria decision making the process of choosing a single preferred solution from among the computed alternatives.

Interactive methods lie between these two categories. The principle idea of these methods is that a single Pareto optimal solution is computed and presented to the decision maker (DM), who either accepts the given solution or guides the optimization process based on her preferences and using the information included in the current and previous Pareto optimal solutions. This process forms an iterative loop, where new Pareto optima are generated, until the DM is satisfied with the results. An interactive approach might be preferable, if the DM is very active and if the computation of a representative subset of Pareto optima is too expensive. A number of interactive methods as well as a thorough discussion about their philosophy and benefits can be found in [7].

The purpose of the present paper is to assess and compare the results that MCDM methods give in building design problems. The aim is to shed light on the usability of the different methods and to study their fundamental differences from the point of view of the decision maker. The approach chosen for carrying out the comparison is to apply the methods to multicriteria optimization problems that have been documented in the literature. This approach imposes certain limitations on the conclusions that can

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be drawn about the methods. Also, based on only few test problems, one method can hardly be stated as superior over the others. However, as the test problems cover varying amount of criteria and alternatives, the differences of the methods can be expected to appear.

In the MCDM literature, the task of generating the alternatives for the DM is often left for the designer, who may or may not be the actual decision maker. The alternatives can be generated, for example, by the designers involved in the design process, or by computational optimization procedures. In this paper, we assume that the building design problem has been formulated as a multicriteria optimization problem that has been solved by some applicable method, which means that a finite number of Pareto optimal (non-dominated) solutions has been obtained. The MCDM methods operate on this set of alternatives, providing a ranking list of the designs.

A selection of methods for comparison was chosen such that a wide range of approaches would be covered. The considered methods are the weighted sum method (WSM), weighted product method (WPM), VIKOR, PROMETHEE, and TOPSIS. Additionally, a method based on the PEG-theorem [8] is employed. This method differs from the others in that it does not require any preference information from the DM.

The paper is organized as follows. In Section 2, the basic concepts of multicriteria optimization and MCDM relevant to the paper are presented, along with a discussion on optimization problems in building design. In Section 3, the methods to be compared are briefly introduced. Then, in Sections 4–6, the methods are applied to three building design case studies. The first two cases are taken from the literature, and the third is formulated here for the first time. Observations and discussion are presented in Section 7, and final conclusions are given in Section 8.

1.2. Related work

Comparisons of MCDM methods have been presented in the literature. Zanakis et al. [6] compare eight methods, namely ELECTRE, TOPSIS, weighted product method, weighted sum method and four versions of analytical hierarchy process (AHP), using computer-generated data. The simulated problems have 5–20 criteria and 3–9 alternatives. The methods are compared against the weights and ranks of the weighted sum approach by several measures. Salminen et al. [9] compare the performance of ELECTRE II, PROMETHEE I, II and SMART on application problems concerning environmental decision-making situations. Again, the number of criteria is large, and only few alternatives are available. The differences are analyzed from the point of view of construction of criterion models, definition of outranking relation and the ranking procedure. Opricovic and Tzeng [10] present a comparison of VIKOR and TOPSIS methods, which are based on distance measures. The focus of the comparison is on the properties of the aggregating function as well as on the normalization. Parkan and Wu [11] study the differences of the AHP, data envelopment analysis (DEA) and operational competitiveness rating (OCRA) methods by considering a process selection problem related to electronics manufacturing.

A common outcome of the comparisons mentioned above is that in many situations, the results of the different methods are similar, but there are cases, where the results differ substantially. Also, the authors of the comparisons avoid preferring one method over another. This is understandable, since such a statement would require either a solid theoretical rationale or comparison on a large number of cases with actual decision makers, and typically neither of these can be presented. Nevertheless, comparing MCDM methods on problems of different fields is still needed, since each field has optimization problems with special characteristics that may affect the choice of the MCDM method.

2. Multicriteria optimization in building design

Most design problems involve several conflicting aspects or criteria that the designer tries to improve simultaneously. The final result is a compromise, where human judgment and decision-making is involved. Multicriteria optimization provides a valuable tool for the designer (or decision-maker) to find the best compromise solutions and to get quantitative information on the rate of conflict of the criteria.

In general, a design problem can be formulated as a multicriteria optimization problem as follows

$$\min_{\mathbf{x}\in\Omega} \mathbf{f}(\mathbf{x}) = \{f_1(\mathbf{x})\, f_2(\mathbf{x})\ \cdots\ f_k(\mathbf{x})\} \tag{1}$$

where $\mathbf{f}$ is the vector-valued objective function consisting of k criteria, f_i, that are mutually conflicting. The design variable vector, $\mathbf{x}$, must belong to the feasible set Ω that generally includes the constraints of the problem in form of inequalities or equalities:

$$\Omega = \{\mathbf{x} \in \mathbb{R}^n \mid g_r(\mathbf{x}) \leqslant 0,\ r \in I,\ h_q(\mathbf{x}) = 0,\ q \in J\} \tag{2}$$

where g_r and h_q are the inequality and equality constraint functions, respectively, and I and J are the index sets containing as many elements as there are inequality and equality constraints, respectively.

The most fruitful definition for optimality in multicriteria problems has been proposed by Pareto [12], stating that a design is optimal, if none of the criteria can be improved without deteriorating at least one criterion. To be more specific, a design $\mathbf{x}^* \in \Omega$, is *Pareto optimal*, if there does not exist another design $\hat{\mathbf{x}} \in \Omega$ such that $f_i(\hat{\mathbf{x}}) \leqslant f_i(\mathbf{x}^*)$ for all $i = 1, 2, \ldots, k$ and $f_j(\hat{\mathbf{x}}) < f_j(\mathbf{x}^*)$ for at least one $j = 1, 2, \ldots, k$ (see, for example, [13]).

The literature on multicriteria optimization offers a multitude of methods for computing Pareto optimal solutions. Theoretical results and classical methods are summarized in [7], and evolutionary solution techniques are presented in [14,15].

Two MCDM methods applied in this paper use the *ideal solution* in their computations. The ideal solution is defined as the point in the criterion space, whose components consist of the individual minima of the criteria. That is, let $\mathbf{f}^{\mathrm{ID}}$ denote the ideal solution. Then, $f_i^{\mathrm{ID}} = \min_{\mathbf{x}\in\Omega} f_i(\mathbf{x})$. In the context of MCDM methods, the ideal solution is taken from the set of computed alternatives instead of actually computing k separate minimization problems.

For the results of the optimization to be practical, the formulation of the optimization problem needs to include all essential features of the design problem at hand. Common optimization criteria in building design are various costs such as initial capital cost and annual operating cost [1], and life cycle cost [2], energy consumption [16–18] and recently environmental impact [2]. Most applications in the literature concern the early phase of the design, which means that the design variables involve, for example, the choice of materials and dimensions, number of storeys, wall types etc. The constraints assure that the final design complies with building codes and fulfils the functional requirements imposed by the designer.

It is important to identify the type of optimization problem so that an appropriate solution method can be chosen. First, the design variables are often both continuous (e.g. dimensions of the building) and discrete (e.g. material type, number of columns), so the problem is a mixed-integer problem. Second, most often there are constraints or criteria that depend on the design variables nonlinearly. Therefore, most building design problems are *multicriteria mixed-integer nonlinear optimization problems*, which are very difficult to solve in general. Most often these problems are solved by genetic algorithms or other heuristic methods that overcome the difficulties due to discrete variables.

In this paper, we assume that the number of computed Pareto optima varies from tens to hundreds. On the other hand, the number