MULTI-CRITERIA DECISION MAKING TECHNIQUES IN CIVIL ENGINEERING EDUCATION FOR SUSTAINABILITY

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Abstract

In recent times, a great deal of interest has emerged from different sectors of society towards sustainability and sustainable product design. Decision makers are increasingly encouraged to take into consideration the economic, environmental and social dimensions of reality when dealing with problems. Sustainability is of particular importance in the field of civil engineering, where structures are designed that are long lasting and shall cause significant impacts over a long period of time, such as bridges or dams. Consequently, when addressing a structural design, civil engineers shall account for the three dimensions of sustainability, which usually show conflicting perspectives. Multi-criteria methods allow the inclusion of non-monetary aspects into the design process of infrastructure.

In the postgraduate course 'Predictive and optimisation models for concrete structures', offered at the Masters in Concrete Engineering of the Universitat Politècnica de València, civil engineering students are taught how to apply such tools within the framework of sustainable design of concrete structures. The present paper conducts a state-of-the-art review of the main multi-criteria decision making methodologies taught in the course in the context of sustainability. Articles are searched in recognized databases, such as SCOPUS and Web of Science. The most significant methods, such as Analytical Hierarchy Process (AHP), Elimination and Choice Expressing Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) or Complex Proportional Assessment (COPRAS) are systematically discussed, identifying the actual trends concerning the use of such methodologies in the field of civil engineering. The review provides a deep insight in the multi criteria techniques that are most frequently used when assessing sustainability of infrastructure designs.

Keywords: Postgraduate education, multi-criteria decision making, sustainability, structural design, state of the art review.

1 INTRODUCTION

Civil engineering studies have traditionally focused on the functionality, strength and durability of structures, guiding the capabilities of their students towards the attainment of economic results. Recently emerging needs of different sectors of the society call for a paradigm shift in the conventional civil engineering education. Important training gaps have been detected in higher education programs regarding the introduction of new concepts, such as sustainable design or construction management [1-3]. With regard to sustainable design, sustainability implies guaranteeing the satisfaction of current needs without compromising the ability of future generations to meet their own needs. Sustainable design is therefore of paramount relevance when it comes to designing infrastructure projects, given that infrastructures are products meant to serve a significant group of the population during a long, intergenerational timeframe. In this sense, it is therefore unquestionable that engineering education should gradually provide students with the necessary tools to combine the other two pillars of sustainability, namely environment and society, with the traditional economic dimension of their designs.

Multi-Criteria Decision Making (MCDM) methods are tools of special relevance when considering sustainability aspects in the design of products, as they serve for the assessment in the decision-making among different alternatives taking into consideration the different dimensions of a problem. In general, such problems consist of four phases. First, the problem to be assessed, as well as the criteria to be taken into account, shall be precisely defined. Then, particular weights for each criterion shall be determined. After that, alternatives are evaluated individually with respect to each criterion for, at last, aggregate the results considering the weight defined for each criterion. Different MCDM methodologies have been developed over time that allow the decision maker to assign particular weights to each dimension of the assessment problem.

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Over the last few years, efforts have been made to incorporate sustainable design concepts into the curricula of civil engineering universities. In the postgraduate course 'Predictive and optimisation models for concrete structures', offered at the Masters in Concrete Engineering of the Universitat Politècnica de València, participants are provided with basic knowledge of heuristic optimization techniques and the most up to date MCDM methodologies applied to the design of concrete structures. Its academic content is largely the result of the of the research work of the academics [4, 5]. The present study conducts a systematic state of the art review of the main MCDM techniques to identify the current trends of their application in the field of civil engineering for the sustainable assessment of infrastructures.

2 RESEARCH METHODOLOGY

In the present study, a systematic literature review was conducted. In a first stage, the objective was to create a preliminary set of contributions for a later filtering and expanding according to particular criteria established based on the experience of the research team. This first search is carried out through the scientific databases *SCOPUS* and *Web of Science*, combining terms such as 'Sustainability', 'Multi-criteria decision making', 'MCDM' and other engineering field-related terms with Boolean operators 'AND' and 'OR' so as to generate an adequate search algorithm that tracks relevant papers in the field of sustainability applied to civil engineering and infrastructures design. The search period is established from 1995 on until the present (2018), since there is no evidence of relevant articles prior to that date. Some exclusion criteria were followed to select the contributions that conform the preliminary set. Firstly, the articles included in the set are limited to peer-reviewed papers and conference proceedings. Second, only those manuscripts that clearly identify the MCDM technique used are considered. In addition, articles were excluded that did not consider at least two of the three dimensions of sustainability in the assessment. From this first search phase, 47 contributions were selected. The initial set is completed by analyzing in depth the references of the selected articles. The filtering criteria mentioned above were used again during this phase. Table 1 shows the MCDM techniques identified within the resulting 95 documents, where it is distinguished between two types of approach. Under single approach, the number of publications is included that use only the mentioned MCDM technique in their assessments. Under hybrid approach, those articles are included that use the mentioned method combined with other MCDM techniques. The relative impact factor of each methodology has been obtained here as the quotient between the number of publications using the particular assessment techniques considering both approaches and the total number of articles conforming the final set.

Table 1. State of the Art review – Analysis of the final contribution set.

MCDM technique	Acronym	Single approach	Hybrid approach	Relative Impact
Analytical Hierarchy Process	AHP	42	11	0.56
Technique for Order of Preference by Similarity to Ideal Solution	TOPSIS	7	9	0.17
Preference Ranking Organization Method for Enrichment of Evaluations	PROMETHEE	7	1	0.08
Elimination and Choice Expressing Reality	ELECTRE	6	2	0.08
Complex Proportional Assessment	COPRAS	4	2	0.06
Analysis and Synthesis of Parameters under Information Deficiency	ASPID	3	0	0.03
Simple Additive Weighting	SAW	3	0	0.03
Multi-Attribute Utility Theory	MAUT	2	0	0.02
Quality Function Deployment	QFD	0	2	0.02
Cost-Benefit Analysis	CBA	1	0	0.01
Compromise Programming	CP	1	0	0.01
Analytic Network Process	ANP	0	1	0.01

The present study analyzes more in depth those techniques that have resulted significant. As a cut-off criterion, only those methods whose relevance factor exceeds 0.05 are reviewed, namely AHP, TOPSIS, PROMETHEE, ELECTRE and COPRAS. Consequently, the filtered final set includes 81 contributions.

3 MULTI-CRITERIA ASSESSMENT TECHNIQUES

3.1 AHP

The Analytic Hierarchy Process has been found to be the most used technique when dealing with sustainability problems in civil engineering. This method is applied in three steps. First, the decision problem is decomposed in a structure of smaller problems, which are organized hierarchically and are considered independent from each other. The problem is modelled in so many levels as needed to make the assessment comprehensive to decision makers. Therefore, sustainability is usually decomposed in a first level comprising the well-known economic, environmental and social criteria, and, in turn, each of these criteria is split in different sub-criteria depending on the scope of the assessment. Once such hierarchy is established, decision makers evaluate the criteria at one level by performing a pairwise comparison. AHP technique converts these priority scores into weights for each criterion, thus allowing for the evaluation of the weights of each level of the hierarchy until the last level is reached. AHP is included in a broader set of MCDM methods known as additive weighting techniques.

Table 2 shows the topics covered by the analysed studies. AHP has been used mainly in the sustainability assessment of buildings (35.8%) and bridges (24.5%), dealing with particular engineering and construction aspects as shown in Table 2. An exponential increase in the use of this methodology has been observed. From the analysis, it is derived that AHP methods used in the context of sustainability has acquired particular relevance since 2015, as 50.9% of the articles reviewed have been published only in the range of years between 2015 and 2018.

Table 2. AHP technique – Engineering and construction fields covered in literature.

Main Topic	Nº Papers	Aspects assessed
Building	19	Design of columns [6], slabs [7], flooring and roof systems [8, 9], energy efficiency of building projects [10-14], use of alternative building materials [15, 16]. Attention is also paid to particularities of industrial [17-19], school [20] and residential modular buildings [21]. Site location of building projects is also evaluated [22]. KPIs for the sustainability assessment are identified [23, 24]
Bridges	13	Studies are focused on three main aspects: comparison of design alternatives [25-28], selection of the best maintenance strategy [29-33], and design optimization [34] of bridge superstructures. Construction methods are evaluated as well [35, 36]. Bidding strategies are also assessed [37]
Hydraulic Infrastructures	6	Water supply systems and water management [38-40], urban drainage [41], sewerage systems [42] and dams [43]
Energy Infrastructures	5	Sustainability of different energy generation systems [44-46] with special emphasis on wind towers [47, 48]
Transport Systems	4	Pavements [49, 50], location of roads [51] and evaluation of urban transport systems [52]
Others	6	Tunnels [53, 54], Ports [55], construction materials [56] and construction projects in general [57, 58]

3.2 TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution is based on the idea that the preferable alternative should have the shortest geometric distance to the best solution, which takes the highest possible scores in each criterion. This technique allows for the compensation of criteria, where bad or negative results in one criterion can be balanced by good or positive results in another criterion. TOPSIS is designed to allow for the simultaneous consideration of quantitative and qualitative criteria in the assessment.

This method has been used in the context of sustainability mainly in the assessment of building design and construction, with 40% of the contributions dealing with aspects such as the use of alternative materials [15,59] or the comparison of alternative systems attending to structural [60] or functional requirements [21, 9]. Redevelopment alternatives for derelict buildings have also been evaluated [59]. The second main aspect covered by the analysed studies is related to the assessment of water management systems [40, 62, 63]. On the other hand, 20% of the analysed studies using TOPSIS deal with the evaluation of alternative transport [64, 65] or pavement systems [66]. The rest of the reviewed papers deal with issues related to different topics. Malekly et al. [67] combine TOPSIS for the selection of the preferable bridge superstructure alternative with the QFD technique, which is employed in the previous construction of the design requirements. Saparauskas [68] compares the assessment of the sustainability of the construction sector by using both TOPSIS and SAW techniques. Gumus et al. [69] apply TOPSIS method to evaluate the different life cycle phases of a wind farm, including manufacturing, transport, construction and use phase. Publications assessing sustainability in the field of construction and civil engineering by using TOPSIS technique have been found only since 2008, showing an average rate of 2 publications/years since that date.

3.3 PROMETHEE

The Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) is an outranking MCDM technique able to take into account both qualitative and quantitative criteria which is based on the pairwise comparison of alternatives and its prioritization so as to determine the dominant ones with respect to the selected decision criteria. To use this method, preference functions are assigned to each criterion so as defined by the decision-making team. Six to eight types of preference functions are usually considered, which can be constant, linear, staggered, Gaussian or logistic, depending on the nature and data availability regarding the criterion under evaluation. PROMETHEE method does not associate a particular utility to each criterion, as usual for additive techniques, but works evaluating the deviation between two alternatives on that criterion.

According to the analysis of the present literature review, the first published paper using this MCDM technique relating sustainability with the construction and engineering sector dates back to 2004 [70] and deals with the selection of the best location for a dam along a river basin. The sustainability of bridge construction methods has been addressed using PROMETHEE [71, 72]. Gervásio and Da Silva [27] combine the PROMETHEE and the AHP methodologies to compare alternative bridge designs considering the impacts derived from the different life cycle stages, where AHP is used to assist the construction of the preference functions of the criteria under analysis. Montajabiha [73] extends the PROMETHEE method by including fuzzy theory aspects for addressing the sustainability of energy planning. Diakoulaki et al. [74] and Kowalski et al. [75] also assess sustainable energy planning. Samani et al. [76] uses PROMETHEE to identify the best material for housing solutions combining criteria such as structural strength, environmental impacts and user's well-being and safety.

3.4 ELECTRE

ELECTRE method (Elimination and Choice Expressing Reality) is a so-called outranking MCDM technique, where alternatives are compared pairwise taking into account individual criteria. Since its introduction in 1966, three new versions have been developed, all based on the same principle but incorporating significative improvements for dealing with concepts such as fuzzy logic (ELECTRE III). A common property for all versions of ELECTRE is that this method, dissimilar to other MCDM techniques, is not compensatory. Weights for each criterion are considered here as importance coefficients rather than criteria substitution rates. Then, comparing the alternatives under evaluation and discarding the dominated or outranked options, the application of ELECTRE results in a set of nondominated alternatives.

The first application of ELECTRE for the sustainability assessment in the field of construction dates back to 2006 [77]. Since then, several aspects have been assessed, such as the management of urban water systems [77, 78] or building materials [60] and design alternatives for industrial [79] and residential buildings [21]. ELECTRE III has been used for the assessment of site location problems of different infrastructure types, such as wind farms [80] or waste facilities [81], establishing fuzzy outranking relations between the considered criteria. Medina-González et al. [82] use ELECTRE IV technique for addressing the optimal design of an energy supply system, which improves the previous versions of the method by avoiding the source of subjectivity in the establishment of the outranking and preference relations. The use of ELECTRE methods is concentrated in the period between 2015 and 2018, where 75% of the articles reviewed in the present study were published. The publication rate since 2015 in the field under study is constant, at a rate of 2 publications per year.

3.5 COPRAS

COPRAS (Complex Proportional Assessment) technique was first introduced in 1996 as a decision assessment tool to select the preferable alternative among a set of plausible solutions and the reliability of its results have been widely acknowledged [14]. This method, which allows for the assignation of particular uncertainty levels to the criteria values, uses positive and negative values depending on if the criterion is considered as a benefit or a cost in relation to the desired objective. The priority of the alternatives is then determined by evaluating its relative significance (or the equivalent quantitative utility) as a function of the beneficial and non-beneficial attributes assessed in a previous step.

In the field under study, the most publications using COPRAS date from 2018. Invidiata et al. [14] combine the use of COPRAS and AHP to assess the environmental, economic and social impacts derived from different structural systems of a residential building. Other authors have also used COPRAS in the assessment of buildings [83-85], where Amoozad et al. [85] combine COPRAS with the Best-Worst Method (BWM) under a fuzzy environment. Hatefi [86] to explore improvement alternatives for urban transportation systems also uses fuzzy COPRAS. Hashemkhani et al. [51] evaluates the most suitable road location under sustainable criteria combining the AHP method for the determination of the criteria weights, and the COPRAS technique for the final ranking of the results.

4 CONCLUSIONS

In the postgraduate course ‘Predictive and optimisation models for concrete structures’, offered at the Masters in Concrete Engineering of the Universitat Politècnica de València, students are provided with basic knowledge on the most frequently and trending multi-criteria decision techniques used in the field of civil engineering. The present communication has exposed the results of the systematic state of the art review regarding the application of the main MCDM techniques in the field of construction and civil engineering for the sustainable assessment of infrastructures. 81 studies published since 1995 were analysed, showing the ability of these techniques to assess a variety of particular cases related to the field of civil engineering. The results show that the Analytic Hierarchy Process is by far the technique most extensively used in sustainability assessments, used by 65.4% of the reviewed contributions, followed by TOPSIS, which has been applied in 12.3% of the cases. In addition, the exponential trend in the use of AHP method during the last few years has been exposed. In view of the results, multi-criteria techniques are posited as a powerful tool to help decision-makers to better select the most suitable alternative from the point of view of sustainability within a wide range of construction problems

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