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A review of application of multi-criteria decision making methods in construction

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ABSTRACT

Construction is an area of study wherein making decisions adequately can mean the difference between success and failure. Moreover, most of the activities belonging to this sector involve taking into account a large number of conflicting aspects, which hinders their management as a whole. Multi-criteria decision making analysis arose to model complex problems like these. This paper reviews the application of 22 different methods belonging to this discipline in various areas of the construction industry clustered in 11 categories. The most significant methods are briefly discussed, pointing out their principal strengths and limitations. Furthermore, the data gathered while performing the paper are statistically analysed to identify different trends concerning the use of these techniques. The review shows their usefulness in characterizing very different decision making environments, highlighting the reliability acquired by the most pragmatic and widespread methods and the emergent tendency to use some of them in combination.

KEYWORDS

Construction; Decision Making; Multiple Criteria Analysis

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1. Introduction

Decision making is a key factor to achieve success in any discipline, especially in a field which requires handling large amounts of information and knowledge as construction. Most construction processes and procedures are a compendium of many different tasks, processes and requirements, involving a great variety of factors and aspects to consider. In this manner, making decisions in such environments can often be an arduous and difficult operation to tackle. For these reasons, the need for a mechanism capable of assisting the characterization of such complex scenarios arises. Multi-criteria decision analysis (MCDA) emerged as a branch of operations research destined to facilitate the resolution of these issues. Since then, a great variety of multi-criteria decision making methods (MCDM) have been developed to tackle them under different circumstances and fields of application [1-5].

Besides multi-criteria methods per se, some complements especially suitable for decision making problems, as e.g. fuzzy sets or numerical simulations, are also included in the review. Even lacking the basics and typical structure needed to perform a multi-criteria analysis, these tools have proved very useful to deal with aspects as uncertainty or risk, which are very common in decision making environments but unapproachable by traditional MCDM methods. No discriminatory filter was made when selecting the methods to be included in the review; indeed, the aim was to report the most relevant papers implementing multicriteria analysis in construction activities, attending to factors such as number of citations and variety in the field of application, regardless their conceptual basis. A brief description of the total of methodologies and systems studied throughout the paper is provided in Table 1.

Table 1. Summary of the methods included in the review

On the other hand, the application cases assessed here are divided into single and hybrid approaches, depending on whether the paper under study uses a unique method or two or more in combination. Thus, single methods which count with at least two papers of application have their own subsection, whilst the rest are collected in "Others". Meanwhile, hybrid approaches have been categorized according to the importance of their components. Therefore, those methods showing a notable preponderance on at least two different appearances are separated, whilst those cases whose hierarchy is not clear are grouped in "Others". The observation period in which they all were gathered ranges from 1992 to 2013. While the search was performed, an increase in the return of results was observed coinciding with the mid 90's, which led to set the lower limit of study around two decades before the last full calendar year, time long enough to arrive to consistent conclusions.

Summarizing, this review collects a total of 88 research papers related to the application of multi-criteria decision making methods in the construction industry, most of them (82) belonging to scientific journals and a few (6) presented at selected congress proceedings. From another point of view, the review includes 50 (56.82%) single and 38 (43.18%) hybrid approaches based on the use of 25 different MCDM methods. Table 2 shows the occurrence ratio of the methods used, both separate and in combination.

Table 2. Proportional use of the methods under review

Each of the application cases studied and contained in Table 2 are one to one revised hereinafter. Therefore, the aim of this paper is to offer an overview of the benefits of application of multi-criteria analysis to construction problems, by concisely describing each of the publications gathered during the observation period individually, in order to demonstrate the worth and versatility of the methods on which they are based in very different situations.

2. Single approaches

2.1. AHP

One of the first applications of the AHP in construction is owed to Skibniewski and Chao [6], who discussed the benefits that this technique could introduce within technical and economic evaluations. A case study based on the selection process of a tower crane was submitted to exhibit the applicability of the method.

El-Mikawi and Mosallan [7] employed the AHP as an assistance tool to assess the utilization of composite materials in structural civil engineering applications by means of a quasi-sustainable structural hierarchy. In turn, Hastak and Halpin [8] effectuated a weighing-AHP of the necessary factors to develop a Life Cycle Benefit Cost Assessment of composite materials in construction. The proposition was clarified through a practical example in which the rehabilitation of bridge columns was studied by using either composite or traditional solutions.

Kalamaras et al. [9] used a simple scoring aggregation procedure combined with the AHP method for the selection of highway alignments. In this manner, five different alternatives were evaluated according to a set of four criteria: minimum curvature radius, cumulative length of normal sections, cumulative length of tunnel sections and cumulative length of viaduct sections.

Al-Harbi [10] conducted a study in which the AHP is implemented as a decision making method to evaluate the problem of contractor prequalification. Thus, pairwise comparisons were executed to correlate the performances of several possible contractors respect to every single criterion and to contrast the importance of each criterion over another. In a similar way, Topcu [11] and Abudayyeh et al. [12] carried out another selection models to establish a preference ranking to prequalify contractors.

As a complementary tool of a heuristic system to determine the best combination of building assemblies in design phases, Nassar et al. [13] used the AHP method to measure the relative importance among a set of criteria. Once preferences were

established, the problem was structured as a network in which an algorithm locates the best solution by searching for the longest path.

Saphira and Goldenberg [14] adapted the AHP system to build up an equipment selection model for construction projects. Its hierarchy was structured by dividing the problem into four criteria and eighteen sub-criteria, which were tackled in accordance to three perspectives: cost evaluation, benefit evaluation and total evaluation.

Chou [15] undertook a study to estimate the costs that maintenance pavement operations imply. A case-based reasoning (CBR) method was modelled to manage it, so that the similarity between current and previous cases was measured after establishing pairwise comparisons through the AHP technique.

In view of the lack of a quantitative guide to administer construction project budgets in Taiwan, Lai et al. [16] presented an AHP-based method to better distribute them. Parallel to the weighting of criteria by means of this system, a simulation-cost model was also performed to generate a cumulative distribution of a project budget.

Lin et al. [17] delved into the weaknesses that a 9-value scale involves in terms of accuracy when establishing preferences. To overcome them, the called A^3 model was proposed. Based on the use of Genetic Algorithms, both the consistency ratio and the difference between original and adapted comparisons were stated as objective functions to minimize. A case study in selecting the most valued bid was presented to demonstrate the worth of the approach when tackling the discrete nature of the traditional AHP.

Zayed et al. [18] aimed to decrease the inherent risk that highway construction projects entail by developing a model based on the AHP technique. The first step consisted of gathering information about the risk and uncertainty sources likely to affect the construction project. Then, the AHP system was used to build an evaluation model aimed to determine a risk index by aggregating a series of score weights previously obtained.

Nowadays, Life Cycle Assessment (LCA) is one of the most utilized tools to determine the environmental impacts of products and processes. Bahareh et al. [19] utilized the AHP to weight the environmental impacts associated to a sustainable analysis of different flooring systems. Thus, the combination of AHP and LCA was claimed to be a consistent and efficient method to appraise construction proceedings in a sustainable manner. Also within this field, Kim et al. [20] worked up an eco-friendly decision making process which enables the integration of Life Cycle Cost (LCC) and LCA in civil structures by means of an AHP model.

Knoeri et al. [21] conducted an AHP-based study to assess the attitude of construction stakeholders at the reuse of recycled mineral construction materials (RMCM) and the criteria in which is based their modus operandi in this respect.

Zavadskas et al. [22] proposed a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to evaluate the most convenient management strategy for construction enterprises. Several criteria were defined for each pillar of the SWOT, after which their relative importance was calculated by applying either an AHP model or the Expert Judgment method.

Inasmuch as one of the most difficult tasks for a civil engineer is the design of structures able to cope with earthquake solicitations, Bitarafan et al. [23] noted the need of a multi-criteria approach to consider such natural phenomenon. Among its components, a traditional AHP approach was used to process the pairwise comparisons provided by a group of selected experts.

Kayashta et al. [24] introduced the AHP method within a model aimed to create a Landslide Susceptibility Index to localize the most susceptible areas to this type of failure in west Nepal. All the factors that have influence on ground instabilities were ranked and then integrated by using the weighted linear sum procedure.

Wankhade and Landage [25] devised a non-destructive testing methodology to detect internal failures in concrete structures. One of the components of such system was the AHP, responsible for weighing the values of the selected criteria to assess the state of the structure.

2.2. DEA

Odeck [26] proposed a DEA approach to assess how rock-blasting works in Norway could be improved. Inputs were divided into transport, machine capita, commodity and labour, whilst the output was defined as the volume of blasted rock during the process. After applying the measure system introduced by Førsund and Hjalmarsson [27], it was concluded that both inputs and outputs can be much more efficiently managed. As a sequel to the previous paper, Hjalmarsson and Odeck [28] developed a DEA model to calculate the efficiency of trucks during roads' construction and maintenance stages.

El-Mashaleh et al. [29] applied DEA to determine the efficiency of 45 construction contractors in terms of safety performance. A Charnes-Cooper-Rhodes (CCR) model [30] was used to run the analysis by expressing the inputs as the expenses on safety and the outputs as the number of accidents suffered by the contractor.

DEA was also utilized by Ozbek et al. [31] to assess the efficiency of seven different counties of Virginia during the maintenance stage of a bridge. The proposed model, composed of 21 decision making units (DMUs), contained a Variable Returns to Scale formulation (VRS) and a series of refinements concerning the output values.

Tatari and Kucukvar [32] used two DEA models (CCR and restricted DEA) to estimate the eco-efficiency of exterior wall finishes. Such concept was defined as an input-output ratio, in which several environmental impacts represented the inputs (LCA) and the economic value added was the output (LCC).

Li et al. [33] developed a DEA system to contrast the performance of three different warm asphalt mixtures and a conventional hot-mix asphalt mixture. The comparison

was accomplished in terms of sustainability, so that the inputs were defined by the unit costs, while the outputs were a series of environmental factors.

2.3. ELECTRE

Hokkanen and Salminen [34] adopted the ELECTRE III method to assess various waste management systems in Finland. Several decision-makers proceeding from Finnish municipalities contributed to the definition of both criteria weights and veto thresholds, which were used to evaluate several alternatives in economic and environmental terms.

Martin et al. [35] studied the implementation goodness of different stormwater best management practices (BMPs) by means of an ELECTRE III model. An 8x8 comparison matrix was constructed and both preference and veto thresholds were established either as a percentage of the variations between different performances or as a constant value.

Marzouk [36] used the ELECTRE III method as a help tool to tackle the contractor selection problem. Thus, ascending and descending distillations were executed to provide a complete ranking of several contractors according to five criteria. This same author [37] reused this technique to assess various different types of glass in the context of value engineering.

Dealing with construction and demolition wastes (CDWs) is an increasingly important task for civil engineers, which led Banias et al. [38] to develop an ELECTRE III system to find the optimal location of a CDW facility. The preference threshold (p_i) was defined as the difference between the maximum and minimum values of each criterion divided by the total number of alternatives, whilst the indifference threshold (q_i) was calculated as a percentage of p_i.

2.4. TOPSIS

Rahman et al. [39] developed a Knowledge-based Decision Support System (KDSS) to support the roofing materials selection procedure. Multi-criteria analysis appeared within the process in the form of the TOPSIS method, which operated as part of the inference engine of such technology.

Şimşek et al. [40] applied a TOPSIS-based Taguchi approach to optimize the mixture proportions of high strength self-compacting concrete (HSSCC), resulting in a multi-response problem whose aim is to optimize six control factors characterizing it. The results were compared with those obtained by using the response surface method (RSM).

2.5. ANP

The interdependences among construction risk problems in urban bridge projects led Lu et al. [41] to develop an ANP system to accurately appraise the impact of such factors. Thereby, by building a supermatrix of interrelationships among the risk elements, their effects were measured by interpreting the set of priority weights obtained.

Bobylev [42] carried out a multi-criteria comparison of several underground construction technologies likely to replace an old conduit sewer. The ANP was selected to model the interdependencies among the set of selected criteria. The values thus obtained for each criterion were then synthetized by using two different formulas: Additive-Negative and Multiplicative.

2.6. GST

Wang et al. [43] tackled the construction bid evaluation issue by means of a Grey Target Decision (GTD) model. In this manner, once the pursued target has been defined, some grey concepts are then introduced to determine the closeness of several scenarios to such value. Without leaving the bidding problem, Hong-yan [44] proposed the calculation of a grey relational coefficient for selecting the nearest bidder to the

ideal. The evaluation indicators were standardized according to a range of index values reflecting the tenderers preferences.

2.7. Others

Xia [45] applied a three-round Delphi method to determine the selection criteria for Design-build operational variations. A panel of experts was requested to list a set of possible criteria to define the problem along with their corresponding ratings according to their importance, in order to reach a consensus solution representing a wide spectrum of the construction industry.

Augeri et al. [46] utilized a DRSA-based methodology to determine the maintenance urgency level of a series of road sections. Thus, the proposed model used a set of if-then inference rules to process either quantitative or qualitative data about this problem, in order to obtain the urgency degree of maintenance for each section. Such information was expected to assist decision-makers to better allocate their resources.

With the aim to provide with a logical and understandable method to process environmental impacts, de Siqueira Campos Boclin and de Mello [47] proposed a system based in fuzzy sets and inference rules. Thereby, several environmental inputs were structured in a tree shape, so that each one was evaluated through its membership functions to enable their conversion into crisp outputs by means of the centre of area method.

Zavadskas et al. [48] developed a computer program called LEVI 3.0 to support the choosing procedure in production processes belonging to the building sector. Based on the Game Theory principles, the architecture of such software enables the use of different solution methods and decision making transformations, in order to obtain a comparison of results when the state of equilibrium is not possible.

Pons and de la Fuente [49] presented a MIVES model to assess the sustainability of structural concrete columns. Both the hierarchical structure of the problem and the

weights of its components were determined during a seminar involving different representatives of the building sector, so that a total of 12 column alternatives were analysed in such terms.

Chen et al. [50] proposed a selection method for the construction of concrete buildings. The process was divided into two stages: first, a list of feasible attributes to define the decision making problem was identified; then, MAUT was applied to determine how suitable were the alternatives to fulfil the problem requirements, taking into account uncertainty and risk attitude.

Aguiar Costa and Valadares Tavares [51] developed a web-based multi-criteria assessment tool to guarantee the quality of construction e-procurement procedures. The evaluation model consisted of three main criteria (cost, duration and expected reward), each of which was defined according to MAVT by a scoring function and several scoring rules.

Korkmaz et al. [52] evaluated the active control performance of cables in tensegrity structures by determining the most efficient cable configuration through a MCDM approach. After obtaining a set of likely cables using a Pareto filtering, a PROMETHEE model was employed to rank them in terms of two criteria: deflexion index and stress index.

Coutinho-Rodrigues et al. [53] developed a GIS-based multi-criteria decision system to enhance the planning procedure of urban infrastructures. Four types of infrastructure were evaluated according to a set of criteria through three different MCDM methods (SAW, ELECTRE and TOPSIS) incorporated into the proposed Spatial Support Decision System (SDSS) architecture.

Lahdelma et al. [54] demonstrated the usefulness of multi-criteria analysis when choosing the location of a waste treatment plant. Four alternatives were studied according to a set of environmental factors by applying the Stochastic Multicriteria

Acceptability Analysis with Ordinal criteria (SMAA-O), resulting in a ranking exactly opposite to the intuitive classification previously established.

Tam et al. [55] applied the SIR technique to select the optimal concrete pump type for a building construction project. A simple additive weighting procedure was utilized to obtain the superior and inferior flows of ten different pump models evaluated according to nine criteria related to their technical and economic features.

Hatush and Skitmore [56] described a MCDM technique based on Utility Theory (UT) to comprehensively evaluate the bidder selection problem. The proposed model comprises the following steps: (1) define a set of selection criteria, (2) weigh them by direct assignment, (3) determine the utility functions for the criteria (including the attitude of decision-makers to risk) and (4) aggregate the resulting values using an additive model.

Meszek and Thiel [57] analysed the health of several construction companies in terms of their financial and economic situations. The UTA method was introduced to establish an integrated ranking of preference among them through their values of utility function. The results were validated by checking their convergence with those obtained by using the Altman Index.

3. Hybrid approaches

3.1. AHP

3.1.1. AHP + FSs

Filippo et al. [58] presented a fuzzy MCDM method to prioritize highway restoration activities according to environmental validity. A Mamdani fuzzy inference system was employed to convert a set of inputs defined by trapezoidal fuzzy numbers into a series of triangular fuzzy outputs. The AHP method was introduced to weigh the relative importance between the criteria defining the decision making problem.

Pan [59] proposed a fuzzy AHP model to assess the suitability of different bridge construction methods. The conventional AHP method is not considered to be capable of dealing with the uncertainty and vagueness involved by the criteria, which justified their treatment through fuzzy numbers characterized by several α-cut levels.

Jaskowski et al. [60] went one step further within the contractor prequalification problem by proposing a Fuzzy AHP model capable of taking into account the vagueness and imprecision that linguistic judgments implicate. The assessments of fifteen experts regarding the importance of the criteria were processed to create a series of fuzzy numbers representing them, whose membership functions were then aggregated for each α-cut through linear programming.

Risk management is a topic frequently tackled as a multi-criteria decision problem. Xiang et al. [61] analysed the risks that submerged floating tunnels involve during investment, design and planning stages. After a gathering data procedure, a fuzzy AHP method was applied to get an overall risk score allowing acting according to the needs of each case. Both Nieto-Morote and Ruz-Vila [62] and Khazaeni et al. [63] approached the same problem under similar perspectives, i.e. assessing risks by making use of the synergistic action of Fuzzy sets and the AHP methodology.

Shahhosseini and Sebt [64] inquired into the assignment of human resource departments to construction projects. A two-stage fuzzy adaptive decision making model was presented to select competent staff; first, the decision factors were weighted by executing a FAHP analysis, whilst the candidates were ranked according to their competency through an Adaptive Neuro-Fuzzy Inference System (ANFIS).

Hui et al. [65] developed a fuzzy assessment model to prevent fire hazards during construction operations. Fuzzy logic was used along with the AHP to analyse various factors affecting this problem, in order to establish a safety index related to the fire conditions of the construction site.

Akadiri et al. [66] developed the fuzzy extended AHP method (FEAHP) to improve the selection process of sustainable materials for building projects. In order to consider the three pillar of sustainability, an AHP approach based on triangular fuzzy numbers was used to state the priorities among different criteria, which were then synthetized by conducting a fuzzy extent analysis.

3.1.2. AHP + Delphi + FSs

Liu and Chen [67] presented a MCDM-based rock classification system to be implemented in slope stability assessments. The evaluations provided by a group of experts according to the AHP comparison scale regarding the criteria were synthetized through a fuzzy Delphi model, in order to determine the slope rock mass quality for each case. Finally, a Linear Discriminant Analysis (LDA) was executed to decide whether a slope is stable or not.

3.2. ANP

3.2.1. ANP + FSs

Liu and Lai [68] suggested a fuzzy decision making approach to assist the approval procedure of Environmental Impact Assessments (EIAs). Fuzzy logic was used to deal with the imprecision involved by human judgments, whereas the significance-acceptability transformation (SAT) was applied to incorporate standards and decision-makers risk attitude into the analysis. Meanwhile, the fuzzy ANP method was applied to set the interdependences among several environmental factors, in order to provide a global assessment of each proposal.

3.2.2. ANP + MCS

El-Abbasy et al. [69] proposed an interdependent and uncertain analysis of the contractor selection procedure by combining the ANP with Monte Carlo Simulations (MCS). The priorities among the criteria defining the problem are established by

applying the ANP technique, whilst the performances of three contractors are determined through their probability distributions of achieving a certain score.

3.3. TOPSIS

3.3.1. FSs + TOPSIS

Wang and Elhag [70] pointed to the weaknesses that crisp solutions involve when solving fuzzy MCDM problems. To avoid them, a fuzzy TOPSIS method based on α-cuts was proposed and applied to bridge risk assessment. Thus, the relative proximities to the ideal solution were obtained by means of a non-linear programming (NLP) procedure.

Li et al. [71] proposed a fuzzy based model to deal with construction contractor prequalification issues. In this manner, two scales of linguistic variables based on triangular fuzzy numbers were suggested in order to define both the criteria values and the alternatives ratings, respectively. Either direct assignment or pairwise comparisons were used to determine the first, whilst the rating process may be solved by applying several different approaches: fuzzy number recognition method, weight centre method, fuzzy TOPSIS method and simple defuzzification method.

Awasthi et al. [72] employed a fuzzy TOPSIS approach to assess the contribution to sustainability of different transportation systems. A panel of experts provided their ratings of the alternatives regarding a series of sustainable criteria previously defined. These values were then aggregated through the fuzzy TOPSIS method to rank the set of alternatives. Additionally, a sensitivity analysis was conducted to evaluate the influence of criteria weights on the results.

KarimiAzari et al. [73] applied a fuzzy TOPSIS model to evaluate the risks that a road construction project involves. The decision matrix was obtained by synthetizing the ratings provided by a group of experts regarding both the criteria and the alternatives through the nominal group technique (NGT), from which the fuzzy TOPSIS method

was developed to determine the relative closeness coefficients. Similarly, Fouladgar et al. [74] used a fuzzy TOPSIS approach to handle the risks involved by tunnelling projects. The results thus obtained were compared with those provided by the traditional probability-impact matrix method.

Nieto-Morote and Ruz-Vila [75] used a combination between fuzzy logic and TOPSIS to address the contractor prequalification problem. A set of candidates was evaluated according to eight criteria and twenty five sub-criteria characterized by triangular fuzzy numbers and α-cuts.

3.3.2. IFSs + TOPSIS

Ning et al. [76] employed an Intuitionistic fuzzy TOPSIS model to carry out the selection phase for construction site layout planning projects. Prior to this stage, several optimization models were applied to solve the design phase. Intuitionistic fuzzy sets were introduced to deal with the difficulties that people usually have to state their preferences.

3.3.3. GST + TOPSIS

Lin et al. [77] tackled the subcontractor selection problem by extending the traditional TOPSIS methodology through the inclusion of grey numbers. Furthermore, the Minkowski distance and the aggregation operation were respectively introduced to increase the reliability of the process and to integrate the assessments of a panel of experts.

3.4. MIVES

3.4.1. AHP + MIVES

San-José Lombera and Garrucho Aprea [78] used MIVES to assess the sustainable performance of two different industrial buildings. Their value indexes were obtained by

evaluating them according to six main aspects (functionality, environment, economy, society, safety and aesthetics), whose relative weights were determined through the AHP method.

Pons and Aguado [79] proposed a combination of MIVES and Life Cycle Assessment (LCA) to evaluate the most sustainable design to build schools in Catalonia. The AHP method was used to weight the components of the decision making problem, whose main requirements were the three pillars of sustainability: economy, society and environment, being this latter established in the shape of a LCA.

Due to its success of application, the MIVES methodology was included in the Spanish Structural Concrete Instruction (EHE-08), resulting in the known as Index of Contribution of the Structure to Sustainability (ICES). Aguado et al. [80] assessed the sustainable performance of a sports centre by means of the ICES, again with the help of the AHP technique.

3.4.2. AHP + MIVES + MCS

Later, some of the authors of the last paper [81] re-address the same issue by including MCS within the procedure, with the purpose of better characterizing those variables involving vagueness and uncertainty. By implementing this complement, the risk involved in the decision making environment can be also assessed.

3.5. PROMETHEE

3.5.1. AHP + FSs + PROMETHEE

San Cristóbal [82] developed a Fuzzy AHP-PROMETHEE model to determine the critical path of construction projects. For this purpose, seven different paths were examined according to four criteria by characterizing their values as triangular fuzzy numbers. Thereby, the preferences between criteria were established through the AHP

method, whilst the performance of each path was ranked by means of the PROMETHEE technique.

3.5.2. AHP + MCS + PROMETHEE

Gervásio and Simões da Silva [83] proposed a probabilistic hybrid method between the AHP and PROMETHEE techniques to assess the life-cycle sustainability of three different bridge types. Thus, the synergic performance of both systems was aimed to generate a robust and integrated method. Uncertainty was managed by executing MCS for each non-deterministic criterion.

3.6. VIKOR

3.6.1. AHP + VIKOR

Liu and Yan [84] utilized a combined AHP-VIKOR model to deal with the bidding procedure of construction projects. A set of four candidates was selected to be evaluated according to five performance criteria: quotation, construction design, firm's competence, quality and time schedule. Thereby, both methods were respectively applied to calculate the priority eigen-vector and the alternatives final ranking.

3.6.2. ANP + FSs + VIKOR

Ali-Mohammad et al. [85] proposed a hybrid MCDM methodology to determine the critical path in complex projects. Since there are some dependencies between the activities that constitute this problem, a fuzzy ANP model is selected to determine their interrelationships and priorities. Then, a fuzzy VIKOR method is applied to find the closest path to the critical one.

Ebrahimnejad et al. [86] studied the fuzzy environment that surrounds the construction projects selection process by developing a two-stage MCDM approach. A committee of experts was asked to provide their judgments with regard to the pairwise

comparisons among criteria and their risk attitude towards the project. A FANP method was employed to build the priority supermatrix corresponding to such values, which then were used to rank the set of alternatives by means of the VIKOR system.

3.7. TOPSIS

3.7.1. AHP + FSs + TOPSIS

Golestanifar et al. [87] evaluated the convenience of different rock tunnel excavation methods in multiple criteria terms. Seven criteria regarding the excavation methods and the rocks characterization were weighted by means of an AHP model based on triangular fuzzy numbers, after which three different alternatives were ranked by applying the TOPSIS algorithm.

Yazdani-Chamzini and Haji Yakhchali [88] approached the problem of Tunnel Boring Machine selection under a fuzzy perspective. Thus, as a result of the vagueness and inconsistency that surrounds this field of decision, variables were defined as triangular fuzzy numbers. The problem was solved by integrating two multi-criteria techniques as fuzzy AHP and fuzzy TOPSIS.

3.7.2. FSs + HOQ + TOPSIS

Malekly et al. [89] developed a two-phase hybrid multi-criteria method to select the most suitable superstructure design for highway bridges. Firstly, a fuzzy House of Quality was built to convert user demands into design criteria, whose weights were obtained from the lower and upper values of α-cuts in the fuzzy normalized relationship. Then, this structure was the basis on which a fuzzy TOPSIS model was implemented to calculate the best alternative.

3.8. Others

3.8.1. AHP + ELECTRE + FSs

Ka [90] proposed a combination between the AHP and ELECTRE II methods to study the location selection process of dry port construction projects. Several experts were requested to give their assessments regarding the importance of six criteria by using a λ-fuzzy scale derived from the original AHP technique. From these values, the ELECTRE II methodology was applied to obtain the ascending and descending distillations and so to classify the alternatives.

3.8.2. AHP + FSs + MCS

Chou et al. [91] suggested a mixed method composed of fuzzy sets, AHP, MCS and a regression model to support decision making when bidding. The first two were expressed in combination by means of triangular fuzzy numbers subsequently defuzzificated through the centroid method. Meanwhile, a cumulative probability distribution was generated from the values returned by the regression parameters to produce bid amounts according to different confidence levels.

3.8.3. AHP + TOPSIS / VIKOR

San Cristóbal [92] conducted a comparative analysis of the contractor selection procedure for a road building project by employing the TOPSIS and VIKOR methods. In both cases, the AHP was utilized to weight the criteria and thus to generate the decision matrix. The consequent results of applying both ranking methods point out to the same alternative as the best one.

3.8.4. AHP + COPRAS + GST

Bitarafan et al. [93] carried out a study in order to evaluate the validity of cold-formed steel structures for reconstructing damaged areas by natural crises. For this purpose, a group of experts was created to participate in all the phases comprised between the determination of the set of decision factors and the establishment of pairwise

comparisons among them through the AHP technique. Then, the COPRAS-G method was applied to evaluate and select the best alternative.

3.8.5. AHP + COPRAS / MEW / SAW

Medineckienė and Björk [94] examined the energetic efficiency of apartment buildings by combining the action of the AHP technique, which was used in the weights assignment, with three different valuation methods as COPRAS, MEW and SAW. The authors advocated the usefulness of applying several different multicriteria methods as these to get a balanced overview when making decisions.

3.8.6. AHP + DEA + SAW

In order to overcome the limitations involved by the traditional AHP methodology, Wang et al. [95] proposed a triple combination of the AHP, DEA and SAW methods to tackle bridge risk assessments. Thereby, the AHP was applied to weight the criteria, whilst DEA was used to transform the linguistic terms defining the risks into discrete values. The SAW method was employed to obtain the overall risk score for each bridge structure.

3.8.7. AHP + UT

Hsueh et al. [96] suggested a combination between the AHP and Utility Theory (UT) to reduce risks when international constructors try to state Joint Ventures in China. After weighing a set of criteria defined from bibliographic knowledge through AHP, risks were converted into numeric rates by means of the utility functions, in order to determine the Expected Utility Value (EUV) of each scenario.

4. Discussion

4.1. Overview

The application areas covered by the total of 88 analysed papers were divided into 11 different groups. Figure 1 summarizes the breakdown of the review according to such categories, including the number of times each of the 25 methods is applied to each. Furthermore, the number of times each method appears both in single and hybrid approaches is indicated in brackets (Single/Hybrid). On the other hand, the review can also be classified geographically, resulting in the 13 portions represented in the pie graph.

Figure 1. Graphical summary of methods, fields of application and geographical origins

The AHP method clearly highlights above the rest with regard to use, either alone or combined, due to its simplicity of application and flexibility. Thanks to these features, it can be adapted to the specifics of each field of application without requiring great expertise from the decision-maker. Furthermore, the AHP is a technique easily combinable with other methods, frequently as a mechanism to weigh the importance of the criteria defining the decision making problem. The ANP is a general form of the AHP to be applied in those cases wherein there are interdependences between the elements of a decision making problem. However, it is stiffer and more time consuming than the AHP, which prevents it from having a greater presence.

Meanwhile, the reason why fuzzy sets (FSs) are also very present in hybrid approaches may lie in the distrust that these methodologies generate concerning their capability to take into account concepts like uncertainty and vagueness in data. Precisely, FSs were originally proposed to capture such aspects, which make them a valuable tool when tackling this kind of problems. Besides, their integration within a multi-criteria method can be carried out in many different ways, conforming to the environment of the situation at issue. As an extension of the original concept of FSs, Intuitionistic fuzzy sets (IFSs) also consider the hesitancy usually present in imprecise and incomplete scenarios. Somehow, they try to show how sometimes it is easier to express the non-belongingness of an element to a set than its belongingness. Nevertheless, they involve an additional complexity in conceptual terms which has limited their use so far. The grey system theory, based on the concept of grey as a degree of information between black (absolute lack of information) and white (perfectly

complete information), can aid to model decision making problems in different forms (e.g. through grey relational analysis or grey numbers), but its utilization in construction is not very widespread in terms of multi-criteria analysis, probably due to a lack of awareness of the potential of the applications derived from this theory in this discipline.

Turning to methods principally used in isolation, DEA stands a bit out of the traditional structure of MCDM techniques, since it is normally used to measure efficiency rates according to a series of DMUs. For this reason, its combination with an ad hoc complement to model ambiguity can be more complex. Another method which mainly appears individually is the ELECTRE, usually implemented to perform environmental studies by making use of its thresholds to model the inherent uncertainty in these valuations.

On the other hand, considering FSs more as a complement than a MCDM method by itself, the TOPSIS technique appears as the second most employed option after the AHP. Based on the concept of closeness to the ideal and anti-ideal solutions to a decision making problem, TOPSIS is a method easy to compute and algorithmically structured, which considerably automates its implementation procedure. Similarly, the VIKOR method searches for the closest solution to the overall ideal, but unlike TOPSIS, its normalization process is made linearly, instead of vectorially. In any case, the greater difference resides in their diffusion grade; VIKOR's spread is far from that of TOPSIS, presumably because the first became known to the public several years after the second.

For the rest, the MIVES methodology stands out with a total of 5 research papers with different applications in construction, by virtue of its capacity to introduce the concept of value functions within its hierarchical architecture. At most, the PROMETHEE techniques have a relatively significant number of appearances, but its tendency to dilute the explicitness of the results when the number of criteria is large limits its use. All other methods have an almost symbolic presence compared to those previously reported.

Regarding the fields of implementation, “Building and Structures” occupies nearly a quarter of the application range of MCDM methods in the construction sector. Structures is probably the most delicate discipline within construction branches, since its design and execution is likely to affect the state of individuals, goods and services in several different aspects, which supports its in-depth and integrated assessment. Another 32% is concentrated in planning procedures such as “Bidding” and “Project Management”. These issues require a comprehensive analysis of multiple factors whose knowledge can often be difficult to process. Other areas of study like “Geotechnics” and “Roads and Highways” have also been regularly approached in terms of MCDM, because of the combination of importance and complexity they involve. Another relevant cluster may be formed by joining the fields referred to the resources management, either in terms of acquisition (“Resource Allocation”) or choice (appropriate selection of “Materials” and “Equipment”).

Finally, the papers were also analysed attending to their geographical origins. China accounts for almost 25% of the production of MCDM papers applied to construction activities. Iran, U.S.A. and Spain are also prolific in the use of multi-criteria tools with constructive purposes. The remaining countries have a rather testimonial presence, especially those included within the category “Rest”, which only count with one publication each (Russia, Jordan, Sweden, Saudi Arabia, France, Norway, Israel, Belgium, Greece, India and Italy).

4.2. Statistical analysis

While conducting the review, some trends related to the data collected were aprioristically observed. In order to validate them, a statistical analysis is carried out. As a first step, the data can be structured in the form of a contingency table composed of rows (Fields of Application) and columns (Methods). Thus, a simple correspondence analysis was developed by using the IBM SPSS Statistics 22.0 software [97] with the aim of reducing the original interactions between both variables, according to their frequencies. Conforming to the values obtained from standard deviation and correlation, those elements achieving an extreme score in dimensions were discarded,

limiting the spectrum of analysis to the range ([-0.5, 1.0]; [-1.5, 2.5]). The results are graphically depicted in Figure 2.

Figure 2. Row and Column Points: Symmetrical Normalization

The information shown in Figure 2 must be treated carefully, since the frequency of application of a certain method to a field is not a sure value; i.e. even though data were sought through various sources (Scopus, Web of Science, ASCE Library or IEEE Xplore Digital Library) applying different search filters, this review might not cover all the papers of application of multi-criteria methods in construction. Moreover, one cannot issue categorical judgments based on punctual or non-representative enough observations. Under these premises, and whereas the variables under study are dichotomous, the Phi's correlation coefficients are calculated for each pair of elements Field*Method. The results show that four interactions were statistically significant (see Table 3).

Table 3. Phi values between MCDM methods and fields of application

The clearest relationship in this regard points to the MIVES method, which has been always applied to Building and Structures. In fact, its successful utilization throughout the years in this field has motivated its inclusion within the Spanish Structural Concrete Instruction (EHE-08) [98]. The use of FSs or GST in activities as Bidding or Project Management is explained considering that these processes require dealing with ambiguous and qualitative data. Also in this sense, a geotechnical problem involves different instabilities derived from natural phenomena which are inaccessible if non-crisp concepts as fuzzy sets are not used.

From another point of view, if the number of cases is limited to hybrid papers, correlations related to the combinability of the methods constituting the approaches can be determined. Sometimes, the presence of a certain method involves the absence of other, or vice versa, usually as a consequence of either the lack of completeness or the overlap of properties they involve. Analogously as explained above, the Phi's correlation coefficients were obtained as shown in Table 4.

Table 4. Phi values between different MCDM methods

The first correlation is obvious, since the AHP and the ANP are supplementary techniques and they only could share presence in a paper if its purpose was to compare their performance when solving the same problem separately. The disassociation between the AHP and TOPSIS methods is striking because their architectures are very synergic and, not in vain, they can be found performing together recurrently in many other scientific areas [99-103]. In contrast, most of the hybrid papers based on the VIKOR method use the ANP technique to carry out their weights assignment phase. Note that VIKOR and ANP are based on the same principles than TOPSIS and AHP, respectively, to the extent that they constitute their immediate alternatives. On the other hand, despite fuzzy sets are the most utilized tool along with the AHP in hybrid approaches and MIVES mainly appears in combination, the resulting assessments of applying the latter have never considered uncertainty.

Finally, the data were also handled to model the evolution of multi-criteria publications applied to the construction sector in time, by adjusting the distribution of the number of scientific papers divulged during the period of observation through a regression analysis determined with a confidence level of 95%. Thereby, after classifying the observations according to three categories, namely Single, Hybrid and Total, the data compiled in each of them are fitted through quadratic regression models, as shown in Figure 3. This type of adjustment presents the most balanced ratio between percentage of explained model and number of parameters needed.

Figure 3. Evolution and forecast of production of MCDM papers in construction

During almost the first fifteen years covered by the study period encompassed by this review, only single approaches were conducted and rarely exceeding a biannual publication frequency. Around 2007 there was an important increase in the production of papers based on single approaches, while the hybrid ones started to be widely used. Indeed, the combined methods appeared as a solution to some of the shortcomings presented by the traditional approaches when used individually. Moreover, this idea explains why the forthcoming growth of the combined methods might be higher than

that of the individual ones. In overall terms, the trend becomes even more pronounced, indicating that multi-criteria theory has increasingly better reception within the construction industry.

5. Conclusions

This paper studies the applications of multi-criteria decision analysis to construction through a one to one review of a total of 88 scientific publications presented throughout the last two decades. The survey shows the potential of 25 multi-criteria methods, by demonstrating their ability to assess a multitude of specific cases belonging to 11 different construction fields. Moreover, the review demonstrates how their use is gradually spreading all over the world, although Asia and Europe clearly excel in this respect, with almost 80% of the total of papers.

Thereby, multi-criteria analysis is postulated as a powerful tool to aid decision-makers to better select their options in a wide range of construction problems. Significantly, the review reveals that the construction sector has notably evolved when considering conflicting criteria to make decisions. Environmental and social aspects are increasingly important and their adequate synergy with economic considerations is a cornerstone to succeed in any constructive work or procedure. The cases reviewed throughout the paper show the broadmindedness provided by these methods and the clairvoyance they can raise in decision makers. Indeed, the time evolution in use of these techniques clearly points to an increased confidence in their helpfulness.

Specifically, according to the tendencies inferred from the results, the most successful methods are those which combine antiquity and ease of application. Stated differently, experience and speed are relevant factors when selecting a MCDM method to tackle a certain decision making problem in the construction industry. Such circumstance is also influenced by the fact that the architectures of many methodologies share various features in common. Thus, among several similar alternatives, decision makers tend to use the most widely applied so far, which generally also results in time savings, due to the fact that there is a deeper knowledge about it in literature. On the other hand,

most of multi-criteria techniques are not comprehensive enough to adequately address a multi-criteria problem by themselves, which has propitiated an increase in use of hybrid approaches, wherein two or more single methods perform together. Consequently, this paper shows the preponderance in use of the AHP and TOPSIS methods, especially when acting in combination along with other techniques.

Future directions in this research field within the construction sector should point to both its expansion and automation, in order to favour its implementation at any scenario of decision related to constructive activities. Multicriteria methodologies can often be rather complex, which hinders their diffusion at unspecialized levels and, consequently, puts into question their real degree of application. For this reason, the adaptation of such approaches to easily understandable and manageable formats as simple software products or web-based systems, where users only need to express their preferences in a conventional semantic, would spread the use of these techniques, while increasing their reliability. In addition, this course of action can be combined with another good practice when making decisions such as involving representatives from different areas of knowledge (private companies, public entities, research institutions), with the aim of obtaining balanced and consensual points of view.

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Figures

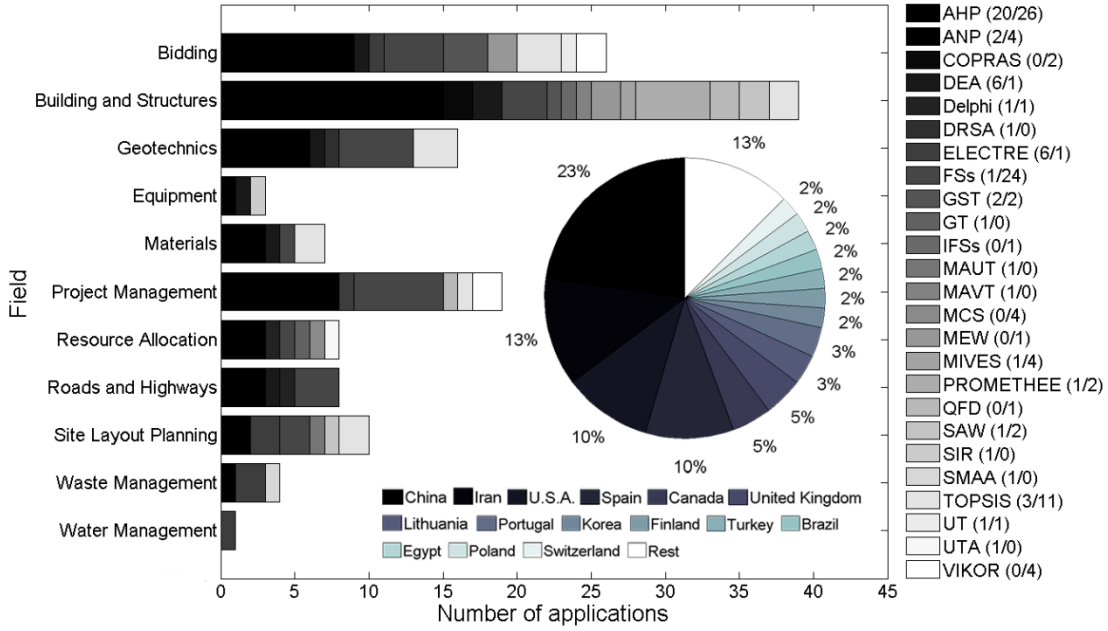


Figure 1. Graphical summary of methods, fields of application and geographical origins

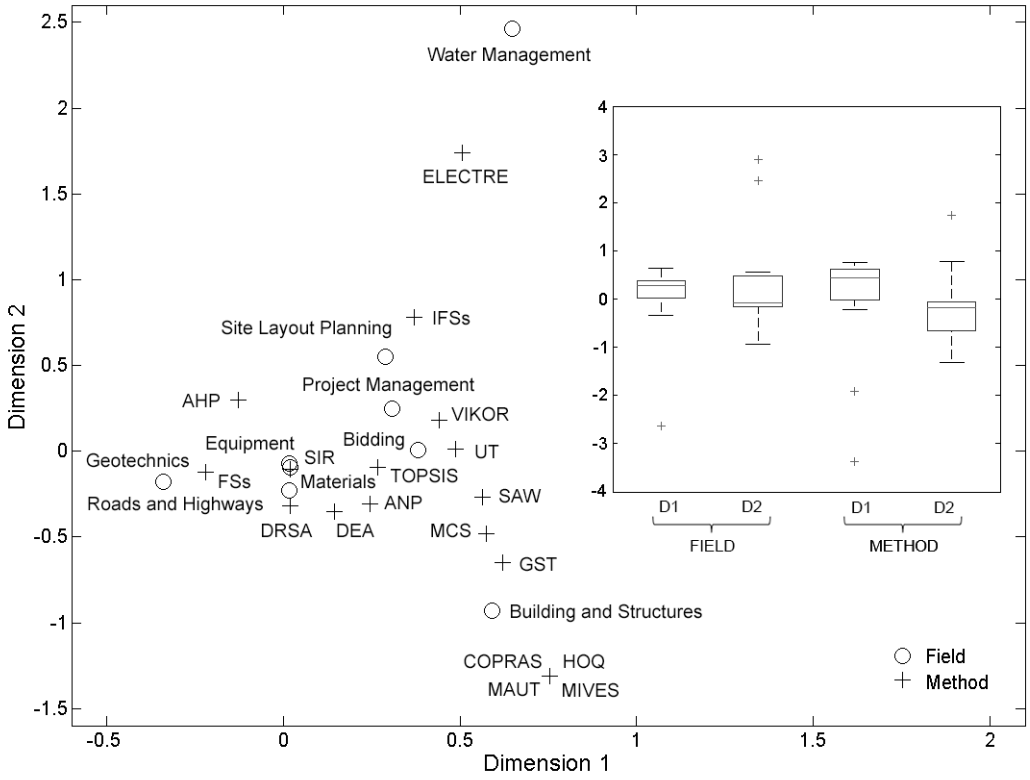
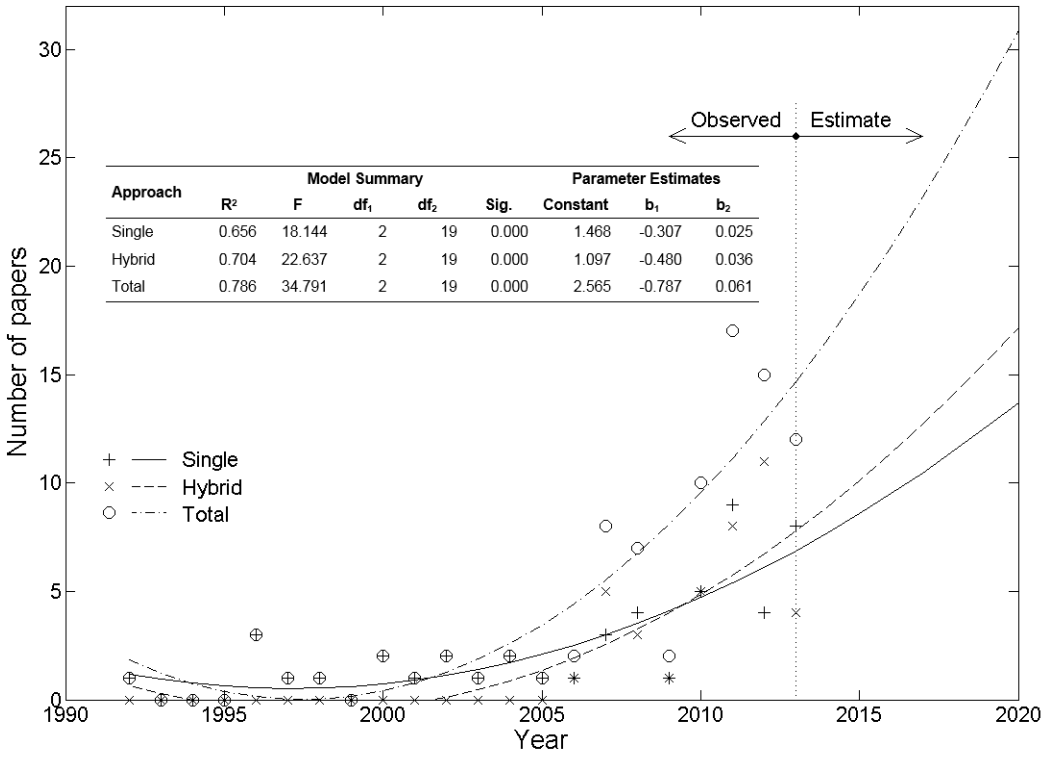


Figure 2. Row and Column Points: Symmetrical Normalization



Approach	Model Summary					Parameter Estimates		
	R^2	F	df_1	df_2	Sig.	Constant	b_1	b_2
Single	0.656	18.144	2	19	0.000	1.468	-0.307	0.025
Hybrid	0.704	22.637	2	19	0.000	1.097	-0.480	0.036
Total	0.786	34.791	2	19	0.000	2.565	-0.787	0.061

Figure 3. Evolution and forecast of production of MCDM papers in construction

Tables

Table 1. Summary of the methods included in the review

Abbreviation	Method	Description
AHP	Analytic Hierarchy Process	Structured technique for analysing MCDM problems according to a pairwise comparison scale.
ANP	Analytic Network Process	Generalization of the AHP method which enables the existence of interdependences among criteria.
COPRAS	Complex Proportional Assessment	Stepwise method aimed to rank a set of alternatives according to their significance and utility degree.
DEA	Data Envelopment Analysis	Non-parametric system for measuring the efficiency of a set of multiple decision making units.
-	Delphi	Iterative method designed to obtain the most reliable consensus from a group of experts responding to a series of questionnaires.
DRSA	Dominance-Based Rough Set Approach	Derivation of rough set theory which allows defining a MCDM problem through a series of inference rules of the type "if… then".
ELECTRE	Elimination Et Choix Traduisant la Realité	Group of techniques addressed to outrank a set of alternatives by determining their concordance and discordance indexes.
FSs	Fuzzy Sets	Extension of the traditional concept of crisp sets which states that the belongingness of an element to a set may vary within the interval [0, 1].
GST	Grey System Theory	Philosophy of handling data according to the information contained in them, from black (no information) to white (complete information).
GT	Game Theory	Area of applied mathematics that studies the interaction of formalized structures to make strategic decisions.
HOQ	House of Quality	House-shaped diagram that transforms user demands into quality design criteria through a relationship matrix and a correlation matrix.
IFSs	Intuitionistic Fuzzy Sets	In addition to the belongingness grade of an element to a set proposed by FSs, IFSs also considers its non-belongingness grade (hesitancy).
MAUT	Multi-Attribute Utility Theory	Methodology employed to make decisions by comparing the utility values of a series of attributes in terms of risk and uncertainty.
MAVT	Multi-Attribute Value Theory	Compensatory technique that converts the attributes forming a MCDM problem into one single value through the called value functions.
MCS	Monte Carlo Simulations	Non-deterministic methods used to find approximate solutions to complex problems by experimenting with random numbers.
MEW	Multiplicative Exponential Weighting	Aggregative scoring system in which alternatives are evaluated by the weighted product of their attributes.
MIVES	Modelo Integrado de Valor para Evaluaciones Sostenibles	Nested methodology which combines two concepts as MCDA and Value Engineering to synthesize any type of criteria in a value index.
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations	Family of outranking methods based on the selection of a preference function for each criterion forming a MCDM problem.
SAW	Simple Additive Weighting	Technique aimed to determine a weighted score for each alternative by adding the contributions of each attribute multiplied by their weights.
SIR	Superiority and Inferiority Raking	Method that uses six generalized criteria to establish the preferences of a decision maker by determining the superiority and inferiority flows.
SMAA	Stochastic Multiobjective Acceptability Analysis	Methodology that determines the acceptability index of an alternative as the variety of measurements making it the preferred one.
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	Technique based on the concept that the best alternative to a MCDM problem is that which is closest to its ideal solution.
UT	Utility Theory	Method for measuring the degree of desirability provided by tangible and/or intangible criteria through their utility functions.
UTA	Utilités Additives	Methodology that uses linear programming to optimize the use of utility functions to properly reflect the preferences of decision makers.
VIKOR	Visekriterijumska Optimizacija I Kompromisno Resenje	Method for determining the compromise ranking-list of a set of alternatives according to the measure of closeness to the ideal solution.

Table 2. Proportional use of the methods under review

Approach	Method	Nº of occurrences	% of Single / Hybrid	% of Total
Single	AHP	20	40.00	22.73
	DEA / ELECTRE	6	12.00	6.82
	TOPSIS	3	6.00	3.41
	ANP / Delphi / GST*	2	4.00	2.27
	Others	1	2.00	1.14
Hybrid	AHP	26	68.42	29.54
	FSs	24	63.16	27.27
	TOPSIS	11	28.95	12.50
	ANP / MCS / MIVES / VIKOR	4	10.53	4.54
	COPRAS / GST / PROMETHEE / SAW	2	5.26	2.27
	Others	1	2.63	1.14

* The term GST comprises the use of sub-concepts as Grey Numbers, Grey Target Decision or Grey Relational Analysis

Table 3. Phi values between MCDM methods and fields of application

Field*Method	Phi		
	Value	Approx. Sig.	N of Valid Cases
Bidding*GST	0.308	0.004	88
Building and Structures*MIVES	0.438	0.000	88
Geotechnics*FSs	0.239	0.025	88
Project Management*FSs	0.251	0.018	88

Table 4. Phi values between different MCDM methods

Method$_1$*Method$_2$	**Phi**		
	Value	**Approx. Sig.**	**N of Valid Cases**
AHP*ANP	-0.505	0.001	38
AHP*TOPSIS	-0.565	0.000	38
ANP*VIKOR	0.441	0.006	38
FSs*MIVES	-0.449	0.005	38