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Invited/Review Article

Hybrid multiple-criteria decision-making methods: A review of applications in engineering

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Abstract. To support evaluation and selection processes in engineering, formal decision-making methods can be used. A great number of works applying diverse Multiple-Criteria Decision-Making (MCDM) techniques for engineering problems have been published recently. A new approach of hybrid MCDM methods has been developed, rapidly, during the past few years. The current paper aims at filling the gap and summarizing publications related to applications of hybrid MCDM for engineering. The study is limited solely to papers referred in Thomson Reuters Web of Science Core Collection academic database. It aims to review how the papers have been distributed by period of publishing and by country; multiple-criteria decision-making methods have been used, most frequently, in developing hybrid approaches and in domains the methods have been applied for. For a more detailed analysis of applications, journal articles from engineering research area were grouped by research domains and further by analyzed issues. Findings of the current review paper confirm that hybrid MCDM approaches, due to their abilities in integrating different techniques, can assist in handling miscellaneous information taking into account stakeholders' preferences when making decisions in engineering.

1. Introduction

A head of a company or department, project managers, designers, and other professionals are constantly faced with the necessity of making important decisions, often based on some partial or incomplete information. To form such a decision, a variety of universal information systems are used [1-3].

Every organization or company as well as every member of the staff simultaneously pursues multiple objectives (economic, social, moral, legal, technical, technological). Some of the objectives can be achieved more easily, others harder. Moreover, not all the objectives are equally important. Therefore, if a stakeholder reaches not every desired objective, but the important ones, he/she can be satisfied.

It is not easy to formulate an objective in an organization such as a business because almost all of its employees have their own opinion. But, the decision-making process becomes more objective when expert and multi-criteria analysis methods are used.

A special role is played by multi-criteria analysis and evaluation methods [4-7]. Multiple Criteria Decision-Making (MCDM) has grown out of operations research, concerned with designing mathematical and computational tools for supporting the subjective eval-

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uation of performance criteria by decision-makers [8]. The importance of multiple-criteria methods to estimate the optimal solutions in the design of technical systems was repeatedly emphasized in Hojjat Adeli et al. research works [9-12].

The first references about multiple-criteria methods have already been mentioned in 1772, 1785, 1881, 1896 by Franklin [13], de Condorcet [14], Edgeworth [15], Pareto [16-18]. The first decision-making axioms were formed by Ramsey in 1931 [19]. In 1944, John von Neumann and Oskar Morgenstern introduced Theory of Games and Economic Behavior [20]. Later, Samuelson [21], Kantorovich [22], Danzig [23], Nash [24], Arrow [25], Koopmans [26], Simon [27], Debreu [28], Frisch [29], and Sen [30] were awarded the Nobel Prize in economics for the creation of decision-making theoretical frameworks.

Very important works in the field of decision-making theory were published in 1954-1978 by Edwards [31], Gass and Saaty [32], Luce and Raiffa [33], Fishburn [34,35], Zadeh [36], Roy [37], Zeleny [38], and Charnes et al. [39].

The title of MCDM was used for the first time in a paper by Zeleny in 1975 [40]. In 1979, this new notion was explained by Zionts [41]. Later significant research related to theory of MCDM was published by Keeney and Raiffa [42], Saaty [43], and Zeleny [44].

MCDM methods can be classified into two categories: discrete MADM (Multiple Attribute Decision-Making) methods and continuous MODM (Multiple Objective Decision-Making) methods. Hwang and Masud [45] reviewed MODM in 1979, and Hwang and Yoon [46] reviewed MADM methods in 1981.

Since 1980, MCDM methods have rapidly been developing and applied in various areas. MCDM methods were reviewed in books by Hwang, and Lin [47], Roy [48], Saaty [49], Brauers [50], Figueira et al. (eds.) [51], Kahraman [52], Triantaphyllou [53], Zopounidis, and Pardalos (Eds.) [54], Tzeng and Huang [55,56], and Köksalan et al. [57]. The use of MCDM methods was also discussed by Zavadskas and Zavadskas et al. [58-61], Kaplinski [62,63], Chen and Li [64], Zavadskas and Kaklauskas [65], Koo [66], Kaklauskas and Zavadskas [67].

The evolution of MCDM during 1975-2015 was comprehensively analyzed in a number of review articles by Zavadskas and Turskis [68], Liou and Tzeng [69], Mardani et al. [70-74], and Antucheviciene et al. [75]. A special issue on multiple criteria decision-making and operations research was published by Peng and Shi [76]. A special issue on applications in engineering was issued by Wiecek et al. [77]. Applications in a separate area of civil engineering were presented by Zavadskas et al. [78], Jato-Espino et al. [79]. Reviews devoted to Decision-Making (DM) in related areas such as infrastructure management [80] and asset management [81] were published. An interesting issue of using multiple-criteria decision-making approaches for green supplier evaluation and selection was analyzed by Govindan et al. in 2015 [82]. Zavadskas et al. [83] summarized reviews (review papers and books) on a topic of MCDM in 2014.

An important moment in the developments of decision-making was the publication of the Fuzzy Sets Theory by Zadeh in 1965 [36]. Last year was the 50th anniversary of the introduction of this theory. To commemorate this date, the journal Technological and Economic Development of Economy released a special anniversary issue. The introductory article was authored by Herrera-Viedma [84]. On the same occasion, the International Journal of Computers Communications & Control published a special issue as well. This special issue had the introduction written by Ronald R. Yager [85].

Another significant milestone was development of applied artificial intelligence (AI). While the concept of AI, in its rudimentary form, was introduced in late 1950s and early 1960s, it was not until 1980s that it received significant tractions with important applications in the form of knowledge-based expert systems. Adeli and associates introduced applications of AI in civil engineering with a number of ground-breaking books and articles [86-92].

Neural network computing has been another very active and expanding frontier of research in the past twenty five years [93,94]. The first journal article on civil engineering applications of neural networks was published in 1989 by Adeli and Yeh [95]. Since then, a large number of articles have been published on neural networks in civil engineering, including several influential books [96-100]. In 1998, Hojjat Adeli and his former Ph.D. student, H.S. Park, were awarded a rare U.S. patent for their neural dynamics model for robust optimization of large-scale structures (Patent Number: 5,815,394). In 1996, the patented model was used for fully automated optimum design of a 144-story superhighrise building structure with more than 20,000 members on a high-performance connection machine within an hour, an engineering feat at the time [101].

Recently, a new trend in MCDM is being developed, rapidly, named Hybrid Multiple-Criteria Decision-Making (HMCDM) methods. The current paper aims at filling the gap and to summarize publications related to development and especially to applications of HMCDM methods, including those for engineering.

2. Research methodology

In the paper, the literature related to hybrid MCDM is reviewed, comprehensively, on the basis of documents

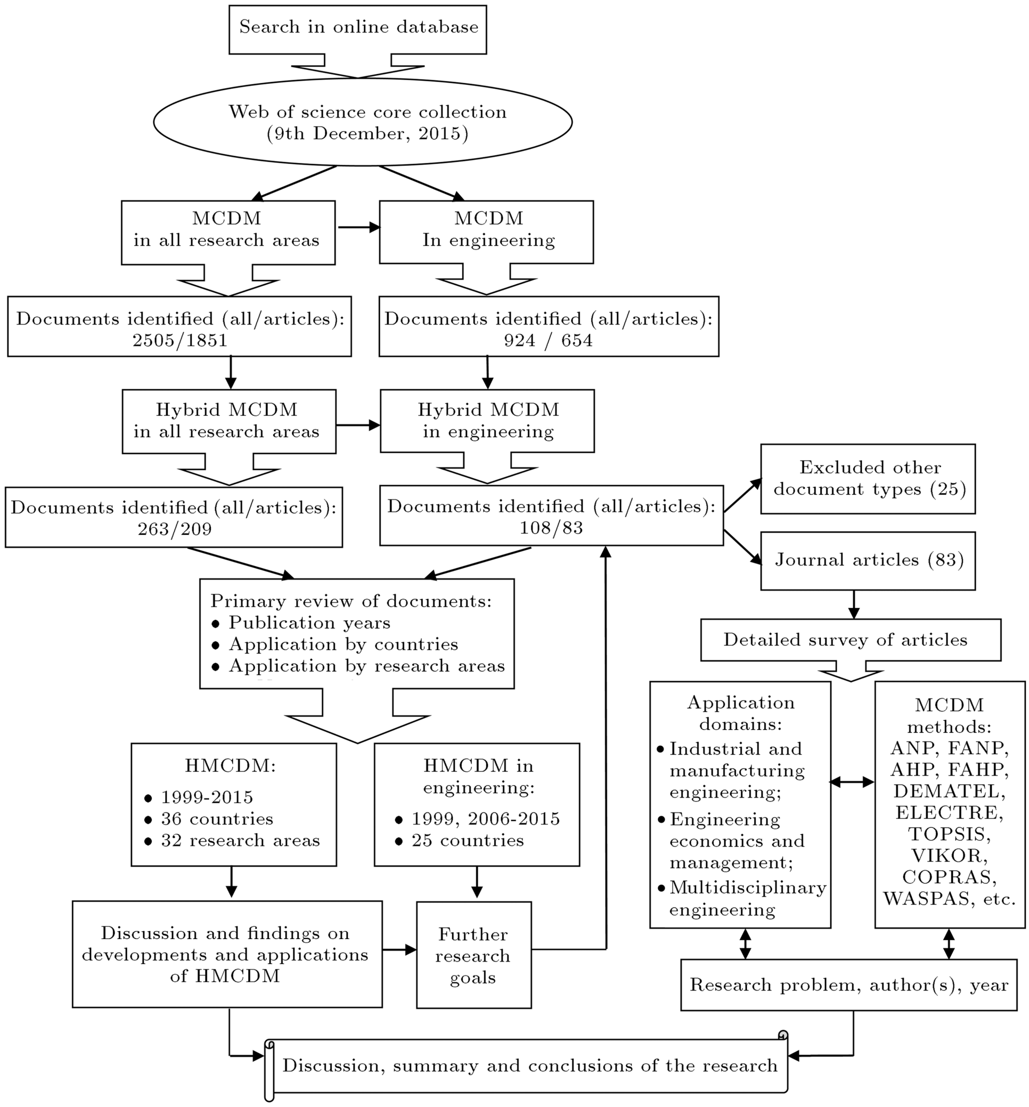

Figure 1. Summarized procedure of the research.

referred to in Thomson Reuters Web of Science academic database.

Following a methodological analysis (Figure 1), the first publications in the area up to December 2015 are reviewed.

Hybrid MCDM involves various combinations of several decision-making methods. Four groups of combinations of the methods devoted to calculating relative significance of criteria and ranking of alternatives can be identified:

1. MCDM method + method for identifying importance (relative significance) of criteria;
2. MCDM method + fuzzy sets, grey numbers;
3. MCDM method + MCDM method(s);
4. MCDM + other method(s).

At first, the presented research attempts to answer the following questions: What part of papers is devoted to hybrid MCDM in various areas of MCDM development and application? What part of papers involves applications in engineering research area? How the papers are distributed by period of publishing and by origin? Next, a more detailed research is aimed at the following issues: In what domains of engineering hybrid MCDM is applied? What problems are analyzed? Which multiple-criteria decision-making methods are used frequently in hybrid methods?

3. Primary review results

There are 2505 publications on the topic of MCDM referred to in Web of Science Core Collection database (December 9, 2015) and covering all the document types, including research articles (1851), reviews, proceedings papers, and other documents (Table 1).

Analyzing publications assigned to Engineering Research Area in Web of Science Core Collection

Table 1. Publications on the topic MCDM, MCDM in engineering and Hybrid MCDM in engineering.

Type of publications	Number of publications (all/articles)
Publications on MCDM methods	2505/1851
Publications on MCDM in engineering	924/654
Publications on hybrid MCDM in all research areas	263/209
Publications on hybrid MCDM in engineering	108/83

database, it is found that 37 percent, i.e. 924 publications out of 2505 on the topic of MCDM are devoted to MCDM applications in engineering. Scholarly articles on MCDM in engineering cover 35 percent of articles on the topic of MCDM.

10.5 percent, i.e. 263 publications out of 2505, are devoted to hybrid MCDM developments and applications. Scholarly articles on HMCDM account for 11.3 percent of the articles on the topic of MCDM.

11.7 percent, i.e. 108 publications out of 924 on the topic of MCDM in engineering, are devoted to hybrid MCDM in engineering. Scholarly articles on HMCDM in engineering cover 12.7 percent of the documents on the topic of MCDM in engineering.

Finally, it is found that a significant part of documents, i.e. 41.1 percent of publications on hybrid MCDM, is observed in engineering research area (108 documents). Scholarly articles on HMCDM in engineering account for 39.7 percent (83 articles out of 209) of articles on the topic of hybrid MCDM.

The extent of research in developments and applications of hybrid MCDM has been increasing rapidly during the past several years, as observed in Figure 2. 80 percent of publications in the area are issued during the past five years (2011-2015).

Applications in different Web of Science categories are presented in Figure 3. Application of the methodology is observed in 32 research areas.

As for the extent of research on applications of hybrid MCDM in engineering, the same tendencies are observed for all applications of the methods. A single publication is observed in 1999, while most publications are issued in the last ten years and the number of papers is rapidly increasing, as observed in Figure 4. 78 percent of articles in the area of HMCDM in engineering were published during the past five years (2011-2015).

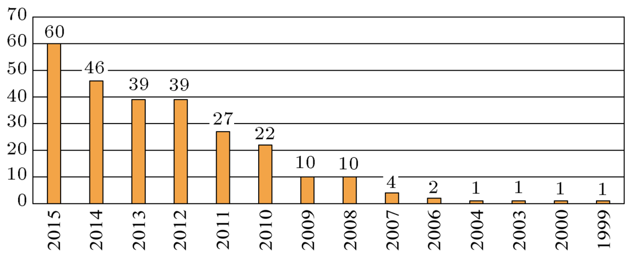

Figure 2. Number of publications on the topic of hybrid MCDM (total 263).

Application of hybrid MCDM methods for engineering problems is also analyzed by countries. Information on distribution of articles by countries is presented in Figure 5.

Apparently, the leader is Taiwan. Next come Iran, Turkey, India, USA, People's Republic of China, Lithuania, and Malaysia (5-12 papers).

4. Detailed review results

The subject of the detailed review is journal articles that apply Hybrid MCDM for engineering problems. 83 papers (research articles and review papers) assigned to "Engineering" Research Area in Web of Science Core Collection are involved in the analysis.

At first, the papers are grouped into three Application Domains as presented in Figure 6. The largest domain is Industrial and Manufacturing Engineering, involving almost half of the analyzed papers. Almost one-third of the papers are assigned to Engineering Economic and Management domain. The last group of papers covers Engineering Multidisciplinary applications. All the papers are analyzed by research problem, methods, and tools used for hybrid approaches for the publication period.

4.1. HMCDM applications in industrial and manufacturing engineering domain

Industrial and Manufacturing Engineering domain covers several issues concerning technology selection or product development and selection, also supplier evaluation, selection, and other issues of green manufacturing, as well as logistic optimization (Table 2).

Technology selection and supplier selection occupy a leading position in the domain. Decision support applying hybrid approaches can be observed in evaluating and ranking different technologies, such as selecting a proper construction [102] or modernization [142] method, the best recycling method [105], equipment, or other technologies in a manufacturing enterprise [107,118]. An interesting application is observed for prioritizing advanced technology projects at NASA [112]. Environmental issues are considered by designing combined energy systems [110] or assess-

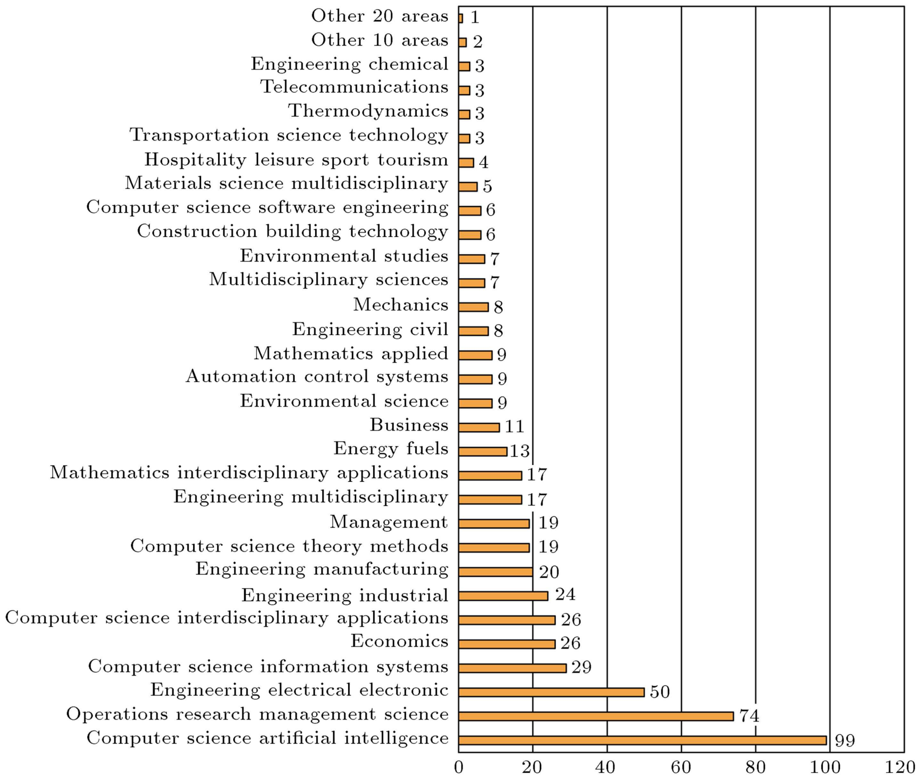

Figure 3. Distribution by Web of Science categories (total 263).

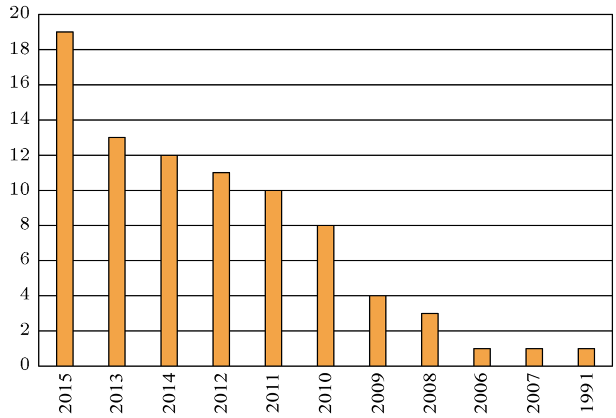

Figure 4. Number of publications on hybrid MCDM in Research Area of Engineering (total: 83).

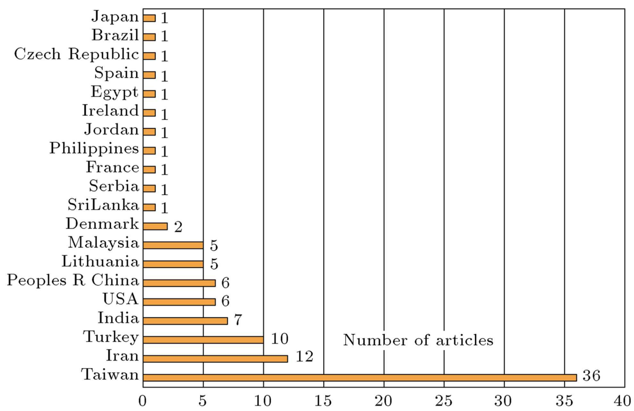

Figure 5. Hybrid MCDM in engineering – applications by countries (total: 83).

ing building energy performance [108], and selecting the most suitable desalination technology for brackish groundwater [111].

It can be observed that the most popular methodological approaches are combinations of crisp AHP with TOPSIS [116] or ANP with TOPSIS [115] as well as their combinations in a fuzzy environment [105,111,112,118]. Combinations with grey numbers are observed in a single publication. Several methods (COPRAS-G, TOPSIS-G, SAW-G, GRA) are applied for equipment selection and the results are compared by Nguyen et al. [107]. Novel methods, SWARA and WASPAS, are used by Bitarafan et al. [109] when evaluating sensors for health monitoring of bridges.

Applications for a new product evaluation are usually related not only to selection but also to development of a product. New product development strategies can be suggested and the best alternative in competitive market environment can be determined with the help of multiple-criteria approaches. Usually, the mentioned fuzzy AHP or fuzzy ANP methods are applied, combined with DEMATEL and VIKOR [120], TOPSIS and VIKOR [123], DEMATEL and TOPSIS [122], and Permutation method [143].

Supplier evaluation and selection is the most mod-

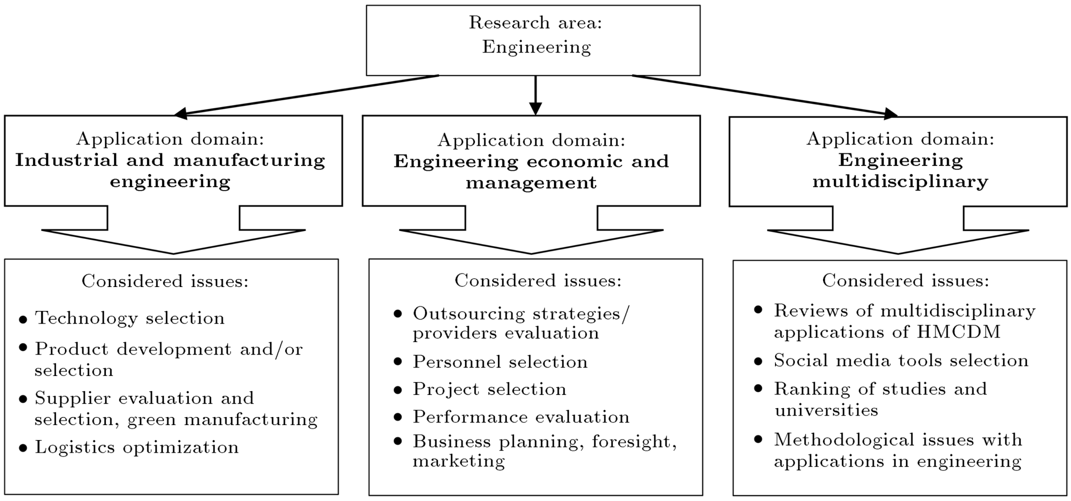

Figure 6. Application domains of HMCDM in engineering.

ern issue in the domain. It includes papers published in 2011-2015. Selecting supplier with emphasis on sustainability [127,144-146] is a major topic in modern manufacturing. Accordingly, green suppliers' evaluation [125,135], or green supply chains [129] are a subject of current research. Sustainable infrastructure systems and environmentally-conscious design were advanced by Adeli in 2002 [147]. In a recent article, Wang and Adeli [148] presented ideas about sustainable building design. In a forthcoming article, Rafiei and Adeli [149] present sustainability in highrise building design and construction. From the methodological point of view, the most popular methods used in hybrid approaches are the same as those used in technology and product selection issues, i.e. various combinations of crisp and fuzzy AHP, ANP, TOPSIS, and DEMATEL. The latest applications use some other methods, such as DANP (DEMATEL-based ANP) and PROMETHEE when evaluating green manufacturing practices in rubber tire industry [128], or grey ELECTRE and grey VIKOR when evaluating environmental performance in service supply chain [126].

Logistic optimization is presented as a separate issue. The best logistic strategy in Belgrade is suggested to be selected by using combination of fuzzy DEMATEL, fuzzy ANP, and fuzzy VIKOR [139]. Kuo [140] suggests selecting the best location for a distribution center in a logistic project by applying fuzzy DEMATEL, AHP, ANP, and TOPSIS. The more original combination of MCDM method with other formal methods is presented and planning of reverse logistics in computers disposal is realized by ANP and ZOGP [141].

4.2. HMCDM applications in engineering economic and management domain

The same combination of ANP and ZOGP can be observed in several papers from the next analyzed domain – Engineering Economic and Management. The domain covers issues of outsourcing strategies or outsourcing providers' evaluation, companies' performance evaluation, resource scheduling [150], project and personnel selection, as well as other problems in business planning, such as procurement, business foresight, and marketing. The analyzed problems and the applied decision support methods are presented in Table 3.

Most papers analyzing outsourcing apply DEMATEL and ANP, coupling them together or combining with other tools. Combination of these two methods is used when evaluating and selecting a proper outsourcing provider in a telecommunication company [151], i.e. Taiwanese airlines [154]. Another method, namely ISM with ANP, is applied for selecting a vendor in a semiconductor industry [155]. The above mentioned combination of ZOGP and ANP, also DEMATEL, is used for developing outsourcing strategy in IT projects [157].

Rabbani et al. [158] suggest using ANP with fuzzy COPRAS in a model of performance evaluation of oil producing companies. Amiri et al. [159] suggest combining the standard AHP and fuzzy TOPSIS with genetic algorithms [177] for evaluating competence of a company.

All the papers devoted to project selection or personnel selection in engineering projects use the same approach: ANP is applied for evaluating relative significances of criteria, while TOPSIS, VIKOR, or DEMATEL are used for prioritizing alternatives. Kabak et al. [160], additionally, use fuzzy ELECTRE when analyzing personnel selection problem. Mohammadi et al. [178] present hybrid Quality Function Deployment and Cybernetic ANP model for project manager selection.

Mesghouni et al. [176] combine genetic algorithm [179], constraint logic programming, and MCDM

Table 2. HMCDM applications in Industrial and Manufacturing Engineering domain.

Considered issues and problems	Applied methods*	Publication author(s), publishing year
Technology selection		
Selecting construction method for urban stormwater collection system	Fuzzy AHP, CP	Ebrahimian et al., 2015 [102]
Detecting and prioritizing failure of marine diesel engine	Fuzzy AHP, fuzzy VIKOR	Balin et al., 2015 [103]
Assessing work safety in hot environments industry	ANP, linguistic fuzzy approach	Ilangkumaran et al., 2015 [104]
Selecting the best plastic recycling method	Fuzzy AHP, TOPSIS	Vinodh et al., 2014 [105]
Improving technologies for the smart phone to satisfy customers' needs	DEMATEL, ANP, DANP (DEMATEL-based ANP), VIKOR	Hu et al., 2014 [106]
Equipment selection to satisfy market's needs; comparison of results by applying different tools	Fuzzy ANP, COPRAS-G, TOPSIS-G, SAW-G, GRA	Nguyen et al., 2014 [107]
Assessing building energy performance	Fuzzy ANP	Kabak et al., 2014 [108]
Evaluating and selecting sensors for structural health monitoring of bridges in earthquake engineering	SWARA, WASPAS	Bitarafan et al., 2014 [109]
Designing effective combined energy systems	Evolutionary multi-objective optimization, fuzzy TOPSIS	Perera et al., 2013 [110]
Selecting the most suitable desalination technology for brackish groundwater, an example of north-east of Iran territory	Fuzzy AHP, TOPSIS	Ghassemi and Danesh, 2013 [111]
Prioritizing advanced technology projects at NASA	Fuzzy ANP, fuzzy TOPSIS	Tavana et al., 2013a [112]
Selecting alternative-fuel buses	Fuzzy TOPSIS, fuzzy PSI method	Vahdani et al., 2011 [113]
Selecting the best technology for light emitting diode	Fuzzy Delphi, DEMATEL, ANP, PCA	Shen et al., 2011 [114]
Proposing combinations of vehicle telematics systems	DEMATEL, ANP, TOPSIS	Lin et al., 2010a [115]
Modelling security systems and evaluating vulnerability factors; an application to power control systems	AHP, TOPSIS	Liu et al., 2010 [116]
Combining classifiers, an application to natural textured images	FC, Bayesian estimation, SO feature, maps, LVQ, fuzzy MCDM	Guijarro and Pajares, 2009 [117]
Selecting technologies in a manufacturing enterprise	Fuzzy TOPSIS, fuzzy AHP	Onut et al., 2008 [118]
Assessment of Radio Frequency Identification/Micro Electro Mechanical System (RFID/MEMS) technology	MCDM, Monte Carlo simulation	Doerr et al., 2006 [119]
Product development/selection		
Determining product's position and suggesting improvements of service	ANP, DEMATEL, VIKOR	Lin, 2015 [120]
Evaluating different new product development strategies, an example of producing lithium-iron phosphate battery	ISM, Fuzzy ANP	Chen et al., 2015 [121]
Developing novel product in competitive market environment	Fuzzy ANP, fuzzy Kano method, fuzzy DEMATEL, TOPSIS, GRA	Chyu and Fang, 2014 [122]

Table 2. HMCDM applications in Industrial and Manufacturing Engineering domain (continued).

Considered issues and problems	Applied methods*	Publication author(s), publishing year
Product development/selection		
Selecting the best biodiesel blend considering multiple criteria	Fuzzy AHP-TOPSIS, Fuzzy AHP-VIKOR	Sakthivel et al., 2013 [123]
Evaluating conceptual alternatives of new product development	Fuzzy ANP	Ayag and Ozdemir, 2009 [124]
Supplier evaluation and selection, green manufacturing		
Evaluating green suppliers in order to improve their performance; an example of thin film transistor liquid crystal display manufacturing	INRM, PROMETHEE	Tsui et al., 2015 [125]
Environmental performance evaluation in service supply chain	Grey ELECTRE, grey VIKOR	Chithambaranathan et al., 2015 [126]
Selecting supplier with emphasis on sustainability issues; an example of packaging in food industry	Rule-based weighted fuzzy method, fuzzy AHP, multi-objective mathematical programming	Azadnia et al., 2015 [127]
Evaluating green manufacturing practices with an example of rubber tires industry in India	DANP, PROMETHEE	Govindan et al., 2015 [128]
Evaluating green supply chain practices	Fuzzy set theory, DEMATEL	Wu et al., 2015 [129]
Selecting supplier to ensure efficient chain; an example of fireworks industry	ISM	Kumar et al., 2014 [130]
Addressing multi-classification problem in supplier selection procedure	Semi-fuzzy kernel clustering algorithm, semi-fuzzy SVDD, CCEVA	Guo et al., 2014 [131]
Selecting suppliers when evaluation criteria are interdependent	TOPSIS, ANP, AHP, preemptive GP	Kasirian and Yusuff, 2013 [132]
Selecting the best supplier in a sustainable supply chain	Fuzzy Delphi, ANP, TOPSIS	Wu et al., 2013 [133]
Selecting a vendor in environmentally conscious manufacturing	DANP, VIKOR	Hsu et al., 2012 [134]
Evaluating green suppliers	Fuzzy DEMATEL, fuzzy ANP, fuzzy TOPSIS	Buyukozkan and Cifci, 2012 [135]
Optimizing production control strategy to achieve better manufacturing performance	Taguchi method, TOPSIS	Lu et al., 2012 [136]
Selecting suppliers; an example of industrial case study for the selection of cans supplier	Fuzzy DEMATEL, fuzzy TOPSIS	Dalalah et al., 2011 [137]
Selecting vendor in a purchase project of a manufacturing enterprise	ANP, DEMATEL	Yang and Tzeng, 2011 [138]
Logistics optimization		
Selecting the best concept of logistic considering various stakeholders, an example of Belgrade	Fuzzy DEMATEL, fuzzy ANP, fuzzy VIKOR	Tadic et al., 2014 [139]
Selecting location for a distribution center in international logistics project	Fuzzy DEMATEL, AHP/ANP, TOPSIS	Kuo, 2011 [140]

Table 2. HMCDM applications in Industrial and Manufacturing Engineering domain (continued).

Considered issues and problems	Applied methods*	Publication author(s), publishing year
	Logistics optimization	
Planning of an environmentally - friendly reverse logistics; example of computers disposal	ANP, ZOGP	Ravi et al., 2008 [141]

*Analytic Hierarchy Process (AHP); Compromise Programming (CP); VIseKriterijumska Optimizacija I Kompromisno Resenje (in Serbian), that means Multicriteria Optimization and Compromise Solution (VIKOR); Analytic Network Process (ANP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Technique for Order of Preference by Similarity to Ideal Solution with grey numbers (TOPSIS-G); DEecision-MAking Trial and Evaluation Laboratory (DEMATEL); DEMATEL-based ANP (DANP); COmplex PRroportional ASsessment (COPRAS) and COmplex PRroportional ASssessment with grey numbers (COPRAS-G); Simple Additive Weighting (SAW) and Simple Additive Weighting with grey numbers (SAW-G); Step-wise Weight Assessment Ratio Analysis (SWARA); Weighted Aggregated Sum Product Assessment (WASPAS); Preference Selection Index (PSI); Patent co-citation (PCA); Fuzzy Clustering (FC); Self-Organizing (SO) feature maps; Learning Vector Quantization (LVQ); Interpretive Structural Modeling (ISM); Grey Relational Analysis (GRA); Influential Network Relation Map (INRM), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE); ELimination Et Choix Traduisant la REalité that means ELimination and Choice Expressing Reality (ELECTRE); Support Vector Domain Description (SVDD), Cooperative CoEVolution Algorithm (CCEVA); Goal Programming (GP); and Zero One Goal Programing (ZOGP).

for balancing workload by selecting the best scheduling. On the whole, 8 out of 13 applications are dated up to 2011 (Table 3). The earlier applications cover optimizing planning decisions in construction industry by using possibilistic linear programming and modified S-curve membership function [175] or supporting business decision-making in shipping by fuzzy axiomatic design [180], quality function deployment, and several MCDM methods [177]. The mentioned combination of ZOGP, ANP, and DEMATEL is applied for evaluating entrepreneurship policy of a company [170]. The latest applications analyze a variety of problems: measuring enterprises readiness for institutionalization [164], decision support for corporate social responsibility [165], examining organizational value cocreation [166], default prediction [181], and prioritizing risks [182]. In terms of methodology, Hashemkhani Zolfani et al. [168] apply a hybrid of two rather novel methods, i.e. SWARA and WASPAS, for selection of the best shopping mall location to ensure a business success.

4.3. HMCDM applications in multidisciplinary domain of engineering

The last domain involves several exclusive issues of engineering applications (Table 4). Four review papers are assigned to the domain. Additionally are presented papers related to application of hybrid methods when selecting media technologies or projects.

As one of the hybridization approaches in combining fuzzy sets theory with crisp multiple criteria methods, a review of applications of fuzzy MCDM techniques in four fields, including engineering, is presented by Mardani et al. [8]. Review of approaches for solving civil engineering problems under uncertainty, including fuzzy and grey MCDM, is presented by Antucheviciene et al. [75]. Kaya and Kahraman [197] compared fuzzy MCDM methods for intelligent building assessment. Review of 26 techniques, including hybrid approaches as applied for supplier selection problem, is presented by Chai et al. [184]. Ahari and Niaki [183] studied 77 tasks and 31 models in gas well-drilling projects. Liu et al. [198] incorporate household gathering and mode decisions in large-scale evacuation modeling.

Selection of some type of engineering technologies or products as social media tools can also be successfully supported by applying hybrid methods, usually consisting of fuzzy approaches [185,188,199], and also combining grey theory with crisp methods [186]. Jia et al. [200] present multiobjective bilevel optimization for production-distribution planning problems using a hybrid genetic algorithm.

A very useful application of the analyzed approaches, involving many stakeholders and a lot of evaluation criteria, is for studies and learning problems. Wu et al. [189] suggest weighting performance evaluation indices with the help of AHP and ranking of universities using VIKOR method. Shakouri and Tavassoli [190] use fuzzy MCDM for sorting the requests of students at university. One of the oldest applications in the area involves evaluation of e-learning programs by combining fuzzy integral, DEMATEL, and AHP [192]. Lee at al. [193] study the possibilities of the popular method, DEMATEL, to be used in hybrid approaches.

5. Conclusions

Multiple-Criteria Decision-Making (MCDM) methods can be useful to support evaluation and selection processes in engineering. During the last decade, combining two or more methods to solve the same MCDM problem (hybrid MCDM) has been used increasingly to support decision-making. A decision-maker or a

Table 3. HMCDM applications in Engineering Economic and Management domain.

Considered issues and problems	Applied methods*	Publication author(s), publishing year
Outsourcing strategies/providers evaluation		
Modelling evaluation and selection of proper outsourcing provider, an example of a telecommunication company	DEMATEL, Fuzzy ANP	Uygun et al., 2015a [151]
Selecting proper outsourcing provider, an example of IT provider in industry	Fuzzy inhomogeneous MADM	Qiang and Li, 2015 [152]
Selecting an outsourcing provider to improve costs and competitiveness; an example of Taiwanese company	DEMATEL, ANP, DANP	Hsu et al., 2013 [153]
Selecting an outsourcing provider; an example of Taiwanese airline	DEMATEL, Fuzzy preference programming, ANP	Liou et al., 2011 [154]
Outsourcing vendor selection in a semiconductor company	ISM, ANP	Lin et al., 2010b [155]
Selecting an outsourcing provider in airlines	VIKOR, ANP, DEMATEL	Liou and Chuang, 2010 [156]
Developing sourcing strategy in IT projects	DEMATEL, ANP, ZOGP	Tsai et al., 2010 [157]
Performance evaluation		
A model for performance evaluation of companies; an example of oil producers	ANP, fuzzy COPRAS	Rabbani et al., 2014 [158]
Evaluating competence of firms in marketplace	Adaptive AHP, fuzzy TOPSIS, Genetic algorithms, Linear assignment method	Amiri et al., 2009 [159]
Personnel selection		
Analyzing personnel selection problem as an important managerial issue	Fuzzy ANP, Fuzzy TOPSIS, Fuzzy ELECTRE	Kabak et al., 2012 [160]
Supporting personnel selection in manufacturing company	ANP, TOPSIS	Dagdeviren, 2010 [161]
Project selection		
Evaluating and improving six sigma projects to achieve the largest benefits	DEMATEL, ANP, VIKOR	Wang et al., 2014 [162]
Evaluating environment watershed projects	ANP, DEMATEL	Chen et al., 2010 [163]
Business planning, foresight, marketing		
Measuring small and medium sized enterprises readiness for institutionalization	Fuzzy DEMATEL, Fuzzy ANP, TOPSIS	Uygun et al., 2015b [164]
Group decision support for corporate social responsibility	Delphi, DEMATEL, ANP, MDS	Wang et al., 2015 [165]
Examining organizational value cocreation behavior	DEMATEL-based ANP	Chuang, 2015 [166]
Measuring internal control of procurement	DEMATEL, VIKOR, ANP, DANP	Chen, 2015 [167]
Foresight of business success by selecting a proper location; an example of shopping mall	SWARA, WASPAS	Hashemkhani Zolfani et al., 2013 [168]
Evaluating of web-based marketing; an example of air transportation companies	DEMATEL, ANP, VIKOR	Tsai et al., 2011 [169]
Evaluating entrepreneurship policy of a company	DEMATEL, ANP, ZOGP	Tsai and Kuo, 2011 [170]

Table 3. HMCDM applications in Engineering Economic and Management domain (continued).

Considered issues and problems	Applied methods*	Publication author(s), publishing year
Business planning, foresight, marketing		
Establishing an investment decision model and portfolio selection	DEMATEL, ANP, VIKOR	Ho et al., 2011 [171]
Optimizing manufacturing management system	Taguchi method, TOPSIS	Lu et al., 2011 [172]
Providing with innovation-oriented techniques for the development of future strategy of airlines	Fuzzy AHP, VIKOR	Chen and Chen, 2010 [173]
Managing business decision-making; an example of shipping	FAD, AHP, TOPSIS, ELECTRE, PROMETHEE, QFD, DEA	Celik and Er, 2009 [174]
Optimizing planning decisions by plant capacity and profit; an example of construction industry	Possibilistic linear programming, modified S-curve membership function	Vasant et al., 2008 [175]
Selecting the best scheduling, balancing of workload	GAs, CLP, MCDM	Mesghouni et al., 1999 [176]

*Multidimensional Scaling (MDS); Fuzzy Axiomatic Design (FAD); Genetic Algorithms (GAs), and Constraint Logic Programming (CLP).

group of decision-makers can be more confident on the results when applying a hybrid MCDM in cases of increasing variety and complexity of information as well as when facing the more challenging problems. The current research establishes general trends, main application domains, and future developments of using hybrid MCDM methods in engineering problems.

Hybrid MCDM accounts for 11 percent of the total amount of papers on developments and applications of MCDM techniques, as referred to in Thomson Reuters Web of Science Core Collection academic database. It is found that interest in HMCDM is rapidly increasing. Although the first paper on HMCDM was published in 1999, 84 percent of articles in the area have been published during the last five years (2011-2015).

Applications of the analyzed methods are observed in 32 Web of Science Research Areas. It is found that a significant part of documents, i.e. 41 percent of publications on HMCDM, belongs to Engineering Research Area (108 documents, including 83 scholarly articles).

Exploring application of HMCDM for engineering issues, three Application Domains are determined. The most active domain, amounting to a half of the analyzed papers, is observed to be Industrial and Manufacturing Engineering, involving technology or product development and/or selection, supplier evaluation and selection, green manufacturing, and logistics optimization. About one-third of the papers are assigned to Engineering Economic and Management domain, involving outsourcing strategies evaluation and selection, personnel selection, project selection, and performance evaluation, as well as other issues of business planning, foresight, marketing. The last group of papers covers multidisciplinary engineering applications, including reviews, methodological issues, and a few additional specific themes not seen in other domains.

Aiming to answer the question about which MCDM methods are most frequently used in developing hybrid approaches, it is found that the most popular ones are well known methods with a strong mathematical background and valuable characteristics, namely AHP, ANP, and DEMATEL (separately or as DANP), also TOPSIS and VIKOR. They are applied for engineering problems in a more or less certain or vague environment, i.e. either crisp methods or, very often, fuzzy approaches are used. The other methods are applied much less frequently. Outranking methods, ELECTRE and PROME- THEE, are observed to be occasionally applied for green manufacturing and supplier selection. Individual applications of three relatively newly developed approaches – COPRAS, SWARA, and WASPAS – are observed for technology selection, location selection, and performance evaluation.

In summary, the findings of the current research confirm that applications of hybrid MCDM approaches for engineering issues are gaining a higher recognition due to their abilities in assisting decision-makers for handling miscellaneous information. Due to the increasing variety and complexity of information, it seems that the number of articles on the topic will be fast-growing and also they will be used in other domains of engineering.

Table 4. HMCDM applications in engineering multidisciplinary domain.

Considered issues and problems	Applied methods*	Publication author(s), publishing year
Reviews on multidisciplinary applications of HMCDM		
Review of applications of fuzzy MCDM techniques in four fields, including engineering as one of the fields	Multiple fuzzy MCDM techniques	Mardani et al., 2015a [8]
Review of approaches for solving civil engineering problems under uncertainty	Fuzzy MCDM, grey MCDM, hybrid MCDM, probabilistic modelling	Antucheviciene et al. [75]
Gas well-drilling projects are analyzed, 77 tasks studied and 31 models prioritized	Neuro-fuzzy network, TOPSIS	Ahari and Niaki, 2014 [183]
Review of different techniques as applied to supplier selection	26 techniques: MCDM, MP, AI techniques	Chai et al, 2013 [184]
Social media tools selection		
Selecting programs for nonprofit TV projects	Fuzzy DELPHI, ANP, TOPSIS	Chang, 2015 [185]
Selecting social media platform as a marketing tool	Fuzzy ANP, COPRAS-G	Tavana et al., 2013b [186]
Developing better blog design by identifying the main factors influencing the design	Factor analysis, DEMATEL	Hsu, 2012 [187]
Evaluating website quality of firms to increase communication with clients	Fuzzy ANP, fuzzy VIKOR	Chou and Cheng, 2012 [188]
Ranking of studies and universities		
Weighting performance evaluation indices for higher education and ranking universities	AHP, VIKOR	Wu et al., 2012 [189]
Sorting the requests of students at university	Fuzzy AHP, fuzzy MCDM, FIS	Shakouri and Tavassoli, 2012 [190]
Selecting the best media mix for student recruiting advertisement	ANP, IP	Chang et al., 2012 [191]
Evaluation of e-learning programs regarding multiple criteria	Fuzzy integral, DEMATEL, AHP	Tzeng et al., 2007 [192]
Methodological issues with applications in engineering		
Analyzing possibilities of DEMATEL to be applied in hybrid methods	DEMATEL	Lee et al., 2013 [193]
Combining imperialist competitive algorithm and MCDM to optimize production system	ICA, TOPSIS	Fallah-Jamshidi and Amiri, 2013 [194]
Solving selection problem of kernel function, an example of power split device of hybrid electrical vehicles	AHP, Entropy	Wang et al., 2013 [195]
Solving problems under risk and uncertainty by applying prospect theory and fuzzy numbers; an example of oil split in the see	Fuzzy logic, Prospect theory, fuzzy TODIM	Krohling and de Souza, 2012 [196]

* Mathematical Programming (MP); Artificial Intelligence (AI); Fuzzy Inference System (FIS); Integer Programming (IP); Imperialist Competitive Algorithm (ICA); TOmada de Decisão interative multicritério (in Portuguese), that means interactive and multiple attribute decision making (TODIM).

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