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MULTI-CRITERIA DECISION MAKING IN CIVIL ENGINEERING. PART II – APPLICATIONS

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Abstract. The first part of the paper shortly presented developments of multi-criteria decision making (MCDM) methods and general data about their use in civil engineering, i.e. distribution by years, countries, authors and journals (Zavadskas *et al.* 2015). The current part of the paper focuses on MCDM application areas and domains. Web of Science Category "Engineering Civil" in Thomson Reuters Web of Science Core Collection academic data base is searched for a topic of MCDM. Only articles and review document types are selected for a detailed survey. They are grouped by Research Areas as presented in Web of Science data base. The most numerous research areas as Construction Building Technology, Transportation, Water Resources and Engineering (other topics) are analysed in detail. Research domains and solved problems are described as well as applied MCDM methods are highlighted. A total of 114 articles are reviewed, showing a wide possibilities of applying MCDM methods for civil engineering problems.

Keywords: MCDM, civil engineering, Web of Science, construction building technology, transportation, water resources, operations research.

Introduction

Multi-criteria decision making (MCDM) is applied in different areas of human activities. In the case of existence of at least two possible options, a person has to make a decision and to select the one which best meets his demands based on a number considered criteria. As it was mentioned in the first part of the paper, the origins of MCDM methods can be dated over 240 years ago. As an individual scientific discipline, it has been widely spreading since the middle of the previous century.

The formal decision making methods, with application of which the current paper is concerned, were intensively developed and applied to various engineering problems in recent decades. Many of the methods were developed outside the field of civil engineering and their applications are very diverse. Several useful reviews of these methods are provided in the books (Figueira *et al.* 2005; Ehrgott *et al.* 2010) as well journal articles (Wiecek *et al.* 2008; Zavadskas, Turskis 2011). Systematically classified information on MCDM methods and applications can be found in the newly published review (Mardani *et al.* 2015a).

Different types of review papers related to MCDM can be distinguished, i.e. reviews of developments and extensions of a particular method as well as on its applications (Behzadian *et al.* 2010, 2012; Balezentis A., Balezentis T. 2014), reviews of applications of different MCDM methods for a particular problem (Chai *et al.* 2013; Kabir *et al.* 2014; Govindan *et al.* 2015; Mardani

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et al. 2015b). The current review paper aims at providing recent developments about the multiple-criteria decision making in the field of civil engineering. This field is extensive and plays an important role in the life of modern society. A very large number of decisions must be made through the life cycle of building. MCDM methods can facilitate making these decisions in a formal way. The presented survey provides numerous examples how can this be done in different research areas and domains of civil engineering.

1. Initial survey and further research methodology

Review is focused entirely on publications refereed in Thomson Reuters Web of Science Core Collection academic data base. As the data base is constantly updated, the current review is based on a state-of-art at a fixed date (November 27, 2015).

The Authors are interested in showing applications of MCDM methods for making decisions in civil engineering. Accordingly, Thomson Reuters Web of Science Core Collection academic data base is searched for papers involving a topic of MCDM and the search is refined for Web of Science Category "Engineering Civil". From the total amount of papers on a topic of MCDM (2494 papers), 5.57 percent are applications of the methods for civil engineering problems (a total of 139 documents). Next, only articles and review document types are selected for a detailed survey, while proceedings papers and book chapters are excluded. Accordingly, 114 journal papers, including 112 articles and 2 reviews are selected for a detailed review.

As the current part of paper focuses on applications, papers are grouped by Research Areas as presented in Web of Science data base. Covered research areas are presented in Figure 1.

As can be seen from the data presented in the figure, the most numerous research areas are Water Resources (33 percent of applications), Construction Building Technology (20 percent) and Transportation (11 percent). These areas are independent and almost no overlapping. While it is noticed, that papers from other research areas are often assigned to several areas, i.e. the categories are overlapping. Interconnections of Research Areas are presented in Figure 2.

Further research is organized following the proposed block-scheme. Based on initial review of papers, four main Research Areas are determined, namely the most numerous areas as Construction Building Technology, Transportation, Water Resources, also other, specific topic of Engineering, that are not included in the mentioned areas. Environmental Sciences Ecology and Materials Science are not analysed as autonomous areas of applications. Materials Science is interconnected with Construction Building Technology and papers related to reconstruction or sustainable building are usually assigned to the both areas. While, papers belonging to Environmental Sciences Ecology overlap with two main areas, namely with the mentioned Construction Building Technology (sustainability or green building issues) and especially with Water Resources, covering ground water quality, wastewater and alike issues. The 6 papers from Geology Area cover groundwater issues and fully overlap with papers assigned to Water Resources. The only paper from 7 observed in Figure 1 analyses seismic retrofitting and is analysed assigning it to Construction Building Technology. Re-

Field: Research Areas	Record Count	% of 114	Bar Chart
ENGINEERING	114	100.000%	
WATER RESOURCES	38	33.333%	
CONSTRUCTION BUILDING TECHNOLOGY	23	20.175%	
TRANSPORTATION	13	11.404%	
ENVIRONMENTAL SCIENCES ECOLOGY	9	7.895%	
MATERIALS SCIENCE	9	7.895%	
COMPUTER SCIENCE	7	6.140%	
GEOLOGY	7	6.140%	
MATHEMATICS	6	5.263%	
ENERGY FUELS	4	3.509%	
BUSINESS ECONOMICS	2	1.754%	
OPERATIONS RESEARCH MANAGEMENT SCIENCE	2	1.754%	
AGRICULTURE	1	0.877%	
METEOROLOGY ATMOSPHERIC SCIENCES	1	0.877%	
OCEANOGRAPHY	1	0.877%	
URBAN STUDIES	1	0.877%	

Fig. 1. Records by research areas

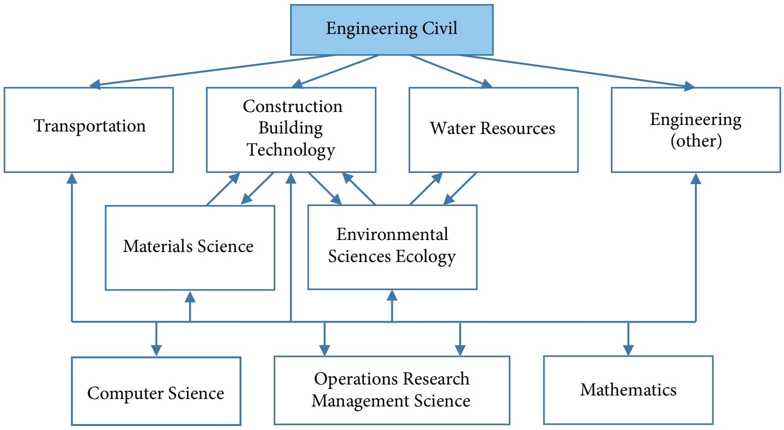

Fig. 2. Interconnections of research areas

search Areas of Computer Science, Mathematics and Operations Research Management Science are presented at the bottom of the scheme (Fig. 2), because they connect all the papers where MCDM methods and operations research techniques are applied for decision making.

Based on the above findings, the detailed review of papers is organized grouping all 114 journal articles by four main Research Areas. Findings are presented in the next Chapters.

2. MCDM applications in Construction Building Technology

After detailed review of the papers, 36 documents are assigned to the current research area. The number of documents does not mismatch with those presented in Figure 1, because a number of papers from area of Engineering are involved in the analysed research area after a detailed survey of their content and analysed problem.

The papers are grouped by research domains. Research domains for Construction Building Technology area are presented in Figure 3.

Firstly, two main domains are distinguished for new building, i.e. application of MCDM techniques for ranking construction technologies or decision support in problems related to building structures. Multi-criteria approach is also applied for the next stages of building life cycle management: modernization or reconstruction, also demolition. The next important domain, especially in later years, is sustainable building and the more modern one – intelligent building. Also seismic retrofitting is separated as an independent domain due to numerous applications of the analysed

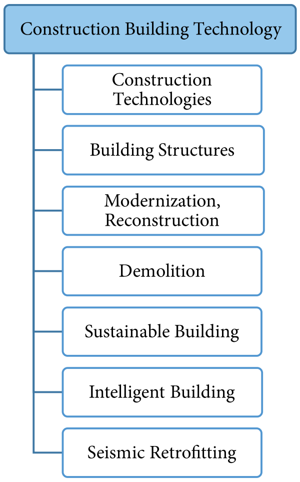

Fig. 3. Research domains in Construction Building Technology

methodology to a specific problem. Detailed review is presented, i.e. particular solved problems are described as well as applied MCDM methods are highlighted in Table 1. Description of MCDM methods by authors and years with references to initial sources are presented in the first part of the paper (history and state-of-art survey).

Different sustainability issues are analysed by applying a single MCDM method or aggregation of methods. Assessment of the whole sustainable building is made by Medineckiene *et al.* (2015), evaluation of separate structural element, i.e. concrete columns with emphasis on sustainability is presented by Pons and de la Fuente (2013), designing of optimal engineering systems for heating, ventilation and air conditioning is made by Soyguder and Alli (2009), urban planning issues are analysed by Wang *et al.* (2013). The most popular methods are observed to be AHP and ANP. They are applied in 5 papers from 7 ones.

Table 1. MCDM applications by research domains in Construction Building Technology research area

Research domain and the problem solved	MCDM method(s) applied	Publication
Sustainable building		
Assessment of sustainable building, integrating LEED criteria and MCDM methods	AHP, ARAS	Medineckiene *et al.* (2015)
Categorization of buildings based on their energy performance	Fuzzy ANP	Kabak *et al.* (2014)
Integrated evaluation of concrete columns sustainability	AHP, MIVES	Pons and de la Fuente (2013)
Planning protected areas in suburb with emphasis on sustainability	AHP	Wang *et al.* (2013)
Analysing alternative dwellings considering a number of criteria	Fuzzy games theory	Medineckiene *et al.* (2011)
Designing optimal heating, ventilation and air conditioning system	Artificial Neural Fuzzy Interface System (ANFIS)	Soyguder and Alli (2009)
Environmental impact assessment and pollution mitigation	AHP	Bose and Chakrabarti (2003)
Intelligent building		
Assessment of intelligent buildings in an uncertain environment	Fuzzy AHP, fuzzy TOPSIS	Kaya and Kahraman (2014)
Developing indicators and a framework for intelligent building	AHP, ANP	Wong *et al.* (2008a)
Evaluating intelligence of a building	AHP, ANP	Wong *et al.* (2008b)
Construction Technologies		
Offered model for comprehensive assessment of technologies	AHP, Permutation	Kildiene *et al.* (2014)
Selecting the most suitable solutions for ensuring safety at a construction site	Entropy, WASPAS	Dejus and Antucheviciene (2013)
Sustainability assessment of building technologies; an example of building a school	MIVES, AHP	Pons and Aguado (2012)
Selecting a pile-column technology	TOPSIS, ARAS, COPRAS, AHP	Zavadskas *et al.* (2012)
Analyzing pile-column alternatives and selecting the best one	Entropy, ARAS	Susinskas *et al.* (2011)
Selecting the best foundation installment variant in aquiferous soil	ARAS	Zavadskas *et al.* (2010)
Building Structures		
Comparison of thin walled steel structures, involving structural, economic and environmental parameters	TOPSIS	Terracciano *et al.* (2015)
Assistance to designers choice in detailed building design	AHP, CBA (Choosing by Advantages)	Arroyo *et al.* (2015)
Selecting structural systems for multi-housing project with different stakeholders	ELECTRE III, PROMETHEE II	Balali *et al.* (2014)
Different shapes of thin walled structures compared in accordance with multiple criteria	COPRAS	Tarlochan *et al.* (2013)
Estimating high-rise building structure systems during the design stage	COPRAS-G	Tamosaitiene and Gaudutis (2013)
Modernization, Reconstruction		
Ranking insulation material when retrofitting historical brick buildings	TOPSIS grey	Zagorskas *et al.* (2014)
Efficiency of residential building modernization with an emphasis on thermal insulation of external walls is analyzed	SWARA, TODIM	Ruzgys *et al.* (2014)

End of Table 1

Research domain and the problem solved	MCDM method(s) applied	Publication
Selecting the most appropriate modernization variant of vernacular buildings	AHP, TOPSIS grey	Siozinyte *et al.* (2014)
Searching for the best compromise solution for improving daylighting in a vernacular building	COPRAS, TOPSIS, WASPAS, AHP	Siozinyte and Antucheviciene (2013)
Ecological and economical assessment of dwellings modernization	COPRAS, WASPAS, TOPSIS	Staniunas *et al.* (2013)
Selecting materials for concrete repair	AHP	Do and Kim (2012)
Assessing owners preferences for residential buildings renovation	SAW, MEW, COPRAS, AHP	Medineckiene and Bjork (2011)
Selecting optimal regeneration strategies and proper localities for abandoned buildings	COPRAS-F	Zavadskas and Antucheviciene (2007)
Ranking strategies for highway bridges rehabilitation	Fuzzy sets, MCDM, utility theory	Sobanjo *et al.* (1994)
Demolition		
Finding the best demolition project; an example of bridge demolition	AHP, ANP	Chen *et al.* (2014)
Seismic Retrofitting		
Retrofitting with metal protection devices and examining the effect of increasing a number of floors in masonry buildings	TOPSIS, ELECTRE, VIKOR	Formisano and Mazzolani (2015)
Selecting the best seismic retrofit technique for a concrete bridge	TOPSIS	Billah and Alam (2014)
Ranking of steel buildings according to their damageability in seismic events	Fuzzy TOPSIS	Shahriar *et al.* (2012)
Selecting a strategy for seismic retrofitting of concrete structure: comparative study of multiple criteria approaches	TOPSIS, WSM, VPM, VIKOR, ELECTRE, PROMETHEE, MAUT	Caterino *et al.* (2009)
Comparing innovative seismic retrofitting possibilities of a reinforced concrete building	TOPSIS	Caterino *et al.* (2008)

Three papers use fuzzy sets for decision in an uncertain environment. Medineckiene *et al.* (2015) applies hybrid method, including AHP for weighting of criteria and ARAS for ranking of alternatives. A similar aggregation of methods Kaya and Kahraman (2014) apply for assessment of intelligent buildings in an uncertain environment. They use fuzzy AHP and fuzzy TOPSIS.

In a domain of construction technologies, selecting a pile-column technology or foundations installment alternatives are dominated issues. A large variety of methods for the current task are applied: AHP, Entropy, TOPSIS, ARAS, COPRAS. A model for comprehensive assessment of technologies applying AHP and Permutation method is offered by Kildiene *et al.* (2014). It is proposed to select the most suitable solution for ensuring safety at a construction site applying a novel method WASPAS combining with Entropy (Dejus, Antucheviciene 2013).

The single application of ELECTRE III, PROMETHEE II methods for selecting structural systems can be observed in a paper of Balali *et al.* (2014). High-rise building structure systems are estimated by applying COPRAS-G method (Tamosaitiene, Gaudutis 2013). It can be stated that application of grey numbers is rather rarer in the analysed area. It is interesting to mention, that two papers are devoted to comparison of thin walled steel structures in accordance with multiple criteria and applying two well-known methods TOPSIS and COPRAS (Terracciano *et al.* 2015; Tarlochan *et al.* 2013).

Modernisation and reconstruction domain partly overlaps with Materials Science research area. Ranking insulation material and evaluating modernisation efficiency for usual residential buildings or historical buildings is presented (Zagorskas *et al.* 2014; Ruzgys *et al.* 2014). Selecting materials for concrete repair is held by Do and Kim (2012). Interesting issue of vernacular building modernisation is analysed by Siozinyte *et al.* (2014) and Siozinyte, Antucheviciene (2013).

As for the methods applied, it can be mentioned that no dominating method can be observed and a great variety of methods are applied: COPRAS, TOPSIS, WASPAS, SAW, MEW, TODIM, SWARA. It is worth to mention that COPRAS-F was firstly presented when selecting regeneration strategies for abandoned rural buildings (Zavadskas, Antucheviciene 2007).

Specific domain of seismic retrofitting problems is presented separately. The domain is very popular in scientific papers. As concerns MCDM methods, they are applied for steel buildings (Shahriar *et al.* 2012) or concrete structures (Billah and Alam 2014; Caterino *et al.* 2008, 2009) or masonry buildings (Formisano, Mazzolani 2015). The TOPSIS method is applied in all papers related to seismic retrofitting. Caterino *et al.* (2009) presented a comparative study of multiple criteria approaches for seismic issues, involving TOPSIS, WSM, VPM, VIKOR, ELECTRE, PROMETHEE and MAUT.

3. MCDM applications in Transportation

The next important and rather autonomous part of civil engineering applications constitute applications for transportation problems. Papers from Transportation Research Area are grouped by research domains as presented in Figure 4. The methods are applied for rational logistics decisions, for air and rail transpor-

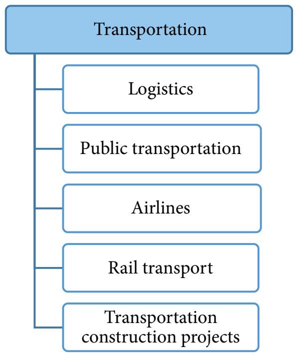

Fig. 4. Research domains in Transportation

Table 2. MCDM applications by research domains in Transportation research area

Research domain and the problem solved	MCDM method(s) applied	Publication
Logistics		
Assisting for a company for selecting the most appropriate way of transportation between particular locations	AHP	Kumru M. and Kumru P. Y. (2014)
Selecting location in logistics and transportation	Fuzzy MCDM	Chou (2009)
Supporting development of a better freight transportation system	Fuzzy AHP, Fuzzy MCDM	Hanaoka and Kunadhamraks (2009)
Public transportation		
Customer satisfaction in public transportation is measured and suggestions for improving a transportation are made	Interval type-2 fuzzy sets, GRA, TOPSIS	Celik *et al.* (2013)
Applications of MCDM/MCDA in public transportation	ELECTRE III	Zak (2011)
Analyzing environmental and social impacts in a context of transportation demand	AHP, CODASID(3) (a method based on a complete concordance and discordance analysis)	Tanadtang *et al.* (2005)
Airlines		
Evaluating service quality of airlines	VIKOR, GRA, interval-valued fuzzy sets	Kuo (2011)
Rail transport		
Risk identification in subway construction	AHP, IAHP (Improved AHP)	Li *et al.* (2013)
Designing a train overhaul maintenance facility	Simulation optimization, MCDM	Um *et al.* (2011)
Evaluating alternative rail transit plans	AHP	Gercek *et al.* (2004)
Transportation construction projects		
Creating and selecting highway alignment alternatives	AHP, GIS	Yakar and Celik (2014)
An empirical study of budget allocation for regional transportation construction projects in Taiwan	FAHP, the fuzzy multi-criteria grade classification model (FMGCM)	Teng *et al.* (2010)
Prioritization of construction projects for funding	AHP, TOPSIS	Shelton and Medina (2010)

tation solutions, and for assessing transportation construction projects.

It is worth to be mentioned that researchers have been applying MCDM methods for transportation solutions since 2004 (Table 2). The first application in the area in an article refereed in Web of Science data base is for evaluating alternative rail transit plans (Gercek *et al.* 2004). The AHP method is applied to compare the alternatives. The application in 2005 is for public transportation problems when searching the best combination of environmental and social impacts in a context of transportation demand with the help of AHP (Tanadtang *et al.* 2005).

The research showed that the crisp or fuzzy AHP method is the most often applied for logistics decisions when assisting for a company for to select the most appropriate way of transportation (Kumru M., Kumru P. Y. 2014) or to develop a better freight transportation system (Hanaoka and Kunadhamraks 2009).

Customers' satisfaction and transportation quality in public transportation are more difficult to evaluate by applying formal crisp methods, that's why fuzzy or grey numbers can be useful. Celik *et al.* (2013) apply Interval type-2 fuzzy sets, GRA and TOPSIS to measure passenger satisfaction, Kuo (2011) evaluates service quality of airlines with the help of VIKOR and GRA in combination with interval-valued fuzzy sets.

Additionally applications for transportation construction projects evaluation should be analysed. Shelton and Medina (2010) prioritizes construction projects for funding by applying the traditional combination of usual methods AHP and TOPSIS. Teng *et al.* (2010) analyses budget allocation for transportation construction projects in an uncertain and risky environment, integrating fuzzy sets theory with multiple criteria decision making and using FAHP as well as the fuzzy multi-criteria grade classification model.

4. MCDM applications in Water Resources management

The most numerous research area in civil engineering is Water Resources. One third of articles (33.33 percent) are assigned to the area (Fig. 1). As the area covers 38 papers, there is a need to categorize them by research domains. 7 research domains are distinguished as presented in Figure 5, starting from domestic water supply to wastewater, also separating specific areas as flood management or irrigation for agriculture purposes. As presented in Figure 2, a lot of papers assigned to Water Resources overlap with papers belonging to Environmental Sciences Ecology research area, because problems related to protection of natural environment are analysed.

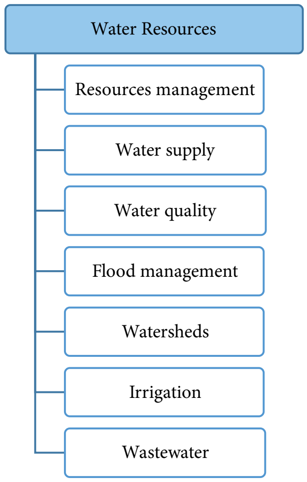

Fig. 5. Research domains in water resources

The papers are grouped by research domains and detailed by analysed problems and applied MCDM methods (Table 3). The research area is the most numerous, and the most widely spread by application years. The papers cover a period of 25 years, starting from 1991 up till now. The oldest applications of MCDM techniques for civil engineering problems are observed in the current area in WoS data base. The research showed that the oldest applications are based on outranking approaches as ELECTRE and PROMETHEE, also Composite programming (CP). Shafike *et al.* (1992) analyses fresh water supply and wastewater disposal and solves a problem of groundwater contamination by applying a combination of CP, ELECTRE II and MCQA II. The latest extension of the method, namely ELECTRE III is used when selecting the most efficient alternatives for a long-term water supply (Netto *et al.* 1996), selecting the best strategies of irrigation (Raju, Duckstein 2004), etc.

The subsequent papers present several new developments of methods with application examples in water resources management problems. Zarghami and Szidarovszky (2009) presents new approach SFOWA: Ordered Weighted Averaging (OWA) operator with stochastic-fuzzy modelling, and solves an example of recourses management of Central Tisza River in Hungary. Roozbahani *et al.* (2012) suggest PROMETHEE with Precedence Order in the Criteria (PPOC) with application to group water management decisions for urban water supply systems. Li *et al.* (2009) presents a new optimization method using fuzzy pattern recognition for optimizing water supply network.

Table 3. MCDM applications by research domains in Water Resources research area

Research domain and the problem solved	MCDM method(s) applied	Publication
Resources Management		
Spatial multiple criteria decision-making model to analyze water demand and different management possibilities	TOPSIS, MODM	Rousta and Araghinejad (2015)
Solving water export conflict through social decision making under uncertainty	Ranking, Voting, Borda, Pairwise comparison, Majoritarian Compromise, Monte-Carlo	Madani *et al.* (2014)
Potential groundwater allocation zones are predicted combining multicriteria analysis and GIS	AHP	Kumar *et al.* (2014)
Measuring performance of different water resources management alternatives	CP	Geng and Wardlaw (2013)
Water reservoirs operations involving uncertainties	Fuzzy-state stochastic dynamic programming (FSDP), MCDM	Akbari *et al.* (2011)
Supporting managers in water resources operations; example of Karun water reservoirs	Fuzzy TOPSIS	Afshar *et al.* (2011)
Allocating potential groundwater resources	AHP integrated with Remote sensing (RS) and geographic information system (GIS)	Machiwal *et al.* (2011)
Recourses management; an example of Central Tisza river in Hungary	SFOWA: Ordered Weighted Averaging (OWA) operator, stochastic-fuzzy modelling	Zarghami and Szidarovszky (2009)
Adequacy of models and techniques for ground-water management are discussed	Compromise programming (CP), ELECTRE III, multiattribute utility function, UTA	Duckstein *et al.* (1994)
Testing effectiveness of several techniques for water resource management task	MATS-PC, EXPERT CHOICE, ARIADNE, ELECTRE	Goicoechea *et al.* (1992)
Water Supply		
Analysis of water users and inter-basin water transfer systems	AHP, ANP, ER, TOPSIS, PROMETHEE II	Abed-Elmdoust and Kerachian (2014)
Group water management decisions for urban water supply systems	PROMETHEE with Precedence Order in the Criteria (PPOC)	Roozbahani *et al.* (2012)
Optimizing water supply network	A new optimization method using fuzzy pattern recognition	Li *et al.* (2009)
Optimizing water distribution networks	AHP, GA (genetic algorithm)	Vamvakeridou-Lyroudia *et al.* (2006)
Evaluating different scenarios of water industry privatization in Korea	WSM	Choi and Park (2001)
Designing alternatives of a system for a long-term water supply and selecting the most efficient ones	ELECTRE III	Netto *et al.* (1996)
Water Quality		
Assessment of drinking water quality through monitoring different parameters in water distribution network	Fuzzy rule-based system, Fuzzy Dempster–Shafer, AHP	Aghaarabi *et al.* (2014)
Improving water quality through selecting the best agricultural practices	A-IFS, MCDM (SAW)	Hernandez and Uddameri (2010)
Identifying various components of hydrological vulnerability and supporting residential decisions	AHP, ELECTRE II	Chung and Lee (2009)
Assisting stakeholders to select the best technology for groundwater remediation	PROMETHEE II	Khelifi *et al.* (2006)

End of Table 3

Research domain and the problem solved	MCDM method(s) applied	Publication
Integrating model for managing water resources and controlling water pollution	AHP, SAW	Karamouz *et al.* (2003)
Nitrate contamination is analyzed and risk for human health prevention alternative are evaluated	Fuzzy MCDM	Lee *at al.* (1994)
Solving problem of groundwater contamination, involving fresh water supply and wastewater disposal	Compromise programming (CP), ELECTRE II, MCQA II	Shafike *et al.* (1992)
Designing network for ground water monitoring	Compromise programming (CP)	Woldt and Bogardi (1992)
Flood Management		
Selecting the best management strategy before and after a river flood; comparing different MCDM methods	ELECTRE I, ELECTRE III, SAW, CP, VIKOR, TOPSIS, M-TOPSIS, AHP	Chitsaz and Banihabib (2015)
Assessment of flood management strategies involving analysis of consequences of inundation velocity and duration	Spatial MCDM (SMCDM), Spatial Compromise Programming (SCP).	Ahmadisharaf *et al.* (2015)
Assessing alternative solutions for flood damage reduction.	PROMETHEE	Su and Tung (2014)
New technique for flood management is developed when integrating MCDM and GIS	Spatial Monte Carlo Analysis (SMCA)	Qi *et al.* (2013)
Supporting decisions in flood management under uncertainty	ANP, remote sensing, GIS	Levy (2005)
Techniques for fitting floods are ranked by applying MCDM methods	Composite programming, ELECTRE, MCQA, fuzzy sets	Duckstein *et al.* (1991)
Watersheds		
Analysing watershed vulnerability and restrictions for land-use activities	Modified VIKOR	Chang and Hsu (2011)
Ecological risk management in watershed	FMCGDM model based on modified Borda scoring method	Hao and Chen (2010)
Ranking watershed resources management alternatives applying different techniques and searching for the most effective technique	15 techniques	Tecle (1992)
Irrigation		
An economic framework for allocation of water resources	Entropy, MCDM	Karamouz *et al.* (2014)
Ranking of alternatives for irrigation planning	Data Envelopment Analysis (DEA); PROMETHEE, EXPROM	Raju and Kumar (2006)
Selecting the best strategies in irrigation area considering environmental, economic and social criteria	ELECTRE III	Raju and Duckstein (2004)
Evaluating management alternatives for irrigation with an emphasis on sustainable development subsystems	PROMETHEE-2, EXPROM-2, ELECTRE III, ELECTRE IV, and Compromise Programming (CP)	Raju *et al.* (2000)
Wastewater		
Analysis of wastewater allocation scenarios, considering different climate change possibilities	TOPSIS	Kim *et al.* (2015)

A distinctive feature of the current research is using Geographical Information Systems (GIS) in combination with MCDM techniques for problems related to location. Kumar *et al.* (2014) predicts potential groundwater allocation zones combining AHP and GIS. Machiwal *et al.* (2011) supports allocating groundwater resources, integrating the mentioned AHP, GIS and Remote sensing (RS). The same combination of three techniques is applied by Levy (2005) for supporting decisions in flood management. Qi *et al.* (2013) suggests a new technique for flood management when integrating multiple criteria analysis and GIS, called Spatial Monte Carlo Analysis (SMCA).

The second distinctive feature from the methodological point of view is that there are several papers applying a number of MCDM methods and comparing the results. The latest researches involve Chitsaz and Banihabib (2015) compare the applicability of different MCDM methods for selecting the best river flood management strategy and applies ELECTRE I, ELECTRE III, SAW, CP, VIKOR, TOPSIS, M-TOPSIS and AHP. Madani *et al.* (2014) solve water export conflict through using Ranking, Voting, Borda, Pairwise comparison, Majoritarian Compromise and Monte-Carlo approaches. Even in 2000 Raju *et al.* (2000) evaluated management alternatives for irrigation using PROMETHEE-2, EXPROM-2, ELECTRE III, ELECTRE IV and CP. Tecle (1992) applies 15 different techniques for ranking watershed resources management alternatives and searches for the most effective technique.

5. MCDM applications in other areas of engineering

The last group of papers is divided into three independent research domains (Fig. 6), characterized by interesting applications (Table 4). Separately are reviewed papers analysing technological or management problems of building infrastructure objects (Kabir *et al.* 2014). The methods are successfully applied for

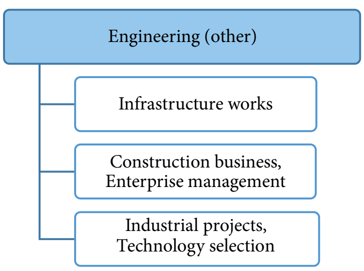

Fig. 6. Other research domains in engineering

construction business planning and construction enterprise management. The numerous applications are observed for technology selection for different industrial projects.

Construction business and enterprise management domain covers procurement, contractor selection, assessing success of construction projects or selecting management strategies in construction enterprises. AHP method as a single technique or aggregated with other approaches is still popular in the domain: Lin *et al.* (2015) ranks procurement methods for public building maintenance, Zavadskas *et al.* (2014) evaluates construction project performance by aggregating AHP and MEW. Zavadskas *et al.* (2011) determine management strategies of construction enterprises using SWOT and select the best strategy applying AHP and permutation method. Chou *et al.* (2010) developed a new approach of AHP with Monte Carlo simulation (MCS) for assessing project performance through earned value management.

Technology selection for industrial project domain covers different interesting and useful applications. A large variety of applied methods is also observed. Kursunoglu and Onder (2015) select the most suitable fan for ventilation of mines by applying well known AHP method. Emovon *et al.* (2015) analyses marine machinery systems and suggests a novel methodology for assessing their risk using VIKOR and CP. Bagocius *et al.* (2014) selects the best location and the most suitable type of wind turbine by WASPAS technique. Fuzzy AHP and fuzzy TOPSIS are applied for selecting a boring machine for tunnelling (Yazdani-Chamzini and Yakhchali 2012) and for evaluating shaft sinking operations and selecting the most appropriate one (Lashgari *et al.* 2011). Concrete pumps selection with the help of ELECTRE III is performed by Ulubeyli and Kazaz (2009).

Conclusions

Limiting the research on Thomson Reuters Web of Science Core Collection academic data base and Web of Science Category "Engineering Civil", 114 papers (articles and review) are included in the detailed review of MCDM applications for civil engineering problems.

When grouping papers by Research Areas following Web of Science distribution, the four main Research Areas are identified, namely Construction Building Technology, Transportation, Water Resourc-

Table 4. MCDM applications by research domains in other research areas of Engineering

Research domain and the problem solved	MCDM method(s) applied	Publication
Infrastructure works		
Selecting the best construction method of collection systems for urban storm water	FAHP and CP (Compromise Programming)	Ebrahimian *et al.* (2015)
An approach for health monitoring of telecommunication towers, based on group visual assessment	Fuzzy TOPSIS	Verma *et al.* (2015)
Selecting intelligent sensors for health monitoring of bridges using	SWARA, WASPAS	Bitarafan *et al.* (2014)
An overview of MCDM applications for infrastructure problems	WSM, WPM, CP, AHP, ELECTRE, TOPSIS, AHP, VIKOR	Kabir *et al.* (2014)
Evaluation of parking infrastructure problems	SAW, TOPSIS, COPRAS, AHP	Palevicius *et al.* (2013)
Construction business, enterprise management		
Evaluating and prioritizing procurement methods for public building maintenance	AHP	Lin *et al.* (2015)
Aggregated evaluation of construction project performance	AHP, MEW	Zavadskas *et al.* (2014)
Accumulating success criteria, comparing and ranking success of construction projects	M-TOPSIS	Pinter and Psunder (2013)
Assessing industrial projects prior to investment	WSM, Simos' procedure	Marzouk *et al.* (2013)
Selection of projects and project portfolio formation in contractor firms	Fuzzy SAW	Abbasianjahromi and Rajaie (2012)
Determining and selecting management strategies in construction enterprises	SWOT, AHP, permutation method	Zavadskas *et al.* (2011)
System for assessing project performance through earned value management	AHP with Monte Carlo simulation (MCS)	Chou *et al.* (2010)
Decision support for strategic partnering	ANP	Cheng and Li (2007)
Industrial projects, technology selection		
Selecting the most suitable fan for ventilation of mines	AHP	Kursunoglu and Onder (2015)
Novel methodology for assessing the risk of marine machinery systems	VIKOR, CP	Emovon *et al.* (2015)
Selecting the most suitable type of wind turbine and the best location in offshore area	WASPAS	Bagocius *et al.* (2014)
Selecting boring machine for tunnelling	Fuzzy AHP, Fuzzy TOPSIS	Yazdani-Chamzini and Yakhchali (2012)
Selecting optimal strategy for recycling in solar energy industry	ANP	Shiue and Li (2012)
Evaluating shaft sinking operations and selecting the most appropriate one	Fuzzy AHP, Fuzzy TOPSIS	Lashgari *et al.* (2011)
Construction equipment selection with an example of concrete pumps	ELECTRE III	Ulubeyli and Kazaz (2009)
Measuring industrial risk	AHP	Heler (2006)
Integrating preferences in environmental risk analysis; an example of oil and gas industry	Fuzzy AHP	Tesfamariam and Sadiq (2006)
Effective managing of hydropower reservoirs	AHP	Karamouz *et al.* (2005)

es and Engineering (other topics, not included in the previous three areas). Papers, included to Materials Science and Environmental Sciences Ecology are not analysed separately, because these document are also assigned to one of the previously mentioned main areas, i.e. usually Materials Science overlaps with Construction Building Technology, and Environmental Sciences Ecology overlaps with Water Resources.

It was found that Construction Building Technology with applications of MCDM techniques covers seven research domains. Construction technologies are selected or Building structures are assessed using the multi-criteria approach. Decisions are supported by MCDM in the whole building life cycle, involving Modernization, Reconstruction and even Demolition issues. Also two very modern domains are covered, namely Sustainable building and Intelligent Building. As an independent domain, Seismic retrofitting of steel buildings or concrete structures can be mentioned. From the methodological side, non-compensatory AHP and ANP methods are used for measurement of intangible criteria when assessing sustainability or evaluating intelligent buildings. Other problems, related to technologies or structures, usually are solved by applying compensatory methods TOPSIS, ARAS, COPRAS, VIKOR, WASPAS.

In Transportation Research Area applications for transportation construction problems, effective decision-making in logistics and assessing transportation problems are observed. Researchers have been applying MCDM methods for transportation solutions since 2004. The earliest applications use the most popular AHP and TOPSIS methods. In the latest papers, covering customer satisfaction or other stakeholders' interests, modifications of techniques by applying fuzzy sets or grey relations appear.

The most numerous research area involving MCDM applications in civil engineering is Water Resources, covering one third of analysed articles. The articles are grouped into 7 research domains, involving water supply, wastewater, floods management, etc. The oldest applications are also observed in the current area and in different domains. The papers published in 1991 and 1992 use MCDM methods for ranking techniques for fitting floods, ranking watershed resources management alternatives, solving problems of groundwater contamination and monitoring. The research showed that the oldest applications are based on outranking approaches as ELECTRE and PROMETHEE. The later papers present several new developments of methods with application examples in water resources management problems. A distinctive feature of the current domain is using Geographical Information Systems (GIS) in combination with MCDM techniques for problems related to location.

The last group of papers covers three independent research domains, characterized by interesting applications, i.e. construction business planning and enterprise management, infrastructure projects and industrial projects. Construction management domain involves assessing success of construction projects or selecting management strategies. AHP method as a single technique or aggregated with other approaches is the most popular decision support tool in the domain. While, in contrast, a great variety of compensatory and non-compensatory outranking MCDM methods for infrastructure problems are applied. Technology selection for industrial project domain also covers different applications in mining, tunnelling, marine, energy industries. For decisions in an uncertain and risky environment a combination of fuzzy AHP and fuzzy TOPSIS are most common in the domain.

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