Taylor & Francis
Taylor & Francis Group
Lietuvos statybininkų asociacija
ENGINEERING STRUCTURES AND TECHNOLOGIES
ISSN 2029-882X / eISSN 2029-8838
2015 7(4): 151–167
doi:10.3846/2029882X.2016.1139664

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

Edmundas Kazimieras ZAVADSKAS[a], Jurgita ANTUCHEVIČIENĖ[a], Oleg KAPLIŃSKI[b]

[a]*Faculty of Civil Engineering, Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223, Vilnius, Lithuania*
[b]*Faculty of Architecture, Poznań University of Technology, Nieszawska 13C, 60-965 Poznań, Poland*

Received 03 December 2015; accepted 28 December 2015

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

Corresponding author:
J. Antuchevičienė E-mail: *jurgita.antucheviciene@vgtu.lt*

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

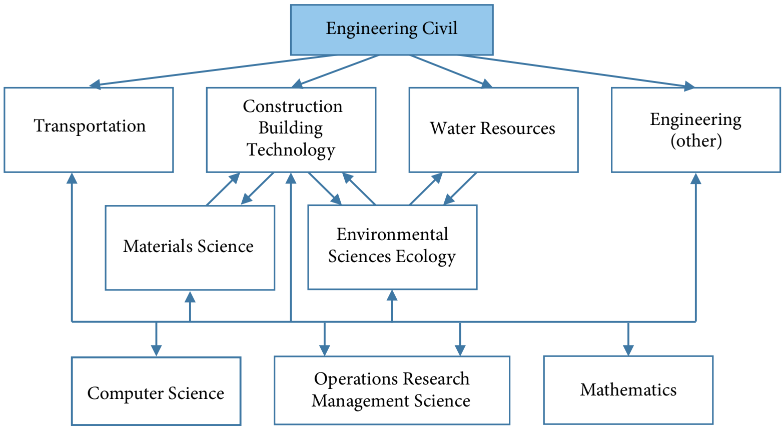

Fig. 2. Interconnections of research areas

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

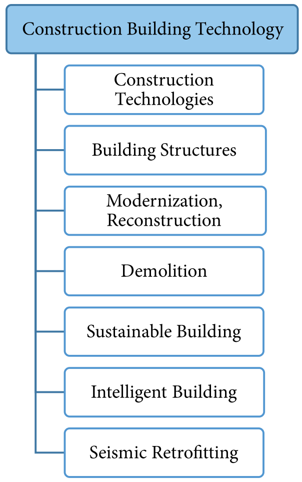

Fig. 3. Research domains in Construction Building Technology

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-

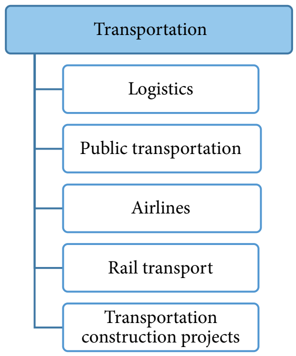

Fig. 4. Research domains in Transportation

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.

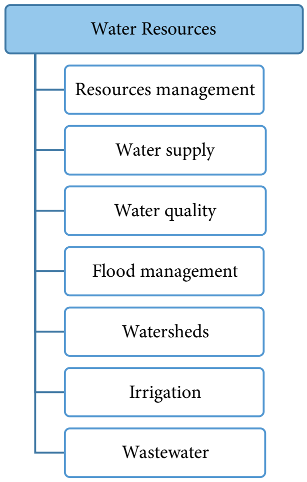

Fig. 5. Research domains in water resources

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

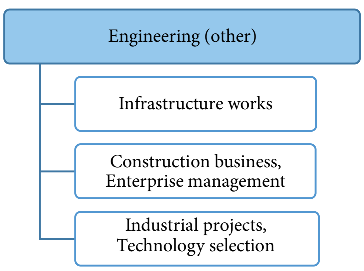

Fig. 6. Other research domains in engineering

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.

References

Abbasianjahromi, H.; Rajaie, H. 2012. Developing a project portfolio selection model for contractor firms considering the risk factor, *Journal of Civil Engineering and Management* 18(6): 879–889. http://dx.doi.org/10.3846/13923730.2012.734856

Abed-Elmdoust, A.; Kerachian, R. 2014. Evaluating the relative power of water users in inter-basin water transfer systems, *Water Resources Management* 28(2): 495–509. http://dx.doi.org/10.1007/s11269-013-0495-9

Afshar, A.; Marino, M. A.; Saadatpour, M.; Afshar, A. 2011. Fuzzy TOPSIS multi-criteria decision analysis applied to Karun reservoirs system, *Water Resources Management* 25(2): 545–563. http://dx.doi.org/10.1007/s11269-010-9713-x

Aghaarabi, E.; Aminravan, F.; Sadiq, R.; Hoorfar, M.; Rodriguez, M. J.; Najjaran, H. 2014. Comparative study of fuzzy evidential reasoning and fuzzy rule-based approaches: An illustration for water quality assessment in distribution networks, *Stochastic Environmental Research and Risk Assessment* 28(3): 655–679. http://dx.doi.org/10.1007/s00477-013-0780-4

Ahmadisharaf, E.; Kalyanapu, A. J.; Chung, E.-S. 2015. Evaluating the effects of inundation duration and velocity on selection of flood management alternatives using multi-criteria decision making, *Water Resources Management* 29(8): 2543–2561.

Akbari, M.; Afshar, A.; Mousavi, S. J. 2011. Stochastic multiobjective reservoir operation under imprecise objectives: multicriteria decision-making approach, *Journal of Hydroinformatics* 13(1): 110–120.

Arroyo, P.; Tommelein, I. D.; Ballard, G. 2015. Comparing AHP and CBA as decision methods to resolve the choosing problem in detailed design, *Journal of Construction Engineering and Management* 141(1). http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000915

Bagocius, V.; Zavadskas, E. K.; Turskis, Z. 2014. Multi-person selection of the best wind turbine based on the multi-criteria integrated additive-multiplicative utility function, *Journal of Civil Engineering and Management* 20(4): 590–599. http://dx.doi.org/10.3846/13923730.2014.932836

Balali, V.; Zahraie, B.; Roozbahani, A. 2014. Integration of ELECTRE III and PROMETHEE II decision-making methods with an interval approach: Application in selection of appropriate structural systems, *Journal of Computing in Civil Engineering* 28(2): 297–314. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000254

Balezentis, A.; Balezentis, T. 2014. A survey on development and applications of the multi-criteria decision making method MULTIMOORA, *Journal of Multi-Criteria Decision Analysis* 21(3–4): 209–222. http://dx.doi.org/10.1002/mcda.1501

Behzadian, M.; Kazemzadeh, R. B.; Albadvi, A.; Aghdasi, M. 2010. PROMETHEE: a comprehensive literature review on methodologies and applications, *European Journal of Operational Research* 200(1): 198–215. http://dx.doi.org/10.1016/j.ejor.2009.01.021

Behzadian, M.; Otaghsara, S. K.; Yazdani, M.; Ignatius, J. 2012. A state-of the-art survey of TOPSIS applications, *Expert Systems with Applications* 39(17): 13051–13069. http://dx.doi.org/10.1016/j.eswa.2012.05.056

Billah, A. H. M. M.; Alam, M. S. 2014. Performance-based prioritisation for seismic retrofitting of reinforced concrete bridge bent, *Structure and Infrastructure Engineering* 10(8): 929–949. http://dx.doi.org/10.1080/15732479.2013.772641

Bitarafan, M.; Zolfani, S. H.; Arefi, S. L.; Zavadskas, E. K. 2014. Evaluation of real-time intelligent sensors for structural health monitoring of bridges based on SWARA-WASPAS; A case in Iran, *Baltic Journal of Road and Bridge Engineering* 9(4): 333–340. http://dx.doi.org/10.3846/bjrbe.2014.40

Bose, P.; Chakrabarti, R. 2003. Application of optimized multicriteria decision-making in an environmental impact assessment study, *Civil Engineering and Environmental Systems* 20(1): 31–48. http://dx.doi.org/10.1080/10286600302230

Caterino, N.; Iervolino, I.; Manfredi, G.; Cosenza, E. 2008. Multi-criteria decision making for seismic retrofitting of RC structures, *Journal of Earthquake Engineering* 12(4): 555–583. http://dx.doi.org/10.1080/13632460701572872

Caterino, N.; Iervolino, I.; Manfredi, G.; Cosenza, E. 2009. Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting, *Computer-Aided Civil and Infrastructure Engineering* 24(6): 432–445. http://dx.doi.org/10.1111/j.1467-8667.2009.00599.x

Celik, E.; Bilisik, O. N.; Erdogan, M.; Gumus, A. T.; Baracli, H. 2013. An integrated novel interval type-2 fuzzy MCDM method to improve customer satisfaction in public transportation for Istanbul, *Transportation Research Part E-Logistics and Transportation Review* 58: 28–51. http://dx.doi.org/10.1016/j.tre.2013.06.006

Chai, J.; Liu, J. N. K.; Ngai, E. W. T. 2013. Application of decision-making techniques in supplier selection: A systematic review of literature, *Expert Systems with Applications* 40(10): 3872–3885. http://dx.doi.org/10.1016/j.eswa.2012.12.040

Chang, C.-L.; Hsu, C.-H. 2011. Applying a modified VIKOR method to classify land subdivisions according to watershed vulnerability, *Water Resources Management* 25(1): 301–309. http://dx.doi.org/10.1007/s11269-010-9700-2

Chen, Z.; Abdullah, A. B.; Anumba, C. J.; Li, H. 2014. ANP experiment for demolition plan evaluation, *Journal of Construction Engineering and Management* 140(2). http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000791

Cheng, E. W. L.; Li, H. 2007. Application of ANP in process models: an example of strategic partnering, *Building and Environment* 42(1): 278–287. http://dx.doi.org/10.1016/j.buildenv.2005.07.031

Chitsaz, N.; Banihabib, M. E. 2015. Comparison of different multi criteria decision-making models in prioritizing flood management alternatives, *Water Resources Management* 29(8): 2503–2525. http://dx.doi.org/10.1007/s11269-015-0954-6

Choi, D. J.; Park, H. 2001. Analysis of water privatization scenarios in Korea with multi-criteria decision-making techniques, *Journal of Water Supply Research and Technology-AQUA* 50(6): 335–352.

Chou, C.-C. 2009. Integrated short-term and long-term MCDM model for solving location selection problems, *Journal of Transportation Engineering-ASCE* 135(11): 880–893. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000057

Chou, J.-S.; Chen, H.-M.; Hou, C.-C.; Lin, C. W. 2010. Visualized EVM system for assessing project performance, *Automation in Construction* 19(5 SI): 596–607.

Chung, E.-S.; Lee, K. S. 2009. Identification of spatial ranking of hydrological vulnerability using multi-criteria decision making techniques: case study of Korea, *Water Resources Management* 23(12): 2395–2416. http://dx.doi.org/10.1007/s11269-008-9387-9

Dejus, T.; Antucheviciene, J. 2013. Assessment of health and safety solutions at a construction site, *Journal of Civil Engineering and Management* 19(5): 728–737. http://dx.doi.org/10.3846/13923730.2013.812578

Do, J.-Y.; Kim, D.-K. 2012. AHP-based evaluation model for optimal selection process of patching materials for concrete repair: focused on quantitative requirements, *International Journal of Concrete Structures and Materials* 6(2): 87–100. http://dx.doi.org/10.1007/s40069-012-0009-9

Duckstein, L.; Bobee, B.; Ashkar, F. 1991. A multiple criteria decision modeling approach to selection of estimation techniques for fitting extreme floods, *Stochastic Hydrology and Hydraulics* 5(3): 227–238. http://dx.doi.org/10.1007/BF01544059

Duckstein, L.; Treichel, W.; Elmagnouni, S. 1994. Ranking groundwater-management alternatives by multicriterion analysis, *Journal of Water Resources Planning and Management-ASCE* 120(4): 546–565. http://dx.doi.org/10.1061/(ASCE)0733-9496(1994)120:4(546)

Ebrahimian, A.; Ardeshir, A.; Rad, I. Z.; Ghodsypour, S. H. 2015. Urban stormwater construction method selection using a hybrid multi-criteria approach, *Automation in Construction* 58: 118–128. http://dx.doi.org/10.1016/j.autcon.2015.07.014

Ehrgott, M.; Figueira, J. R.; Greco, S. 2010. *Trends in multiple criteria decision analysis*. New York: Springer. http://dx.doi.org/10.1007/978-1-4419-5904-1

Emovon, I.; Norman, R. A.; Murphy, A. J.; Pazouki, K. 2015. An integrated multicriteria decision making methodology using compromise solution methods for prioritising risk of marine machinery systems, *Ocean Engineering* 105: 92–103. http://dx.doi.org/10.1016/j.oceaneng.2015.06.005

Figueira, J. R.; Greco, S.; Ehrgott, M. (Eds.) 2005. *Multiple criteria decision analysis: state of the art surveys*. Berlin: Springer. http://dx.doi.org/10.1007/b100605

Formisano, A.; Mazzolani, F. M. 2015. On the selection by MCDM methods of the optimal system for seismic retrofitting and vertical addition of existing buildings, *Computers & Structures* 159(1–13). http://dx.doi.org/10.1016/j.compstruc.2015.06.016

Geng, G.; Wardlaw, R. 2013. Application of multi-criterion decision making analysis to integrated water resources management, *Water Resources Management* 27(8): 3191–3207. http://dx.doi.org/10.1007/s11269-013-0343-y

Gercek, H.; Karpak, B.; Kilincaslan, T. 2004. A multiple criteria approach for the evaluation of the rail transit networks in Istanbul, *Transportation* 31(2): 203–228. http://dx.doi.org/10.1023/B:PORT.0000016572.41816.d2

Goicoechea, A.; Stakhiv, E. Z.; Li, F. 1992. Experimental evaluation of multiple criteria decision-models for application to water-resources planning, *Water Resources Bulletin* 28(1): 89–102. http://dx.doi.org/10.1111/j.1752-1688.1992.tb03156.x

Govindan, K.; Rajendran, S.; Sarkis, J.; Murugesan, P. 2015. Multi criteria decision making approaches for green supplier evaluation and selection: a literature review, *Journal of Cleaner Production* 98: 66–83. http://dx.doi.org/10.1016/j.jclepro.2013.06.046

Hanaoka, S.; Kunadhamraks, P. 2009. Multiple criteria and fuzzy based evaluation of logistics performance for intermodal transportation, *Journal of Advanced Transportation* 43(2): 123–153. http://dx.doi.org/10.1002/atr.5670430204

Hao, F.; Chen, G. 2010. A fuzzy multi-criteria group decision-making model based on weighted borda scoring method for watershed ecological risk management: a case study of three Gorges Reservoir Area of China, *Water Resources Management* 24(10): 2139–2165. http://dx.doi.org/10.1007/s11269-009-9544-9

Hernandez, E. A.; Uddameri, V. 2010. Selecting agricultural best management practices for water conservation and quality improvements using atanassov's intuitionistic fuzzy sets, *Water Resources Management* 24(15): 4589–4612. http://dx.doi.org/10.1007/s11269-010-9681-1

Kabak, M.; Kose, E.; Kirilmaz, O.; Burmaoglu, S. 2014. A fuzzy multi-criteria decision making approach to assess building energy performance, *Energy and Buildings* 72: 382–389. http://dx.doi.org/10.1016/j.enbuild.2013.12.059

Kabir, G.; Sadiq, R.; Tesfamariam, S. 2014. A review of multi-criteria decision-making methods for infrastructure management, *Structure and Infrastructure Engineering* 10(9): 1176–1210. http://dx.doi.org/10.1080/15732479.2013.795978

Karamouz, M.; Ahmadi, A.; Yazdi, M. S. S.; Ahmadi, B. 2014. Economic assessment of water resources management strategies, *Journal of Irrigation and Drainage Engineering* 140(1). http://dx.doi.org/10.1061/(asce)ir.1943-4774.0000654

Karamouz, M.; Zahraie, B.; Araghinejad, S. 2005. Decision support system for monthly operation of hydropower reservoirs: a case study, *Journal of Computing in Civil Engineering* 19(2): 194–207. http://dx.doi.org/10.1061/(ASCE)0887-3801(2005)19:2(194)

Karamouz, M.; Zahraie, B.; Kerachian, R. 2003. Development of a master plan for water pollution control using MCDM techniques: a case study, *Water International* 28(4): 478–490. http://dx.doi.org/10.1080/02508060308691725

Kaya, I.; Kahraman, C. 2014. A comparison of fuzzy multicriteria decision making methods for intelligent building assessment, *Journal of Civil Engineering and Management* 20(1): 59–69. http://dx.doi.org/10.3846/13923730.2013.801906

Khelifi, F.; Lodolo, A.; Vranes, S.; Centi, G.; Miertus, S. 2006. A web-based decision support tool for groundwater remediation technologies selection, *Journal of Hydroinformatics* 8(2): 91–100.

Kildiene, S.; Zavadskas, E. K.; Tamosaitiene, J. 2014. Complex assessment model for advanced technology deployment, *Journal of Civil Engineering and Management* 20(2): 280–290. http://dx.doi.org/10.3846/13923730.2014.904813

Kim, Y.; Chung, E.-S.; Jun, S.-M. 2015. Iterative framework for robust reclaimed wastewater allocation in a changing environment using multi-criteria decision making, *Water Resources Management* 29(SI2): 295–311. http://dx.doi.org/10.1007/s11269-014-0891-9

Kumar, T.; Gautam, A. K.; Kumar, T. 2014. Appraising the accuracy of GIS-based multi-criteria decision making technique for delineation of groundwater potential zones, *Water Resources Management* 28(13): 4449–4466. http://dx.doi.org/10.1007/s11269-014-0663-6

Kumru, M.; Kumru, P. Y. 2014. Analytic hierarchy process application in selecting the mode of transport for a logistics company, *Journal of Advanced Transportation* 48(8): 974–999. http://dx.doi.org/10.1002/atr.1240

Kuo, M.-S. 2011. A novel interval-valued fuzzy MCDM method for improving airlines' service quality in Chinese Cross-Strait Airlines, *Transportation Research Part E-Logistics and Transportation Review* 47(6): 1177–1193. http://dx.doi.org/10.1016/j.tre.2011.05.007

Kursunoglu, N.; Onder, M. 2015. Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process, *Tunnelling and Underground Space Technology* 48: 101–109. http://dx.doi.org/10.1016/j.tust.2015.02.005

Lashgari, A.; Fouladgar, M. M.; Yazdani-Chamzini, A.; Skibniewski, M. J. 2011. Using an integrated model for shaft sinking method selection, *Journal of Civil Engineering and Management* 17(4): 569–580. http://dx.doi.org/10.3846/13923730.2011.628687

Lee, Y. W.; Dahab, M. F.; Bogardi, I. 1994. Fuzzy decision-making in-ground water nitrate risk management, *Water Resources Bulletin* 30(1): 135–148. http://dx.doi.org/10.1111/j.1752-1688.1994.tb03280.x

Levy, J. K. 2005. Multiple criteria decision making and decision support systems for flood risk management, *Stochastic Environmental Research and Risk Assessment* 19(6): 438–447. http://dx.doi.org/10.1007/s00477-005-0009-2

Li, F.; Phoon, K. K.; Du, X.; Zhang, M. J. 2013. Improved AHP method and its application in risk identification, *Journal of Construction Engineering and Management-ASCE* 139(3): 312–320. http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000605

Li, X.; Wang, B.; Mehrotra, R.; Sharma, A.; Wang, G. L. 2009. Consideration of trends in evaluating inter-basin water transfer alternatives within a fuzzy decision making framework, *Water Resources Management* 23(15): 3207–3220. http://dx.doi.org/10.1007/s11269-009-9430-5

Lin, S. C. J.; Ali, A. S.; Bin Alias, A. 2015. Analytic hierarchy process decision-making framework for procurement strategy selection in building maintenance work, *Journal of Performance of Constructed Facilities* 29(2). http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0000529

Machiwal, D.; Jha, M. K.; Mal, B. C. 2011. Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques, *Water Resources Management* 25(5): 1359–1386. http://dx.doi.org/10.1007/s11269-010-9749-y

Madani, K.; Read, L.; Shalikarian, L. 2014. Voting under uncertainty: a stochastic framework for analyzing group decision making problems, *Water Resources Management* 28(7): 1839–1856. http://dx.doi.org/10.1007/s11269-014-0556-8

Mardani, A.; Jusoh, A.; Zavadskas, E. K. 2015a. Fuzzy multiple criteria decision-making techniques and applications – two decades review from 1994 to 2014, *Expert Systems with Applications* 42: 4126–4148. http://dx.doi.org/10.1016/j.eswa.2015.01.003

Mardani, A.; Jusoh, A.; Zavadskas, E. K.; Cavallaro, K.; Khalifah, Z. 2015b. Sustainable and renewable energy: An overview of the application of multiple criteria decision making techniques and approaches, *Sustainability* 7(10): 13947–13984. http://dx.doi.org/10.3390/su71013947

Marzouk, M.; Amer, O.; El-Said, M. 2013. Feasibility study of industrial projects using SIMOS' procedure, *Journal of Civil Engineering and Management* 19(1): 59–68. http://dx.doi.org/10.3846/13923730.2012.734855

Medineckiene, M.; Bjork, F. 2011. Owner preferences regarding renovation measures – the demonstration of using multicriteria decision making, *Journal of Civil Engineering and Management* 17(2): 284–295. http://dx.doi.org/10.3846/13923730.2011.582380

Medineckiene, M.; Zavadskas, E. K.; Bjork, F.; Turskis, Z. 2015. Multi-criteria decision-making system for sustainable building assessment/certification, *Archives of Civil and Mechanical Engineering* 15(1): 11–18. http://dx.doi.org/10.1016/j.acme.2014.09.001

Medineckiene, M.; Zavadskas, E. K.; Turskis, Z. 2011. Dwelling selection by applying fuzzy game theory, *Archives of Civil and Mechanical Engineering* 11(3): 681–697. http://dx.doi.org/10.1016/S1644-9665(12)60109-5

Netto, O. C.; Parent, E.; Duckstein, L. 1996. Multicriterion design of long-term water supply in Southern France, *Journal of Water Resources Planning and Management-ASCE* 122(6): 403–413. http://dx.doi.org/10.1061/(ASCE)0733-9496(1996)122:6(403)

Palevicius, V.; Paliulis, G. M.; Venckauskaite, J.; Vengrys, B. 2013. Evaluation of the requirement for passenger car parking spaces using multi-criteria methods, *Journal of Civil Engineering and Management* 19(1): 49–58. http://dx.doi.org/10.3846/13923730.2012.727463

Pinter, U.; Psunder, I. 2013. Evaluating construction project success with use of the M-TOPSIS Method, *Journal of Civil Engineering and Management* 19(1): 16–23. http://dx.doi.org/10.3846/13923730.2012.734849

Pons, O.; Aguado, A. 2012. Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain, *Building and Environment* 53: 49–58. http://dx.doi.org/10.1016/j.buildenv.2012.01.007

Pons, O.; De La Fuente, A. 2013. Integrated sustainability assessment method applied to structural concrete columns, *Construction and Building Materials* 49: 882–893. http://dx.doi.org/10.1016/j.conbuildmat.2013.09.009

Qi, H.; Qi, P.; Altinakar, M. S. 2013. GIS-based spatial Monte Carlo analysis for integrated flood management with two dimensional flood simulation, *Water Resources Management* 27(10): 3631–3645. http://dx.doi.org/10.1007/s11269-013-0370-8

Raju, K. S.; Duckstein, L. 2004. Integrated application of cluster and multicriterion analysis for ranking water resources planning strategies: a case study in Spain, *Journal of Hydroinformatics* 6(4): 295–307.

Raju, K. S.; Duckstein, L.; Arondel, C. 2000. Multicriterion analysis for sustainable water resources planning: a case study in Spain, *Water Resources Management* 14(6): 435–456. http://dx.doi.org/10.1023/A:1011120513259

Raju, K. S.; Kumar, D. N. 2006. Ranking irrigation planning alternatives using data envelopment analysis, *Water Resources Management* 20(4): 553–566. http://dx.doi.org/10.1007/s11269-006-3090-5

Roozbahani, A.; Zahraie, B.; Tabesh, M. 2012. PROMETHEE with Precedence Order in the Criteria (PPOC) as a new group decision making aid: an application in urban water supply management, *Water Resources Management* 26(12): 3581–3599. http://dx.doi.org/10.1007/s11269-012-0091-4

Rousta, B. A.; Araghinejad, S. 2015. Development of a multi criteria decision making tool for a water resources decision support system, *Water Resources Management* 29(15): 5713–5727. http://dx.doi.org/10.1007/s11269-015-1142-4

Ruzgys, A.; Volvaciovas, R.; Ignatavicius, C.; Turskis, Z. 2014. Integrated evaluation of external wall insulation in residential buildings using SWARA-TODIM MCDM method, *Journal of Civil Engineering and Management* 20(1): 103–110. http://dx.doi.org/10.3846/13923730.2013.843585

Shafike, N. G.; Duckstein, L; Maddock, T. 1992. Multicriterion analysis of groundwater contamination management, *Water Resources Bulletin* 28(1): 33–43. http://dx.doi.org/10.1111/j.1752-1688.1992.tb03152.x

Shahriar, A.; Modirzadeh, M.; Sadiq, R.; Tesfamariam, S. 2012. Seismic induced damageability evaluation of steel buildings: a fuzzy-TOPSIS method, *Earthquakes and Structures* 3(5): 695–717. http://dx.doi.org/10.12989/eas.2012.3.5.695

Shelton, J.; Medina, M. 2010. Integrated multiple-criteria decision-making method to prioritize transportation projects, *Transportation Research Record* 2174: 51–57. http://dx.doi.org/10.3141/2174-08

Shiue, Y-Ch.; Lin, Ch-Y. 2012. Applying analytic network process to evaluate the optimal recycling strategy in upstream of solar energy industry, *Energy and Buildings* 54: 266–277. http://dx.doi.org/10.1016/j.enbuild.2012.07.032

Siozinyte, E.; Antucheviciene, J. 2013. Solving the problems of daylighting and tradition continuity in a reconstructed vernacular building, *Journal of Civil Engineering and Management* 19(6): 873–882. http://dx.doi.org/10.3846/13923730.2013.851113

Siozinyte, E.; Antucheviciene, J.; Kutut, V. 2014. Upgrading the old vernacular building to contemporary norms: multiple criteria approach, *Journal of Civil Engineering and Management* 20(2): 291–298. http://dx.doi.org/10.3846/13923730.2014.904814

Sobanjo, J. O; Stukhart, G.; James, R.W. 1994. Evaluation of projects for rehabilitation of highway bridges, *Journal of Structural Engineering-ASCE* 120(1): 81–99. http://dx.doi.org/10.1061/(ASCE)0733-9445(1994)120:1(81)

Soyguder, S.; Alli, H. 2009. An expert system for the humidity and temperature control in HVAC systems using ANFIS and optimization with fuzzy modeling approach, *Energy and Buildings* 41(8): 814–822. http://dx.doi.org/10.1016/j.enbuild.2009.03.003

Staniunas, M.; Medineckiene, M.; Zavadskas, E. K.; Kalibatas, D. 2013. To modernize or not: ecological-economical assessment of multi-dwelling houses modernization, *Archives of Civil and Mechanical Engineering* 13(1): 88–98. http://dx.doi.org/10.1016/j.acme.2012.11.003

Su, H.-T.; Tung, Y.-K. 2014. Multi-criteria decision making under uncertainty for flood mitigation, *Stochastic Environmental Research and Risk Assessment* 28(7): 1657–1670. http://dx.doi.org/10.1007/s00477-013-0818-7

Susinskas, S.; Zavadskas, E. K.; Turskis, Z. 2011. Multiple criteria assessment of pile-columns alternatives, *Baltic Journal of Road and Bridge Engineering* 6(3): 145–152. http://dx.doi.org/10.3846/bjrbe.2011.19

Tamosaitiene, J.; Gaudutis, E. 2013. Complex assessment of structural systems used for high-rise buildings, *Journal of Civil Engineering and Management* 19(2): 305–317. http://dx.doi.org/10.3846/13923730.2013.772071

Tanadtang, P.; Park, D.; Hanaoka, S. 2005. Incorporating uncertain and incomplete subjective judgments into the evaluation procedure of transportation demand management alternatives, *Transportation* 32(6): 603–626. http://dx.doi.org/10.1007/s11116-005-0645-x

Tarlochan, F.; Samer, F.; Hamouda, A. M. S.; Ramesh, S.; Khalid, K. 2013. Design of thin wall structures for energy absorption applications: enhancement of crashworthiness due to axial and oblique impact forces, *Thin-Walled Structures* 71: 7–17. http://dx.doi.org/10.1016/j.tws.2013.04.003

Tecle, A. 1992. Selecting a multicriterion decision-making technique for watershed resources management, *Water Resources Bulletin* 28(1): 129–140. http://dx.doi.org/10.1111/j.1752-1688.1992.tb03159.x

Teng, J.-Y.; Huang, W.-C.; Lin, M.-C. 2010. Systematic budget allocation for transportation construction projects: a case in Taiwan. *Transportation* 37(2): 331–361. http://dx.doi.org/10.1007/s11116-009-9239-3

Terracciano, G.; Di Lorenzo, G.; Formisano, A.; Landolfo, R. 2015. Cold-formed thin-walled steel structures as vertical addition and energetic retrofitting systems of existing masonry buildings, *European Journal of Environmental and Civil Engineering* 19(7): 850–866. http://dx.doi.org/10.1080/19648189.2014.974832

Tesfamariam, S.; Sadiq, R. 2006. Risk-based environmental decision-making using Fuzzy Analytic Hierarchy Process (F-AHP), *Stochastic Environmental Research and Risk Assessment* 21(1): 35–50. http://dx.doi.org/10.1007/s00477-006-0042-9

Ulubeyli, S.; Kazaz, A. 2009. A multiple criteria decision-making approach to the selection of concrete pumps, *Journal of Civil Engineering and Management* 15(4): 369–376. http://dx.doi.org/10.3846/1392-3730.2009.15.369-376

Um, I. S.; Cheon, H. J.; Lee, H. C. 2011. A simulation-based optimal design and analysis method for designing a train overhaul maintenance facility, *Proceedings of the Institution of Mechanical Engineers Part F-Journal of Rail and Rapid Transit* 225(F5): 523–539. http://dx.doi.org/10.1243/09544097JRRT309

Vamvakeridou-Lyroudia, L. S.; Savic, D. A.; Walters, G. A. 2006. Fuzzy hierarchical decision support system for water distribution network optimization, in 8th International Conference on Computing and Control for the Water Industry, *Civil Engineering and Environmental Systems* 23(3): 237–261. http://dx.doi.org/10.1080/10286600600789706

Verma, M.; Rajasankar, J.; Anandavalli, N.; Prakash, A.; Iyer, N. R. 2015. Fuzzy similarity approach for ranking and health assessment of towers based on visual inspection, *Advances in Structural Engineering* 18(9): 1399–1414. http://dx.doi.org/10.1260/1369-4332.18.9.1399

Wang, Y.; Deng, X.; Marcucci, D. J.; Le, Y. E. 2013. Sustainable development planning of protected areas near cities: case study in China, *Journal of Urban Planning and Development-ASCE* 139(2): 133–143. http://dx.doi.org/10.1061/(ASCE)UP.1943-5444.0000133

Wiecek, M. M.; Ehrgott, M.; Fadel, G.; Figueira, J. R. 2008. Multiple criteria decision making for engineering, *Omega* 36: 337–339. http://dx.doi.org/10.1016/j.omega.2006.10.001

Woldt, W.; Bogardi, I. 1992. Ground-water monitoring network design using multiple criteria decision-making and geostatistics, *Water Resources Bulletin* 28(1): 45–62. http://dx.doi.org/10.1111/j.1752-1688.1992.tb03153.x

Wong, J.; Li, H.; Lai, J. 2008a. Evaluating the system intelligence of the intelligent building systems - Part 1: development of key intelligent indicators and conceptual analytical framework, *Automation in Construction* 17(3): 284–302. http://dx.doi.org/10.1016/j.autcon.2007.06.002

Wong, J.; Li, H.; Lai, J. 2008b. Evaluating the system intelligence of the intelligent building systems - Part 2: construction and validation of analytical models, *Automation in Construction* 17(3): 303–321. http://dx.doi.org/10.1016/j.autcon.2007.06.003

Yakar, F.; Celik, F. 2014. A highway alignment determination model incorporating GIS and multi-criteria decision making, *KSCE Journal of Civil Engineering* 18(6): 1847–1857. http://dx.doi.org/10.1007/s12205-014-0130-1

Yazdani-Chamzini, A.; Yakhchali, S. H. 2012. Tunnel boring machine (TBM) selection using fuzzy multicriteria decision making methods, *Tunnelling and Underground Space Technology* 30: 194–204. http://dx.doi.org/10.1016/j.tust.2012.02.021

Zagorskas, J.; Zavadskas, E. K.; Turskis, Z.; Burinskiene, M.; Blumberga, A.; Blumberga, D. 2014. Thermal insulation alternatives of historic brick buildings in Baltic Sea region, *Energy and Buildings* 78: 35–42. http://dx.doi.org/10.1016/j.enbuild.2014.04.010

Zak, J. 2011. The methodology of multiple criteria decision making/aiding in public transportation, *Journal of Advanced Transportation* 45(1): 1–20. http://dx.doi.org/10.1002/atr.108

Zarghami, M.; Szidarovszky, F. 2009. Stochastic-fuzzy multi criteria decision making for robust water resources management, *Stochastic Environmental Research and Risk Assessment* 23(3): 329–339. http://dx.doi.org/10.1007/s00477-008-0218-6

Zavadskas, E. K.; Antucheviciene, J.; Kapliński, O. 2015. Multi-criteria decision making in civil engineering: Part I – a state-of-the- art survey, *Engineering Structures and Technologies* 7(3): 103–113.

Zavadskas, E. K.; Antucheviciene, J. 2007. Multiple criteria evaluation of rural building's regeneration alternatives, *Building and Environment* 42(1): 436–451. http://dx.doi.org/10.1016/j.buildenv.2005.08.001

Zavadskas, E. K.; Susinskas, S.; Daniunas, A.; Turskis, Z.; Sivilevicius, H. 2012. Multiple criteria selection of pile-column construction technology, *Journal of Civil Engineering and Management* 18(6): 834–842. http://dx.doi.org/10.3846/13923730.2012.744537

Zavadskas, E. K.; Turskis, Z. 2011. Multiple criteria decision making (MCDM) methods in economics: an overview, *Technological and Economic Development of Economy* 17(2): 397–427. http://dx.doi.org/10.3846/20294913.2011.593291

Zavadskas, E. K.; Turskis, Z.; Tamosaitiene, J. 2011. Selection of construction enterprises management strategy based on the SWOT and Multi-Criteria Analysis, *Archives of Civil and Mechanical Engineering* 11(4): 1063–1082. http://dx.doi.org/10.1016/S1644-9665(12)60096-X

Zavadskas, E. K.; Turskis, Z.; Vilutiene, T. 2010. Multiple criteria analysis of foundation instalment alternatives by applying Additive Ratio Assessment (ARAS) Method, *Archives of Civil and Mechanical Engineering* 10(3): 123–141. http://dx.doi.org/10.1016/S1644-9665(12)60141-1

Zavadskas, E. K.; Vilutiene, T.; Turskis, Z.; Saparauskas, J. 2014. Multi-criteria analysis of projects' performance in construction, *Archives of Civil and Mechanical Engineering* 14(1): 114–121. http://dx.doi.org/10.1016/j.acme.2013.07.006

Edmundas Kazimieras ZAVADSKAS is Professor, Head of the Department of Construction Technology and Management at Vilnius Gediminas Technical University, Vilnius, Lithuania, and a chief researcher at Research Institute of Smart Buildings Technologies. He has a PhD in building structures (1973) and DrSc (1987) in building technology and management. He is a member of the Lithuanian and several foreign Academies of Sciences. He is Doctor Honoris Causa at Poznan, Saint-Petersburg, and Kiev universities. He is Editor in Chief and a member of editorial boards of a number of research journals. He is author and co-author of more than 500 papers and a number of monographs. Research interests are: building technology and management, decision-making theory, automation in design and decision support systems.

Oleg KAPLIŃSKI is Professor of Civil Engineering at Faculty of Architecture (IAP), Poznan University of Technology, Poznan, Poland. He lectures economics and organization of the investment process, as well as the theory and principles of work places design. The author of 240 publications. Doctor Honoris Causa of VGTU (1996). Member of the CE Committee of the Polish Academy of Sciences. His current research are: an integral management, integral design, risk management, theory of decision making and research methods in CE and architecture.

Jurgita ANTUCHEVIČIENĖ is Professor at the Department of Construction Technology and Management at Vilnius Gediminas Technical University, Vilnius, Lithuania. She received a PhD in Civil Engineering in 2005. She is author and co-author of about 80 scientific papers. Research interests include: multiple criteria analysis, decision-making theories and decision support systems, sustainable development, construction management and investment.