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Review

Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends

Ivy B. Huang [a], Jeffrey Keisler [b], Igor Linkov [c,*]

[a] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139 United States
[b] College of Management, University of Massachusetts Boston, 100 Morrissey Boulevard, Boston, MA 02125 United States
[c] US Army Engineer Research and Development Center, 3909 Halls Ferry Rd, Vicksburg, MS 39180, United States

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ABSTRACT

Decision-making in environmental projects requires consideration of trade-offs between socio-political, environmental, and economic impacts and is often complicated by various stakeholder views. Multi-criteria decision analysis (MCDA) emerged as a formal methodology to face available technical information and stakeholder values to support decisions in many fields and can be especially valuable in environmental decision making. This study reviews environmental applications of MCDA. Over 300 papers published between 2000 and 2009 reporting MCDA applications in the environmental field were identified through a series of queries in the Web of Science database. The papers were classified by their environmental application area, decision or intervention type. In addition, the papers were also classified by the MCDA methods used in the analysis (analytic hierarchy process, multi-attribute utility theory, and outranking). The results suggest that there is a significant growth in environmental applications of MCDA over the last decade across all environmental application areas. Multiple MCDA tools have been successfully used for environmental applications. Even though the use of the specific methods and tools varies in different application areas and geographic regions, our review of a few papers where several methods were used in parallel with the same problem indicates that recommended course of action does not vary significantly with the method applied.

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* Corresponding author. Tel.: +1 617 233 9869.
E-mail address: Igor.Linkov@usace.army.mil (I. Linkov).

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1. Introduction

Environmental decisions are often complex and draw upon multidisciplinary knowledge bases which incorporate natural, physical social sciences, politics, and ethics. Environmental decision makers rely on many experimental tests, computational models, and tools to assess human health and ecological risks associated with environmental stressors and the impact of remedial and abatement strategies on risk reduction. However, applying these tools is becoming increasingly difficult for three reasons. First, there are many emerging risks (e.g., climate change, nanotechnology, etc.) for which information is not available and decisions should be made under significant uncertainty. Second, for many traditional stressors and situations multiple lines of evidence regarding the same measure (e.g., risk) are available, but they may point to different management alternatives. Finally, stakeholders, who may have vested interest in specific courses of action, are gaining increased access to all available information and, given the data uncertainty, can justify often opposing courses of action. As such, integration the heterogeneous and uncertain information demands a systematic and understandable framework to organize the technical information and requires expert judgment.

Multi-criteria decision analysis (MCDA) provides a systematic methodology to combine these inputs with cost/benefit information and stakeholder views to rank project alternatives. MCDA is used to discover and quantify decision maker and stakeholder considerations about various (mostly) non-monetary factors in order to compare alternative courses of action. There are numerous approaches that all fall under the umbrella of MCDA, each involving different protocols for eliciting inputs, structures to represent them, algorithms to combine them, and processes to interpret and use formal results in actual advising or decision making contexts. Linkov et al. (2004, 2006) reviewed the application of MCDA in environmental management focusing on management of contaminated sites published in 1992–2002. MCDA techniques have been applied to optimize policy selection in the remediation of contaminated sites, the reduction of contaminants entering aquatic ecosystems, the optimization of water and coastal resources, and the management of other resources. In some of these studies, the researchers have explicitly taken into account the opinions of local community groups and other stakeholders through focus groups, surveys, and other techniques and formally integrated these opinions into the decision process. Many papers concluded that the application of MCDA methods provides a significant improvement in the decision process and public acceptance of the suggested remedial or abatement policy.

The last decade brought not only an increased interest in the application of formalized decision-analytical tools, but also better structured and complete databases. The goal of this paper is to review the recent literature and identify current trends in MCDA applications to environmental management, and to discuss the possible reasons that the various methods are gaining attention in different applications. In 2003, our search strategy was to find MCDA applications by all means, including searching gray literature. The current challenge was to limit the number of papers for the analysis to a manageable size but still objectively represent the state of the applications. Similar to Linkov et al. (2004), we consider three main MCDA approaches: MAUT, Outranking (including PROMETHEE and ELECTRE), and AHP. These approaches share common mathematical elements, i.e., values for alternatives are assigned for a number of dimensions, and then multiplied by weights and finally combined to produce a total score. The approaches differ significantly in the details of how values are assigned and combined, meaning that the processes have different information – and knowledge – requirements and the calculated scores have different mathematical properties and thus slightly different meanings. Practitioners often view one of the various approaches as most appropriate due to the priority they place on its relative strengths and weaknesses. (e.g., Figueira et al., 2005; Belton and Stewart, 2002).

2. MCDA methods

MCDA approaches typically require as inputs: scores across several dimensions associated with different alternatives and outcomes; weights relating to tradeoffs across these dimensions. A basic but typical approach is to calculate the total value score for an alternative as a linear weighted sum of its scores across several criteria, i.e., $V = \Sigma_i w_i x_i$, where $\Sigma_i w_i = 1$. Also common (though not universal) is a hierarchical structure (as in value hierarchies described in Keeney, 1992, and essential to the Analytic Hierarchy Process, Saaty, 1994) so that, for example, dimension i is broken down into several subdimensions j, x_{ij} is the alternative's score on the jth subdimension of dimension i, $v_i = \Sigma_i w_{ij} x_{ij}$, and $V = \Sigma_i w_i v_i$.

MAUT, or Multi-Attribute Utility Theory (Keeney and Raiffa, 1976) adds another layer into the model, transforming scores at any level into utility functions (following axioms of von Neumann and Morgenstern, 1944). In a simple case where there is no hierarchical structure and no interactions between attributes, an alternative would have utility $U = \Sigma_i w_i u_i (x_i)$, where the x_i is typically normalized to a range from the worst to best possible values, and u_i ranging from 0 to 1 reflects the decision maker's attitude toward risk within attribute i. Various techniques allow for more sophisticated MAUT models. With a unitary decision maker who is able to clearly express preferences over gambles and clear tradeoffs for specific levels of achievement across dimensions, this approach facilitates rational choices in the sense that the course of action with the highest expected utility would also be the most preferred alternative consistent with the axioms of decision theory.

Outranking approaches PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) and ELECTRE (ELimination and Choice Expressing Reality) are methods that essentially involve holding various "votes" across dimensions. The range of possible scores for different alternatives is considered within each dimension, to derive alternatives that can be combined across dimensions. An alternative's relative score on a specific dimension is thus a function of how well it compares against the set of other alternatives (e.g., its *net flow*, which relates to its performance against other alternatives on that dimension). Then weights are applied across dimensions to come up with an overall attractiveness for each alternative, which may be interpreted as a level of confidence or agreement or in other ways. Variations on outranking methods have used fuzzy intervals for weights or performance scores, in which net flows can be thought of as probabilistic and dependent on how results of a voting process on various dimensions and across dimensions can change as different values are assumed. In contrast to MAUT, the scores calculated with the three voting-type methods are not usually aimed to identify a single correct answer, but rather to drive a deliberative process between multiple stakeholders.

AHP (Saaty, 1994), or the Analytic Hierarchy Process (and its extension the Analytic Network Process). This is a family of approaches that uses pairwise comparisons of criteria which ask how much more important one is than the other (this is generally thought to be simple, and can be flexible when multiple stakeholders are involved). AHP and ANP can function even with incomplete or inconsistent inputs, by using matrix algebra (involving either eigenvalue-based or similar calculation methods, Ishizaka and Lusti, 2006), to produce weights, overall scores, and measures of consistency. Like other MCDA approaches, AHP produces scores for each alternative; in some cases, it is theoretically possible for the alternatives to change order depending on how other aspects of the problem are structured, so these scores are not necessarily interpreted exactly the same as MAUT scores.

The TOPSIS (Technique for Order Preference by Similarity, Hwang and Yoon, 1981) family of methods compares a set of alternatives by identifying weights for each dimension, normalizing scores in each dimension and calculating a distance between each alternative and the ideal alternative (best on each dimension) and the negative ideal alternative (worst) across the weighted dimensions, using one of several possible distance measures (e.g., Euclidean distance). Finally, the ratio between the distance (separation) from the negative ideal and the sum distance from the ideal and negative ideal alternatives is calculated. This ratio is used to calculate alternatives. Benefits of TOPSIS include the facts that the only judgments required are weights, while relative distances depend on the weights and on the range of alternatives themselves, and the non-linear relationship between single dimension scores and distance ratios produces smoother tradeoffs.

Our motivation for this study is to understand what methods were applied in recent years, and where. This has relevance for MCDA researchers and practitioners, as well as for users and potential users of MCDA. For practitioners and researchers, examining recent trends is useful not only to identify where one might find success and a good reception, but also for understanding the reasons for these trends so as to improve the effectiveness of applications in the future. For users, such a study is useful to understand whether a given project is a good candidate for MCDA, which type of approach might be suitable, and where similar applications might be found. Following the direct interpretation of the data from this review, we offer more general judgments about desirable directions for the field based on our reading of the literature.

3. Literature review

Our goal was to conduct a state-of-the-application review of MCDA in the environmental field, identifying trends and tools to aid future decision makers in their applications. The growth of MCDA applications was examined over the last two decades, while detailed analysis of applications based on a developed taxonomy describing MCDA approaches practiced in the field was conducted for papers published in 2000–2009.

3.1. Search methodology

The majority of the scholarly articles came from the Web of Science (WOS) database, which accesses articles from over 10,000 journals worldwide (Reuters, 2010). In addition, Journal of Multi-criteria decision analysis and Integrated Environmental Assessment and Management were searched separately since they are not part of the Web of Science database and publish important papers in the field. The initial search included queries using a combination of MCDA keywords (Table 1) and resulted in 22,159 papers. The results were refined by environmental subject areas provided by WOS, which included Environmental Science, Environmental Studies, Environmental Engineering as well as by subject areas corresponding to decision analysis in general, including Social Science and Mathematical Models, Management Science, and Operation Research and Management Sciences. Queries in the non-environmental subject areas were further refined by adding environmental phrases to the searches listed in Table 1.

Results for papers published in 1990–2000 and in 2000–2009 returned a total of 242 and 765 papers, respectively. Papers published in 1990–2000 were used for historical trend analysis only and were not further classified. Abstracts for papers published in 2000–2009 were screened manually to avoid irrelevant papers with similar phrasings. Of the 461 selected papers, only 412 papers were made available through Google Scholar and the Massachusetts Institute of Technology and Harvard University library system. The full-text papers were reviewed and an additional 100 papers were eliminated based on the application criteria. The final paper count yielded a total of 312 papers.

3.2. Classification scheme

The 312 articles were first classified by the MCDA method used and application area (Table 2). In terms of methods, the papers were categorized based on the MCDA keywords used in the search query such as:

- *AHP/ANP*, *MAUT/MAVT*, *PROMETHEE*, *ELECTRE*, or *TOPSIS*;
- *Others* if other general MCDA tools were used, such as DEMATEL, NAIADE, and DELPHI;
- *Multiple* if several tools were used in one application; or
- *Review* if the use of MCDA for applications was discussed, but no actual case study was presented.

In terms of application area, the papers were classified in three categories based on the emphasis of the research topic presented and the overall scope of the application case study discussed:

- *Environmental Problem* includes application of the MCDA tool focused on waste, water, air, energy, or natural resources management/quality;
- *Intervention Type* focuses on stakeholder participation, sustainable manufacturing/engineering technology, remediation/restoration initiatives, or other strategies, for example life cycle assessment;

Table 1
MCDA search key words and phrases used in the web of science queries. Searches in non-environmental subject areas were refined by environmental phrases. Queries 1–3 were completed using the ISI Web of Science database, and Queries 4 and 5 were completed using the JMCDA and IEAM.

	MCDA keywords		Environmental phrases		Subject areas
Queries 1, 2, 3, 4 and 5	MCDA or Multi criteria decision analysis	Queries 2 and 3	Contamin* or remediat*	Query 1	Environmental sciences
	MCDM or multi criteria decision making		Ecosystem		Environmental studies
	AHP or Analytic hierarchy process		Land		Engineering, environmental
	Outranking		Nano*	Query 2	Social sciences, mathematical methods
	MAUT or Multi-attribute utility theory		Site select*	Query 3	Management science
	MAVT or Multi-attribute value theory		Sustainab*		Operations research and management sciences
	ELECTRE		Waste		
	ANP or analytic network process		Water or coastal		
	Swing weight*		Natural resource*		
	Expected utility		Risk and environ*		
	TOPSIS or Technique for Order Preference by Similarity to Ideal Solution		Aquatic or terrestrial		
	SMAA or Stochastic multicriteria acceptability analysis		Energy		
	PROMETHEE or Preference Ranking Organisation Method for Enrichment Evaluations		Emission or atmosph*		

Table 2
Distribution of MCDA papers by methods and applications.

		AHP/ANP	MAUT/MAVT	PROMETHEE	ELECTRE	Topsis	Multiple	Review	Other	Total
Environmental problem	Waste management	15	5	4	0	0	1	1	4	30
	Water quality/management	4	7	1	2	0	4	0	3	21
	Air quality/emissions	0	1	6	0	0	1	1	1	10
	Energy	14	3	4	3	1	2	2	4	33
	Natural resources	7	1	0	0	0	1	3	2	14
Intervention type	Stakeholders	16	5	1	2	0	3	6	0	33
	Strategy	22	12	6	3	2	3	5	3	56
	Sustainable Manufacturing/engineering	18	2	0	1	2	2	1	2	28
	Remediation/restoration	4	5	1	2	0	1	1	1	15
Complementary tools	Spatial/GIS	24	5	0	0	0	0	1	0	30
	Environmental impact assessment	26	5	2	1	0	2	3	3	42
	Total	150	51	25	14	5	20	24	23	312

- *Complementary tools* focuses non-MCDA methods that complement it, such as environmental impact assessment or applied spatial/GIS analysis.

4. Results and discussion

This section starts with the analysis of historical environmental MCDA publishing trends in 1990–2010. A detailed analysis by specific MCDA method used and application area was conducted only for 2000–2009 time period. Proportions were calculated both ways to determine if either MCDA methods or application areas were disproportionately represented in a given field (Tables 3 and 4).

4.1. Growth of MCDA papers in environmental field

The total number of papers that mention one of the MCDA methods increased from single digit numbers in early 1990s to hundreds towards the late 2000s (Fig. 1, Table 5). One of the reasons could be the overall increase of the total number of papers in the WOS database that are focused on environmental issues. Indeed, the total number of environmental papers (found though a search using only *environ** as the keyword) has increased from few thousands in early 1990s to over tens of thousands in late 2000s. Nevertheless, the fraction of MCDA papers within environmental papers in the WOS database is steadily growing. The ratio in Table 5 was calculated by dividing the number of MCDA papers to the total number of environmental papers published in a specific year and normalized to the ratio in 1990. Fig. 1 shows a relatively slow but steady increase during the first decade (from 1 to about 2.5) and escalated growth during the second decade (from 2.5 to over 8). This observation clearly confirms our hypothesis that the number of MCDA papers published in the environmental field has been growing significantly over the last two decades.

4.2. Trends by MCDA methods

The percentage distribution of MCDA methods per application area is shown in Table 3. In terms of the total number of papers published, AHP/ANP dominates at 48%; MAUT and Outranking (combined ELECTRE and PROMETHEE) are at 16% and 13%, respectively. AHP has its highest penetration, at 80%, in spatial/GIS papers. Only in air quality/emissions is PROMETHEE used more widely than AHP (dominating 60% of the category that includes 10 papers only). Though a distant second in terms of papers published, MAUT/MAVT is evenly distributed across all the application areas. Review papers also appear to be disproportionately represented in the stakeholders and natural resources category. Except for TOPSIS, which only appears in three application areas due to the limited number of papers published, the remaining MCDA methods are well distributed across most of the categories.

We also quantified the chronological distribution of MCDA methods between 2000 and 2009 (Table 6). Except for TOPSIS, which only appears after 2004, the annual increase of papers in most of the methods is fairly steady over the last decade. We observed that the percentage of AHP/ANP papers increased from about 15% in 2000 to over 40% in 2002 and has dominated MCDA methods ever since.

4.3. Trends by MCDA application areas

The percentage distribution of MCDA application areas by method is shown in Table 4. Most of the MCDA methods are evenly distributed across the 11 application areas. Our observations from the previous section also hold, with air quality/emissions, stakeholders, and spatial/GIS penetrating PROMETHEE, Review, and AHP/ANP papers, respectively.

Table 7 summarizes the chronological trend in the number of MCDA papers published by application area. The growth of each

Table 3
Percentage distribution of MCDA methods per application area.

	AHP/ANP	MAUT/MAVT	PROMETHEE	ELECTRE	TOPSIS	Multiple	Review	Other	Total
Waste management	50%	17%	13%	0%	0%	3%	3%	13%	100%
Water quality/management	19%	33%	5%	10%	0%	19%	0%	14%	100%
Air quality/emissions	0%	10%	60%	0%	0%	10%	10%	10%	100%
Energy	42%	9%	12%	9%	3%	6%	6%	12%	100%
Natural resources	50%	7%	0%	0%	0%	7%	21%	14%	100%
Stakeholders	48%	15%	3%	6%	0%	9%	18%	0%	100%
Strategy	39%	21%	11%	5%	4%	5%	9%	5%	100%
Sustainable manufacturing/engineering	64%	7%	0%	4%	7%	7%	4%	7%	100%
Remediation/restoration	27%	33%	7%	13%	0%	7%	7%	7%	100%
Spatial/GIS	80%	17%	0%	0%	0%	0%	3%	0%	100%
Environmental impact assessment	62%	12%	5%	2%	0%	5%	7%	7%	100%

Table 4
Percentage distribution of MCDA application areas by method.

	AHP/ANP	MAUT/MAVT	PROMETHEE	ELECTRE	TOPSIS	Multiple	Review	Other
Strategy	15%	24%	24%	21%	40%	15%	21%	13%
Environmental impact assessment	17%	10%	8%	7%	0%	10%	13%	13%
Energy	9%	6%	16%	21%	20%	10%	8%	17%
Stakeholders	11%	10%	4%	14%	0%	15%	25%	0%
Spatial/GIS	16%	10%	0%	0%	0%	0%	4%	0%
Waste management	10%	10%	16%	0%	0%	5%	4%	17%
Sustainable manufacturing/engineering	12%	4%	0%	7%	40%	10%	4%	9%
Water quality/management	3%	14%	4%	14%	0%	20%	0%	13%
Remediation/restoration	3%	10%	4%	14%	0%	5%	4%	4%
Natural resources	5%	2%	0%	0%	0%	5%	13%	9%
Air quality/emissions	0%	2%	24%	0%	0%	5%	4%	4%
Total	100%	100%	100%	100%	100%	100%	100%	100%

MCDA application area appears to be evenly distributed across the decade. In terms of proportions, only the Environmental Impact Assessment and Strategy categories appear to have a slight edge over the other application areas.

4.4. Geographic analysis of MCDA papers

We also analyzed the distribution of MCDA papers by geographic region. Each paper was assigned a country and continent based on its primary author's place of employment at the time of publication. The result of this analysis is summarized in Table 8, where the distribution of MCDA methods is organized by continent. Europe and Asia dominated the publication of MCDA papers in the environmental field, with 38% and 31%, respectively. In terms of the number of papers published, Europe dominated all the other continents across most of the MCDA methods. However, Fig. 2 shows a few significant exceptions. For example, in Asia and North America, the majority of the field is penetrated by AHP/ANP. In contrast, MAUT/MAVT appears to have a slight edge over AHP/ANP in Europe.

4.5. Influence of multiple methods on decision analysis

Twenty papers out of 312 attempted to apply several MCDA methods to the same decision problem (Table 9). Of the 20 papers we categorized as Multiple, the majority of the papers (~ 85%) employed 2 or 3 methods. Even though application of different methods to the same problem could result in different prioritization of management alternatives, we found that in general the top few alternatives are the same no matter which MCDA methods is used. In a few cases where the top alternative was different, we still observe significant overlaps in their top four alternatives. We also observed that this overlap decreases as the number of alternatives increases. This confirms a mathematical phenomenon (e.g., explored in Triantaphyllou, 2000 and Keisler, 2008), whereby the top alternative (or group of alternatives) is often superior enough that the finer distinctions between methods are not large enough to substantially change rankings — especially because those distinctions are as likely to help as to hurt the score of any given alternative within a given performance dimension (as it is hard to imagine all methods actually being biased toward a single choice). When such robustness is present, decision makers may select methods based on considerations such as ease of use, familiarity, effect on group dynamics, and likely user acceptance of results. For example, identifying the right stakeholders may be the key to making the right choice. The robustness across approaches falls away when objectives are strongly in conflict or otherwise closely interrelated and must be carefully characterized, or where scales of activity are large enough from the perspective of the decision maker (or society) that non-linear values (i.e., utilities) must be carefully characterized in order to correctly identify the most desirable course of action. Beyond these general guidelines, future mathematical

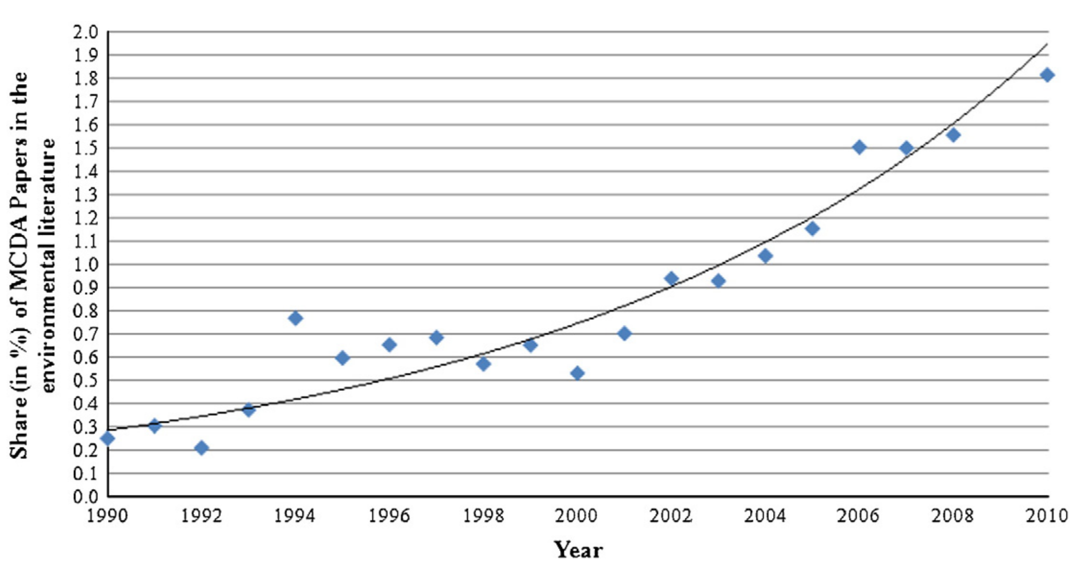

Fig. 1. Ratio of MCDA to Total Environmental Publications in WOS Database normalized to 1990 value. 2010 data are estimated based on first quarter publications.

Table 5
Growth of MCDA applications in the environmental field. Results were obtained using the ISI Web of Science database. Ratio normalized to 1990 value–2010 value based on first quarter estimates.

Year	Number of MCDA papers	Total number of environmental papers	Percentage = MCDA/total	Normalized ratio
1990	2	807	0.25	0.99
1991	7	2323	0.30	1.21
1992	5	2414	0.21	0.83
1993	10	2704	0.37	1.48
1994	23	3008	0.76	3.06
1995	22	3709	0.59	2.37
1996	24	3691	0.65	2.60
1997	31	4550	0.68	2.73
1998	26	4755	0.55	2.19
1999	34	5395	0.63	2.52
2000	26	4885	0.53	2.13
2001	35	5234	0.67	2.67
2002	54	5929	0.91	3.64
2003	57	6207	0.92	3.67
2004	59	6136	0.96	3.85
2005	89	7633	1.17	4.66
2006	94	8190	1.15	4.59
2007	123	8317	1.48	5.92
2008	169	10,791	1.57	6.26
2009	211	11,231	1.88	7.51
2010	200	12,068	1.66	6.63

and empirical research could focus on identifying conditions under which distinctive qualities of each method lead to substantial improvements in decision quality.

5. Conclusion

5.1. Summary

Our review shows that the application of MCDA tools in environmental science has grown significantly over the last two decades. Accounting for the overall growth in environmental publications between 1990 and 2009, we estimated a steady annual percentage growth with the fraction (or share) of MCDA papers increasing by a factor of 7.5. The growth rate was relatively slow but steady in 1990–1999, while significant acceleration is observed during the last decade. Even though the detailed analysis is outside of the scope of this paper, we believe that this growth can be attributed to both increased decision complexity and information availability and regulatory and stakeholders push for transparency in the decision-making process. For example, National Academy of Science has continuously called for the use of formal decision-analytical tools in the environmental decision process (National Research Council, 2009).

All application areas within the environmental field show a significant increase in the number of published papers. Applications that require strategy development, stakeholder engagement, and integrated environmental assessment are more dominant, which is natural due to the interdisciplinary nature of environmental problems. We believe that decision analysis using MCDA tools allows the users to solve complex problems in a technically valid and practically useful manner. Therefore, we view the broad-based increase in the number of environmental MCDA papers as a promising development.

The use of all major MCDA methods (MAUT, outranking and AHP) has significantly expanded over the last decade. In selecting a particular MCDA approach from the possibilities discussed here, it is important to consider the complexity of the decision in terms of scientific, social, and technical factors, as well as understanding the process needs and the level of available knowledge about the problem space. Nevertheless, selection of specific methods in practice seems to be driven by availability of specific expertise and software tools. Even though AHP/ANP is widely recognized to have major limitations (Barzilai, 1997), we observed that it has historically dominated MCDA applications accounting for almost half of the 312 papers. The wide use of AHP may be related to the availability of user-friendly and commercially supported software packages and enthusiastic and engaged user groups. But other situational factors are also important. For example, Europe has a stronger theoretical school and a varied MCDA culture as compared to North America, and this wider range of options may explain why AHP is not so dominant there. An important observation derived from our review of papers that implement several MCDA tools is that all of them tend to favor the same alternatives. This observation is consistent with our previous studies (Linkov et al., 2006; Yatsalo et al., 2007).

5.2. Recommendations

Beyond what could be measured numerically, there are two qualitative observations from the review that relate to the question of how the field of MCDA could progress.

First, we note that the approaches are somewhat similar enough and the differences in the choice of their application may be based more on familiarity and available opportunities than solely on the merits of the different methods themselves. Perhaps the field would benefit if the various tools were better integrated, i.e., shared a single vocabulary, had more compatibility of similar mathematical objects, while keeping as variations those process differences that provide distinct benefits. This would allow decision makers to more rapidly learn about and gain trust in methods. In addition, such integration gives practitioners richer choices for how to proceed. For example, Logical Decisions MCDA software allows users to structure part of a model using AHP methods for convenience, while allowing use of MAUT for transparent calculations. An integrated toolkit would allow a contingent approach such as the decision quality framework (Howard, 1988) to identify the variations that best suit the needs of

Table 6
Distribution of MCDA papers by methods between 2000 and 2009.

Year	AHP/ANP	MAUT/MAVT	PROMETHEE	ELECTRE	TOPSIS	Multiple	Review	Other	Total
2000	2	5	1	1	0	1	2	1	13
2001	4	3	0	0	0	1	2	1	11
2002	9	4	2	0	0	2	0	1	18
2003	10	3	2	2	0	2	1	2	22
2004	10	1	3	1	0	1	4	1	21
2005	13	4	2	1	1	2	1	2	26
2006	10	6	4	1	2	1	6	3	33
2007	28	9	5	3	0	1	2	6	54
2008	27	10	1	4	1	2	2	2	49
2009	37	6	5	1	1	7	4	4	65
Total	150	51	25	14	5	20	24	23	312

Table 7
Distribution of MCDA papers by application area between 2000 and 2009.

Year	Strategy	Environmental impact	Assessment energy	Stakeholders	Spatial/ GIS	Waste management	Sustainable manufacturing/ engineering water	Quality/ management	Remediation/ restoration	Natural resources	Air quality/ emissions	Total
2000	4	1	2	0	1	0	0	1	1	3	0	13
2001	3	3	0	0	2	1	0	0	0	0	2	11
2002	2	4	0	4	1	3	1	1	1	0	1	18
2003	7	2	3	3	2	1	2	1	1	0	0	22
2004	1	6	2	2	1	3	0	3	0	2	1	21
2005	4	2	1	3	5	0	3	3	1	3	1	26
2006	6	4	2	5	3	2	2	4	2	1	2	33
2007	11	6	7	6	0	9	5	4	3	2	1	54
2008	6	4	5	6	10	5	8	1	3	0	1	49
2009	12	10	11	4	5	6	7	3	3	3	1	65
Total	56	42	33	33	30	30	28	21	15	14	10	132

Table 8
Distribution of MCDA methods by continent. A total of 41 unique countries and 22 different U.S. states were examined. Continents are listed in decreasing number of paper frequency.

	Europe	Asia	North America	Australia	Africa	South America	Total
AHP/ANP	28	74	33	8	5	2	150
MAUT/MAVT	31	6	8	4	1	1	51
PROMETHEE	14	1	3	6	0	1	25
ELECTRE	12	1	1	0	0	0	14
TOPSIS	0	3	1	1	0	0	5
Multiple	8	6	1	2	3	0	20
Review	15	1	6	2	0	0	24
Other	12	5	3	3	0	0	23
Total	120	97	56	26	9	4	312

a particular decision situation, such as adequately framing the problem, generating alternatives, acquiring and structuring information, facilitating dialog and clarity about values, and generating agreement and commitment to action (along with other dimensions salient in MCDA, e.g., democracy of the process). Alternatively, the related idea of requisite decision modeling methods (Phillips, 1984), which have already been used with some MCDA applications, could be more easily applied if there were a larger set of mutually compatible modeling choices. Thus, while the diversity of approaches represents a vibrant field, it also causes friction and it may be the right point in the development of MCDA for efforts at synthesis.

One of the initial hopes for this study was to learn about effectiveness of MCDA efforts. However, the literature consists primarily of descriptions of how models were applied or of theoretical innovations. Other than the fact that successful applications are more likely to be published (which also means that they present censored data), there is scant data about what makes some efforts more effective than others. In order to make better judgments about the relative strengths that are possible from simple inspection, and in order to identify the situations in which different strengths are critical to successful projects and decisions, we advocate a program of empirical research. There are isolated examples using action learning (Montibeller et al., 2006), paired experiments (Kiesling et al., 2011), and surveys (Bond et al., 2010) to compare numerical results that would arise from two approaches applied to the same data. Additionally, there are numerous reflective case studies and numerous laboratory investigations about utility weights from the behavioral decision making literature (e.g., Weber et al., 1988). A program for building knowledge about MCDA might set out to answer questions about what works by using these methods more systematically as well as collecting detailed data across a population of projects and incorporating it in structured equation models common in social science research (Linkov and Moberg, in press). At some point,

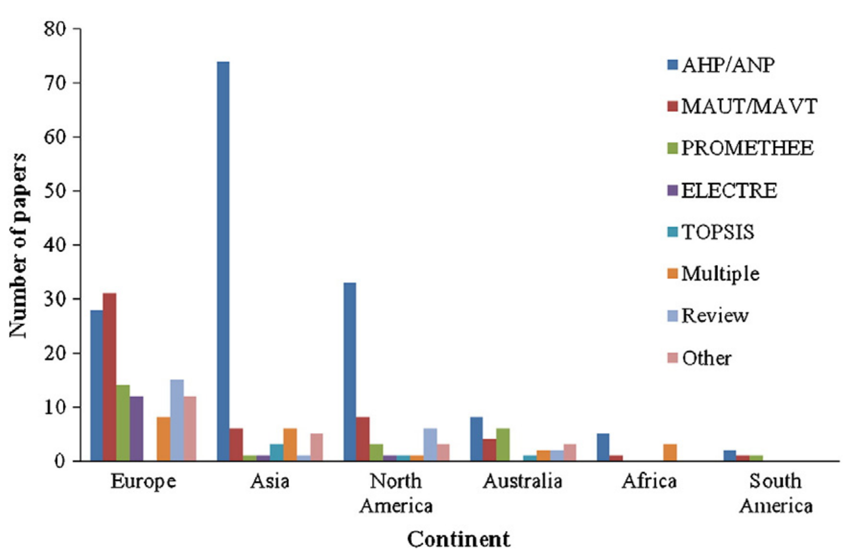

Fig. 2. Geographic distribution of MCDA methods by continent.

Table 9
Summary of number of methods and alternatives considered in the application of Multiple MCDA tools.

Title	Number of methods	Methods	Number of alternatives considered	References	Consistency	Overlap (out of top 4)
Data envelopment analysis of reservoir system performance	6	1) Decision envelopment analysis; 2) AHP; 3) PROMETHEE; 4) TOPSIS; 5) Compromise programming; 6) Simple product weighting	6	Srdjevic et al. (2005)	All except decision envelopment analysis yielded the top alternative	2
Comparison of different multicriteria evaluation methods for the Red Bluff diversion dam	5	1) PROMETHEE; 2) AHP; 3) Compromise programming; 4) ELECTRE; 5) Weighted average	11	Mahmoud et al. (2000)	All except PROMETHEE and CP yielded the same top alternative	0
Stochastic-fuzzy multi criteria decision making for robust water resources management	5	1) ELECTRE; 2) MAUT; 3) Compromise programming; 4) Stochastic-Fuzzy-Ordered Weighted Averaging; 5) Fuzzy compromise programming	5	Zarghami et al. (2009)	All methods yielded the same top alternative	2
A multiple criteria decision making framework for regional aquaculture development	3	1) Multiple objective programming; 2) Compromise programming; 3) weighted goal programming	not listed	El-Gayar et al. (2001)	Comparison of methods, not alternatives	N/A
A MCDM-based expert system for climate-change impact assessment and adaptation planning — A case study for the Georgia Basin, Canada	3	1) Simple additive weighting; 2) TOPSIS; 3) ELECTRE	6	Qin et al. (2008a)	Methods yielded the top alternative	3
Multi-criteria analysis for technique assessment — Case study from industrial coating	3	1) MAUT; 2) AHP; 3) PROMETHEE	9	Geldermann et al. (2005)	All methods yielded same top alternative	4
Applying voting theory in natural resource management: a case of multiple-criteria group decision support	3	1) Voting theory (multicriteria approval); 2) PROMETHEE; 3) AHP	20	Laukkanen et al. (2002)	Methods did not yield the same top alternative	2
A quantitative method for accounting human opinion, preferences and perceptions in ecosystem management	3	1) AHP; 2) Expected Utility Method; 3) Compromise programming	4	Pavlikakis et al. (2003a)	All except EUM yielded the top alternative	4
Integrating humans in Ecosystem Management using Multi-Criteria Decision Making	3	1) AHP; 2) Expected Utility Method; 3) Compromise programming	4	Pavlikakis et al. (2003b)	Methods yielded the same top alternatives	4
Optimization of remediation operations at petroleum-contaminated sites through a simulation-based stochastic-MCDA approach	3	1) Simple additive weighting; 2) TOPSIS; 3) PROMETHEE	12	Qin et al. (2008b)	All methods yielded the same top alternative	4
Alternative approaches to the construction of a composite indicator of agricultural sustainability: An application to irrigated agriculture in the Duero basin in Spain	3	1) Principal component analysis; 2) AHP; 3) MCDM	22	Gomez-Limon et al. (2009)	Disagreement between methods	0
Object-oriented decision support system modeling for multicriteria decision making in natural resource management	2	1) MAVT; 2) MCDM	not listed	Liu et al. (2004)	Comparison of methods, not alternatives	N/A
Accounting for farmers' production responses to environmental restrictions within landscape planning	2	1) MAUT; 2) ELECTRE	not listed	Ahrenz et al. (2009)	Both methods yielded the same alternative (qualitative)	N/A
Application of multicriteria decision analysis to jar-test results for chemicals selection in the physical–chemical treatment of textile wastewater	2	1) AHP; 2) PROMETHEE	12	Aragones-Beltran et al. (2009)	Both methods yielded the same top alternative except for one of the four PROMETHEE scenarios	2
Multicriteria analysis of ventilation in summer period	2	1) MAUT; 2) ELECTRE	8	Blondeau et al. (2002)	Both methods yielded the same top alternative	4
Developing a sustainability framework for the assessment of bioenergy systems	2	1) MCDA; 2) Decision-conferencing	not listed	Elghali et al. (2007)	Comparison of methods, not alternatives	N/A
Multi-criteria evaluation for the optimal adoption of distributed residential energy systems in Japan	2	1) AHP; 2) PROMETHEE	10	Ren et al. (2009)	Both methods did not yield the same top alternative	3
Environmental performance evaluation of suppliers: A hybrid fuzzy multi-criteria decision approach	2	1) AHP; 2) PROMETHEE	5	Tuzkaya et al. (2009)	Methods yielded the same alternative (qualitative)	N/A
Prioritization of water management for sustainability using hydrologic simulation model and multicriteria decision making techniques	2	1) Composite programming; 2) ELECTRE; 3) Regime; 4) EVAMIX	19	Chung et al. (2009)	All except ELECTRE yielded the same top alternative	3
Multicriterion decision analysis approach to assess the utility of watershed modeling for management decisions	2	1) Additive value function; 2) ELECTRE	3	Elshorbagy et al. (2006)	Results for using the two methods were not significantly different	2 (out of 3)

however, models and case studies reach a point of diminishing returns in terms of advancing practice. Unless these models and cases are supplemented by high quality data about how well they connect to reality and how well they achieve their aims, it may be a fruitful point in the development of MCDA for more focus on such research.

5.3. Limitations

Though we did our best to provide this state-of-the-application review, there are multiple caveats that should be taken into consideration when interpreting the results presented in this paper.

First, the WOS database may not include specific fields or areas. For example, oil and gas publications, including environmental aspects associated with oil and gas exploration, tend to be presented in the Journals not covered by WOS. Second, WOS may cover some of the journals only partially. For example, the version of the database that we used did not include first 5 years of Decision Analysis, a major journal in the field. Furthermore, we were unable to find several papers identified in the database as worth considering. Third, we have not attempted to classify papers by quality and sophistication of the analysis. Indeed, some of the applications were very superficial, while others were deep and detailed. Some of the studies attempted an advanced uncertainty and sensitivity analysis, including probabilistic methods, while others did not. Some of the papers presented real applications, while others discussed hypothetical case studies. We aimed to incorporate sound sampling practices in identifying articles, so that this range of applications ought to be a good representation of the current state of practice and its evolution.

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Appendix A

Figs. 1, 2a, and b correspond to information shown in Tables 4 and 6, respectively. They fall under the section Trends by MCDA method. And Figs. 3, 4a, and b correspond to information shown in Tables 5 and 7, respectively. They fall under the section Trends by MCDA application areas.

Appendix B

Complete list of articles reviewed:

Ahrenz H, Kantelhardt J. Accounting for farmers' production responses to environmental restrictions within landscape planning. Land Use Policy 2009; 26: 925–934.

Al-Helal AB, Al-Awadhi JM. Assessment of sand encroachment in Kuwait using GIS. Environmental Geology 2006; 49: 960–967.

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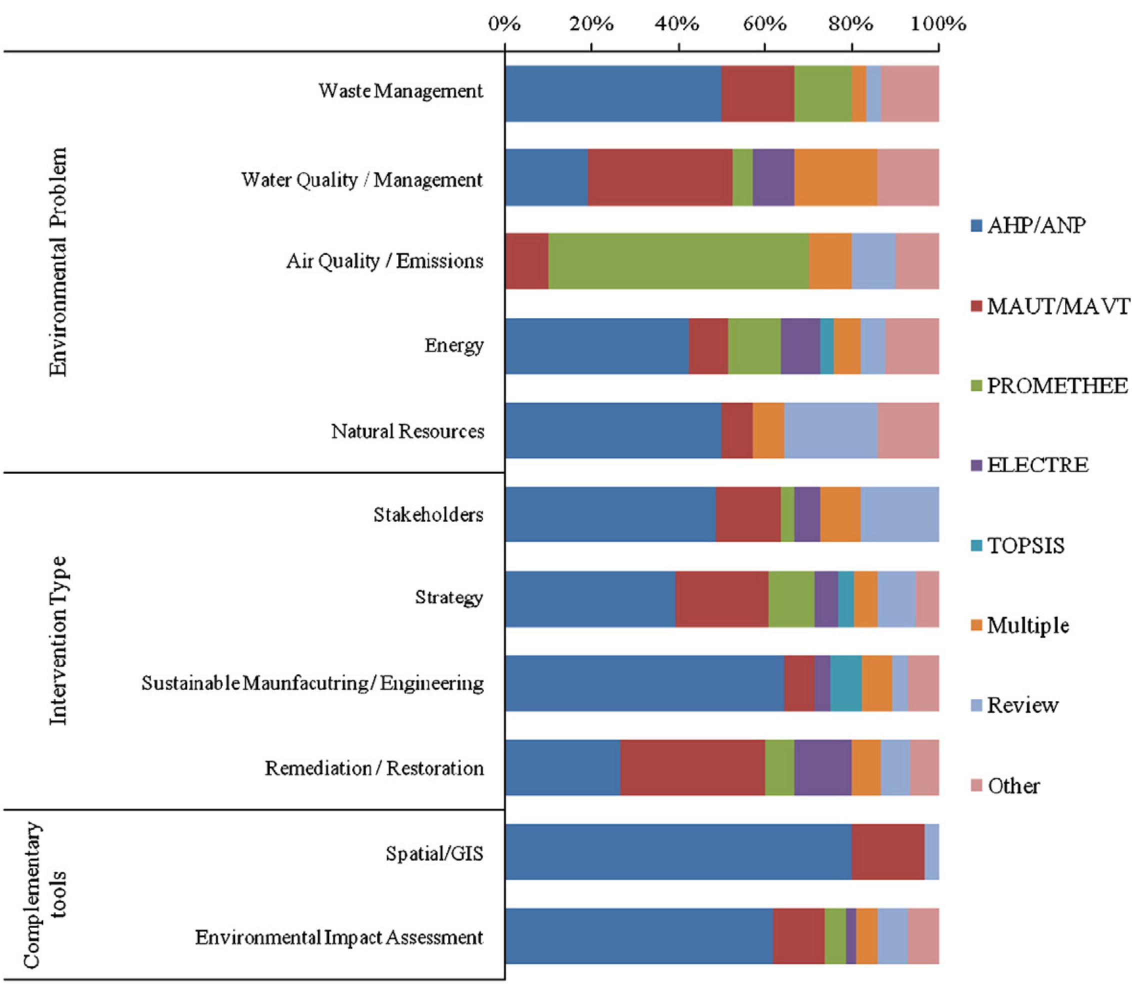

Fig. 1. Percentage distribution of MCDA methods by application areas.

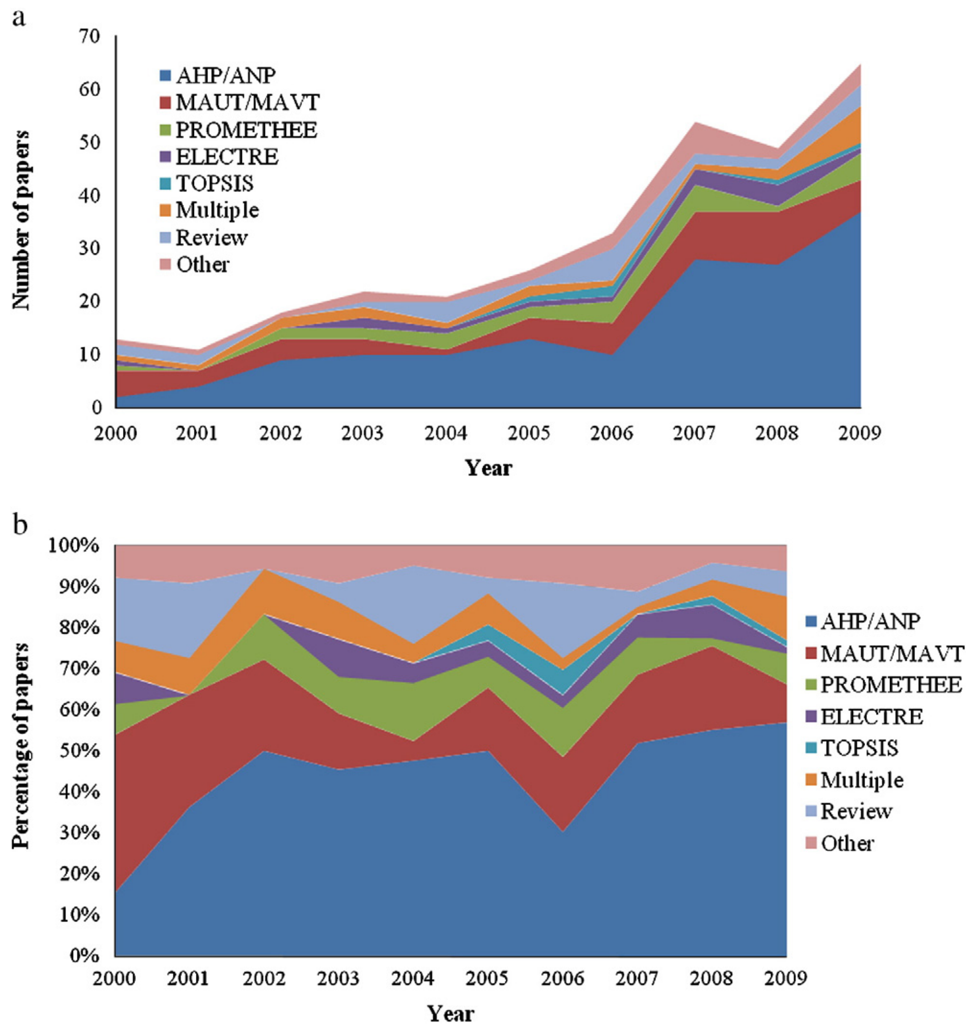

Fig. 2. a. Distribution of MCDA papers by methods between 2000 and 2009. b. Percentage distribution of MCDA papers by methods between 2000 and 2009.

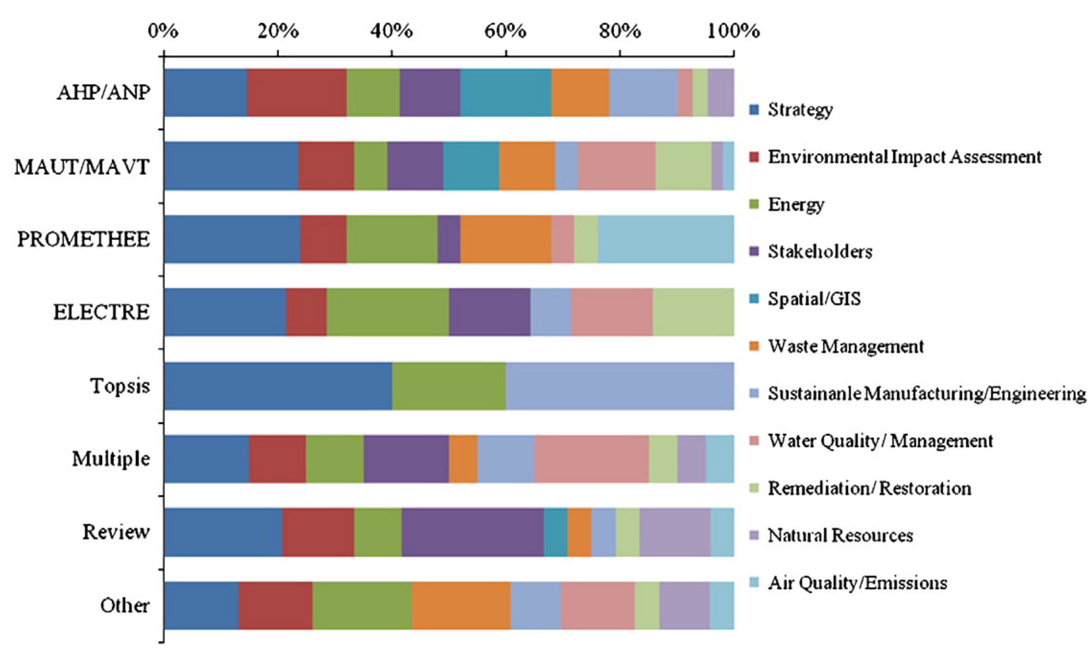

Fig. 3. Percentage distribution of MCDA applications areas by method.

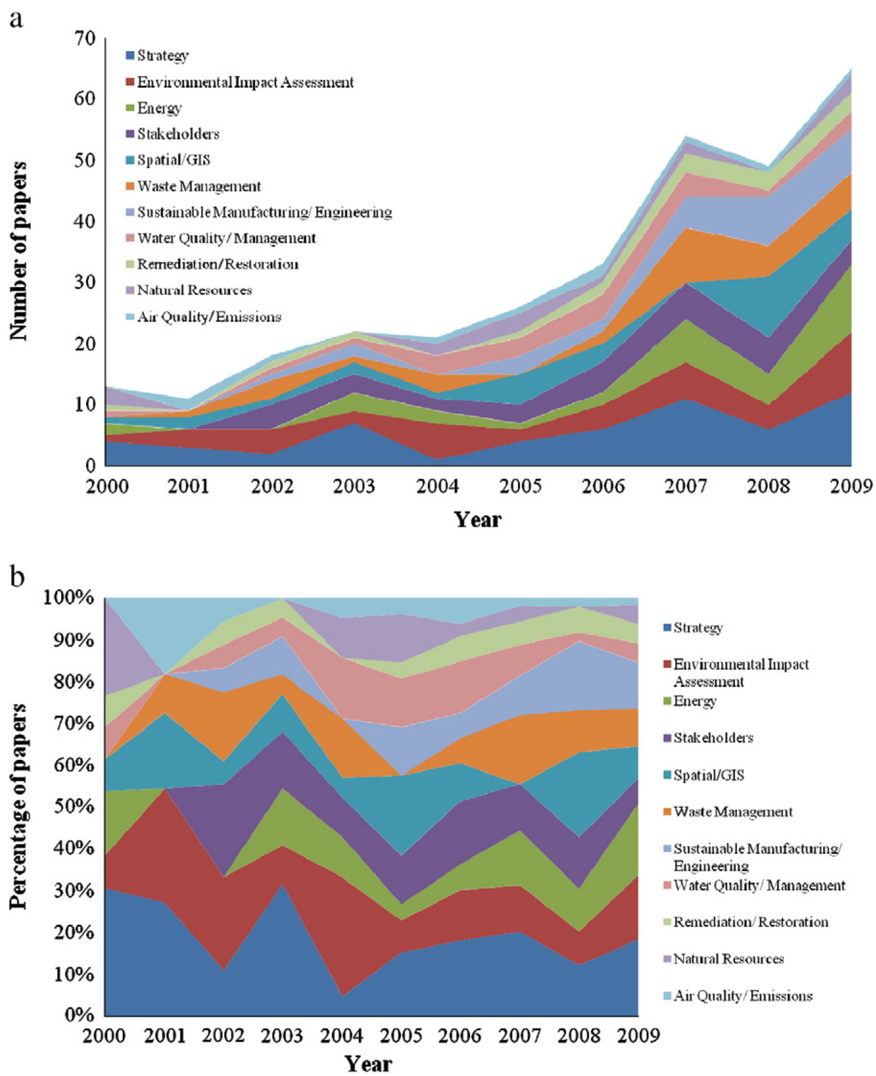

Fig. 4. a. Distribution of MCDA papers by application area between 2000 and 2009. b. Percentage distribution of MCDA papers by application area between 2000 and 2009.

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