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Review Article

GIS-based multicriteria decision analysis: a survey of the literature

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The integration of GIS and multicriteria decision analysis has attracted significant interest over the last 15 years or so. This paper surveys the GIS-based multicriteria decision analysis (GIS-MCDA) approaches using a literature review and classification of articles from 1990 to 2004. An electronic search indicated that over 300 articles appeared in refereed journals. The paper provides taxonomy of those articles and identifies trends and developments in GIS-MCDA.

Keywords: GIS; Multicriteria decision analysis

1. Introduction

Spatial decision problems typically involve a large set of feasible alternatives and multiple, conflicting and incommensurate evaluation criteria. The alternatives are often evaluated by a number of individuals (decision-makers, managers, stakeholders, interest groups). The individuals are typically characterized by unique preferences with respect to the relative importance of criteria on the basis of which the alternatives are evaluated. Accordingly, many spatial decision problems give rise to the GIS-based multicriteria decision analysis (GIS-MCDA). These two distinctive areas of research, GIS and MCDA, can benefit from each other (Laaribi *et al*. 1996, Malczewski 1999, Thill 1999, Chakhar and Martel 2003). On the one hand, GIS techniques and procedures have an important role to play in analyzing decision problems. Indeed, GIS is often recognized 'as a decision support system involving the integration of spatially referenced data in a problem solving environment' (Cowen 1988). On the other hand, MCDA provides a rich collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions. At the most rudimentary level, GIS-MCDA can be thought of as a process that transforms and combines geographical data and value judgments (the decision-maker's preferences) to obtain information for decision making. It is in the context of the synergetic capabilities of GIS and MCDA that one can see the benefit for advancing theoretical and applied research on GIS-MCDA.

There is now a well-established body of literature on GIS-MCDA (e.g. Diamond and Wright 1988, Janssen and Rietveld 1990, Carver 1991, Church *et al*. 1992, Banai 1993, Pereira and Duckstein 1993, Eastman *et al*. 1995, Heywood *et al*. 1995, Jankowski 1995, Laaribi *et al*. 1996, Malczewski 1999, Thill 1999, Laaribi 2000, Chakhar and Martel 2003, Feick and Hall 2004). The main aim of the paper is to

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survey and classify the GIS-MCDA articles published between 1990 and 2004. The remainder of this paper is organized into four sections. The methods used for surveying the GIS-MCDA literature are discussed in the next section. Section 3 provides a general description of the GIS-MCDA database. The articles are classified according to the various perspectives on GIS-MCDA in section 4. Finally, section 5 presents concluding remarks.

2. Literature survey methods

The search for relevant publications was performed using several Web-based scientific search engines, electronic libraries, and databases (see Appendix 1). The search was limited to articles published in refereed journals in the period between 1 January 1990 and 31 December 2004. It was done using a Boolean search containing the following terms: GIS *and* multicriteria (*or* multiobjective *or* multiattribute). Initially, any article containing the search terms was considered as a potential candidate for including into the database of the GIS-MCDA publications.

To supplement the automated search, a manual search was also done. The manual procedure involved searching the reference sections of the papers identified by the automated search. Any relevant references within those papers were followed up on. Each article was reviewed by the author. Inclusion criteria for the review were any theoretical or applied work concerning an integration of the two methodologies or any presentation of a computer-based system integrating the GIS and MCDA methods. Papers identified in the search, but that were clearly irrelevant, were omitted from further consideration, leaving 319 items that were reviewed thoroughly. A complete list of the papers is available at http://publish.uwo.ca/~jmalczew/gis-mcda.htm.

3. The GIS-MCDM literature in 1990–2004

Figure 1 shows the development of GIS-MCDA in terms of the number of refereed articles published in 1990–2004 and the accumulation of those articles. The development of GIS-MCDA has been modest in the first half of the 1990s. Of the 319 articles, there were only 26 papers (or 8.2% of the total) published between 1990 and 1995. While Carver (1991) and Langevin *et al.* (1991) are the earliest papers included in this survey, one should acknowledge that there had been GIS-MCDA studies reported prior to 1991 in referred journals (e.g. Diamond and Wright 1988), book chapters (e.g. Janssen and Rietveld 1990), and conference proceedings (e.g. Moreno and Seigel 1988). It is interesting to note that while Carver (1991) is one of the most widely cited GIS papers (see Fisher 2001), the work by Langevin *et al.* (1991) remains largely unknown to the GIS community. The efforts to integrate GIS and MCDA in the late 1980s and early 1990s can be associated with the proliferation stage of the GIS development (see Waters 1998, Malczewski 2004). The proliferation phase was characterized by the development of the user-oriented GIS technology, which has stimulated a wide range of GIS applications including the GIS-based approaches for tackling spatial decision problems.

From 1995 to 2000 there has been a substantial acceleration in the number of the GIS-MCDA articles published in refereed journals with the total number rising from 9 in 1995 to 40 in 2000. Over the last five years the volume of refereed publications on GIS-MCDA has continued to grow very rapidly. Of the 319 articles, almost 70% were published in the last five years. The rapid increase of the volume of

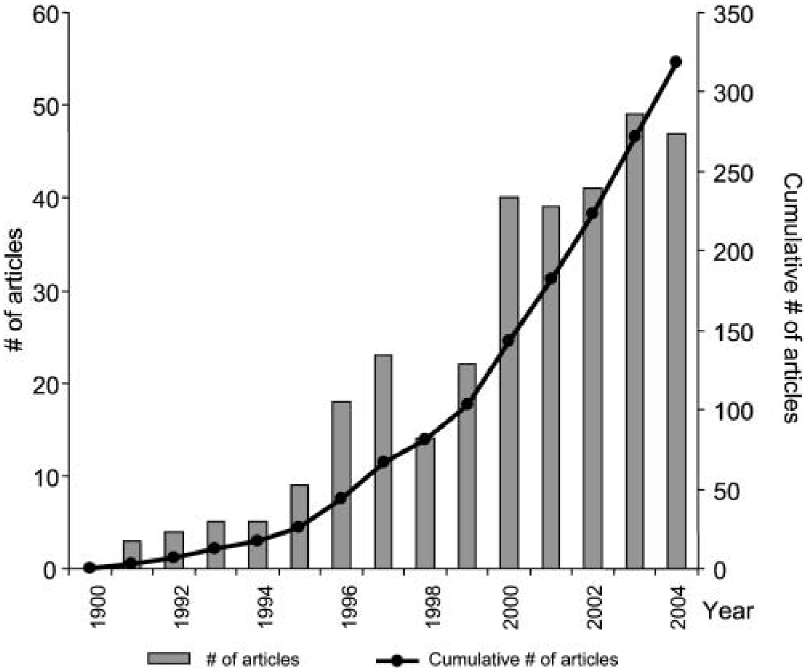

Figure 1. Total number of GIS-MCDM articles per year for the period 1990–2004.

the GIS-MCDA research can be attributed to a number of factors. First, a wider recognition of decision analysis and support as an essential element of GIScience (see the National Center for Geographic Information and Analysis (NCGIA) initiatives on 'Spatial Decision Support Systems (SDSS)', 'Collaborative Spatial Decision Making', 'GIS and Society', and the Varenius project on 'Empowerment, Marginalisation and Public Participation GIS' at http://www.ncgia.ucsb.edu/ncgia.html). Second, the availability of low-cost and easy-to-use MCDA software such as Expert Choice (Expert Choice Inc.1993) and mathematical programming solvers (e.g. LINDO Systems Inc. 1994). Third, the availability of MCDA modules in such systems as IDRISI (Eastman *et al.* 1993) and SPANS (TYDAC Research Inc. 1996), and TNT-GIS (MicroImages Inc. 2001). In particular, the availability of a fully fledged decision support module in IDRISI has been instrumental for stimulating applied research in GIS-MCDA (e.g. Pereira and Duckstein 1993, Aguilar-Manjarrez and Ross 1995, Malczewski 1996, Brookes 1997, Tkach and Simonovic 1997, Giupponi *et al.* 1999, Jiang and Eastman 2000, Kyem 2001, 2004).

The diffusion of the GIS-MCDA research is indicated by the large number and diversity of refereed journals serving as outlets for the GIS-MCDM articles. Over the years, the articles have appeared in 135 different journals. The list of refereed journals known to have published GIS-MCDA articles gives credence to GIS-MCDA's vitality and acceptance (see table 1). It also shows that GIS-MCDA is a significant and relevant approach for a wide variety of fields (see section 4.4). The *International Journal of Geographic Information Systems/Science* leads with 21 publications (6.6%), followed by *Landscape and Urban Planning* with 14 publications (4.4%). *Environment and Planning A/B* comes up third with 12 (3.8%). Thus, the top three among 135 journals have published almost 15% of the GIS-MCDA articles. The top six journals account for approximately 25% of all papers published, while

Table 1. The list of refereed journals that have published four or more articles on GIS-MCDA in 1990–2004.

Rank	Journal	# of articles	%
1	*International Journal of Geographical Information Systems/Science*	21	6.6
2	*Landscape and Urban Planning*	14	4.4
3	*Environment and Planning A/B*	12	3.8
4	*Journal of Geographic Information and Decision Analysis*	11	3.4
5–6	*Computers, Environment and Urban Systems*	10	3.1
5–6	*Journal of Environmental Management*	10	3.1
7–8	*Environmental Modelling and Software*	7	2.2
7–8	*Environmental Management*	7	2.2
9	*Transportation Research Record*	6	1.9
10–16	*Agricultural Systems*	5	1.6
10–16	*Annals of the Association of American Geographers*	5	1.6
10–16	*Ecological Modelling*	5	1.6
10–16	*Forest Ecology and Management*	5	1.6
10–16	*Journal of Environmental Engineering*	5	1.6
10–16	*Photogrammetric Engineering and Remote Sensing*	5	1.6
10–16	*Transportation Research: Part A/B/C/D*	5	1.6
17–20	*Conservation Biology*	4	1.3
17–20	*Decision Support Systems*	4	1.3
17–20	*European Journal of Operational Research*	4	1.3
17–20	*Transactions in GIS*	4	1.3
	Others	170	53.3
	Total	319	100

the top 20 account for almost 50%. Alternately stated, approximately 5% of the journals have published more than a quarter of the papers, while about 15% of the journals account for almost half of all the GIS-MCDA articles.

4. Classifications of the GIS-MCDA articles

A number of approaches to structuring GIS-MCDA have been suggested in the literature (Jankowski 1995, Malczewski 1999, Herwijnen and Rietveld 1999, Laaribi 2000, Chakhar and Martel 2003). Despite differences between the GIS-MCDA frameworks, one can identify five generic components of the GIS-based MCDA procedures: (i) a goal or a set of goals an individual (or a group of individuals) attempts to achieve along with associated *evaluation criteria* (*objectives* and/or *attributes*) on the basis of which the decision-maker evaluates alternative courses of action; (ii) the *decision-maker* or a group of decision-makers involved in the decision-making process along with their preferences; (iii) the set of decision *alternatives* (or the decision variables); (iv) the set of uncontrollable variables or *states of nature* (decision environment); and (v) the set of *outcomes* or consequences associated with each alternative-criterion pair.

Given the generic components of GIS-MCDA, two classification schemes for the GIS-MCDA literature were developed. First, all articles were classified based on the geo-information (GIS) components of the GIS-MCDA methods. This classification involved the following considerations: (i) the geographical data models, (ii) the spatial dimension of the evaluation criteria, and (iii) the spatial definition of decision alternatives. Second, the articles were classified according to the generic elements of the MCDA methods. This taxonomy was based on (i) the nature of evaluation criteria, (ii) the number of individuals involved in the decision-making process, and

(iii) the nature of uncertainties. In addition, the articles were classified according to the extent and direction of the GIS and MCDA integration, and the type of application domain and decision problem.

4.1 *The GIS components*

The taxonomy of the geo-information components of the GIS-MCDA approaches is based on the following dichotomies: (i) the *raster* versus *vector* data models, (ii) *explicitly spatial criteria* versus *implicitly spatial criteria*, and (iii) *explicitly spatial alternatives* versus *implicitly spatial alternatives*.

4.1.1 The raster- and vector-based GIS-MCDA. Of the 319 papers, 152 (47.6%) articles reported the raster-data-based research (e.g. Pereira and Duckstein 1993, Eastman *et al*. 1995, Malczewski 1996, Cromley and Hanink 1999, Aerts *et al*. 2003, Church *et al*. 2003) and 150 (47.0%) articles discussed research involving the vector-based GIS-MCDA (e.g. Can 1992, Jankowski 1995, Laaribi *et al*. 1996, Rinner and Malczewski 2002, Feick and Hall 2004). There were 17 articles which did not provide any information on the geographical data model. It is important to note that some of the works reported in the GIS-MCDA articles have been based on a combination of the raster and vector data models. It was, however, the geographical data structure used in the multicriteria combination rules (see section 4.2.1) that provided the bases for classifying the articles according to the geographical data model. Thus, if the combination rules were performed using the raster data, then the study was categorized as the raster-based MCDA. Similarly, all papers reporting on the vector-based multicriteria combination rules were categorized as the vector-based multicriteria studies, irrespective of the format of the input data. Although the majority of the GIS-MCDA research has been based on the layer view of the real-world represented by the raster or vector data models, an effort has also been made to use the object-oriented paradigm for integrating GIS and MCDA (e.g. Reitsma and Carron 1997, Matthews *et al*. 1999).

4.1.2 Explicitly and implicitly spatial criteria. The raster- and vector-based GIS-MCDA approaches are further subdivided into two categories depending on the nature of criteria. Criterion is a standard of judgment or rule on the basis of which alternative decisions can be evaluated and ordered according to their desirability (see section 4.2.1). Explicitly spatial criteria are present in the decision problems that involve spatial characteristics as criteria. For example, in the context of a site search problem such site characteristics as size, shape, contiguity, and compactness are explicitly spatial criteria (Brookes 1997, Church *et al*. 2003). Many decision problems involve criteria (objectives) which are implicitly spatial (Herwijnen and Rietveld 1999). A criterion is said to be implicitly spatial if spatial data are needed to compute the level of achievement of the criterion. Such criteria (objectives) as the gross marginal return of agricultural production, equity of income distribution, the public investment in the conservation reserve program, the costs of solid waste disposing, etc., can involve spatial attributes such as distance, proximity, accessibility, elevation, slope, etc. (e.g. MacDonald 1996, Antoine *et al*. 1997).

It should be noted that these two categories are not mutually exclusive (see table 2). Indeed, the majority of the studies (almost 70%) involved both explicitly and implicitly spatial criteria (e.g. Kao and Lin 1996, Antoine *et al*. 1997, Lin *et al*. 1997, Seppelt and Voinov 2002, Martin *et al*. 2003, Wu *et al*. 2004). Of the 152 raster-based GIS-MCDA articles, 12 (7.9%) and 45 (29.6%) articles have reported

Table 2. Classification of the GIS-MCDA articles according to the GIS data model and evaluation criterion.

		Criteria			
		Explicitly spatial	Implicitly spatial	Explicit/implicitly spatial	Total
Data model	Raster	12	45	95	152
	Vector	20	12	118	150
	Unspecified	2	7	8	17
	Total	34	64	221	319

research that involved explicitly and implicitly spatial criteria, respectively. Examples of the former category include: Eastman *et al.* (1995), Brookes (1997), Cromley and Hanink (1999, 2003), Seppelt and Voinov (2002), and Church *et al.* (2003). The articles by Nevo and Garcia (1996), Brakewood and Grasso (2000), Fuller *et al.* (2003), Perez *et al.* (2003) and Store and Jokimäki (2003) provide examples of the raster-based implicitly spatial criteria. Similar classification for the vector-based GIS-MCDA showed that there were 20 (13.3%) articles reporting the use of explicitly spatial criteria (e.g. MacDonald 1996, Weigel and Cao 1999) and 12 (8.0%) studies involved implicitly spatial criteria (e.g. Vertinsky *et al.* 1994, Kächele and Dabbert 2002).

4.1.3 Explicitly and implicitly spatial alternatives. Decision alternatives can be defined as alternative courses of action among which the decision-maker must choose. A spatial decision alternative consists of at least two elements: action (what to do?) and location (where to do it?). The spatial component of a decision alternative can be specified explicitly or implicitly. Examples of explicitly spatial alternatives include: alternative sites for locating facilities (e.g. Aguilar-Manjarrez and Ross 1995, Kao 1996, Basnet *et al.* 2001), alternative location-allocation patterns (e.g. Armstrong *et al.* 1992, Cova and Church 2000, Malczewski *et al.* 1997), alternative patterns of land use-suitability (e.g. Eastman *et al.* 1995, Antoine *et al.* 1997, Brookes 1997, Bennett *et al.* 1999). In many decision situations the spatial component of an alternative decision is not present explicitly. However, there may be a spatial implication associated with implementing an alternative decision. In such a case, the alternative is referred to as an implicitly spatial alternative (Herwijnen and Rietveld 1999). Spatially distributed impacts can emerge, for example, through the implementation of a particular solution to minimize flood risks in which favorable impacts are produced at one location while negative consequences result at another (Vertinsky *et al.* 1994, Tkach and Simonovic 1997, Jumppanen *et al.* 2003).

Table 3 shows that the articles reporting on the use of explicitly spatial alternatives accounted for 57 or 37.5 % of all the raster-based GIS-MCDA papers (e.g. Ross *et al.* 1993, Kao 1996, Church *et al.* 2003). The implicitly spatial alternatives were used in 41 (or 27.0 %) articles on the raster-based GIS-MCDA (e.g. Jumppanen *et al.* 2003, Burton and Rosenbaum 2003, Wu *et al.* 2004). The GIS-MCDA database contained 58 articles (38.7%) which have been categorized as the vector-based GIS-MCDA and explicitly spatial-alternative category (e.g. MacDonald 1996, Weigel and Cao 1999, Armstrong *et al.* 2003). There were 49 (32.7%) articles in the vector-based-implicitly spatial-alternative category (e.g. Vertinsky *et al.* 1994, Kächele and Dabbert 2002, Morari *et al.* 2004).

Table 3. Classification of the GIS-MCDA articles according to the GIS data model and decision alternative.

		Decision alternatives			
		Explicitly spatial	Implicitly spatial	Explicit/implicitly spatial	Total
Data model	Raster	57	41	54	152
	Vector	58	49	43	150
	Unspecified	8	4	5	17
	Total	123	94	102	319

4.2 *The multicriteria decision analysis components*

Given the generic elements of GIS-MCDA, one can distinguish three dichotomies: (i) *multiobjective decision analysis* (MODA) versus *multiattribute decision analysis* (MADA), (ii) *individual* versus *group* decision-making, and (iii) decisions under *certainty* versus decision under *uncertainty* (that is, the *probabilistic* and *fuzzy* decision-making). This classification schema is shown in figure 2.

4.2.1 Multiattribute and multiobjective decision analysis (MADA and MODA). Criterion is a generic term including both the concept of *attribute* and *objective*. Thus, MCDA is used as the blanket term which includes both multiobjective and multiattribute decision-making. The multiattribute decision problems are assumed to have a predetermined, limited number of alternatives. Solving this type of problem is a selection process as opposed to a design process. The multiobjective problem is continuous in the sense that the best solution may be

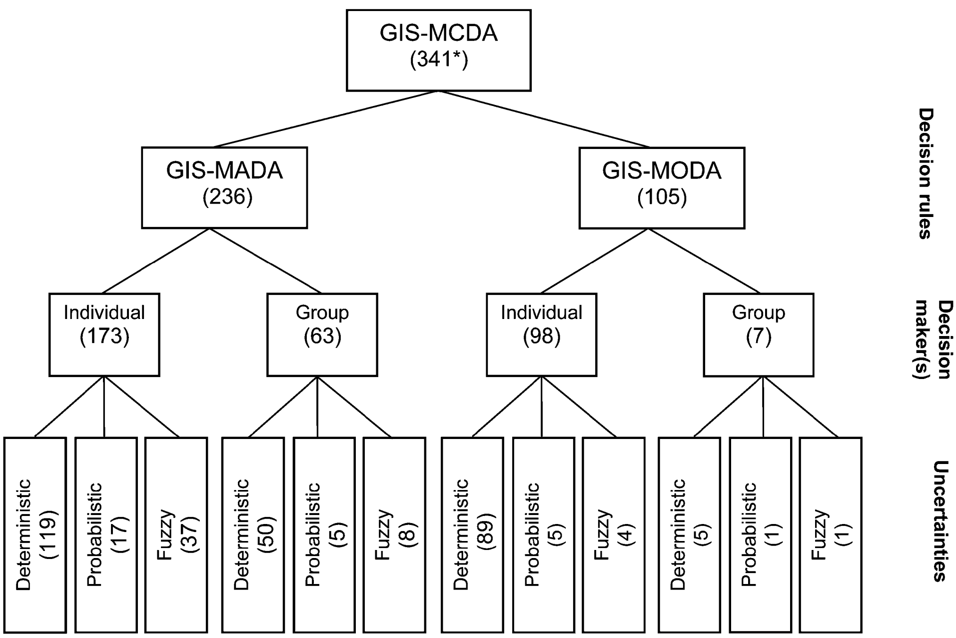

Figure 2. Classification scheme for the GIS-MCDA articles (Note: the number of articles is given in brackets; *22 articles presented both GIS-MADA and GIS-MODA; these articles were included into the two categories).

found anywhere within the region of feasible solutions. Therefore, multiattribute and multiobjective problems are sometimes referred to as discrete and continuous decision problems, respectively (Hwang and Yoon 1981, Goicoechea *et al.* 1982).

Figure 2 shows 341 GIS-MCDA articles (approaches) at the top of the hierarchical classification. This number is greater then the number of surveyed articles, because there were 22 studies which combined the GIS-MADA and GIS-MODA methods (e.g. Guimarães Pereira *et al.* 1994, Vertinsky *et al.* 1994, Kao and Lin 1996, Bojórquez-Tapia *et al.* 2001, Makropoulos *et al.* 2003). These articles were included in both the GIS-MADA and GIS-MODA categories. The results of the survey indicate that a majority of the articles fall into the GIS-MADA category (figure 2). The GIS-MADA approaches account for almost 70% of the total (e.g. Banai 1993, Pereira and Duckstein 1993, Jankowski 1995, Eastman *et al.* 1995, Malczewski 1996, Feick and Hall 1999, Jun 2000, Kyem 2004). More than 30% of the approaches fall into the GIS-MODA category (e.g. Xiang 1993, Antoine *et al.* 1997, Gomes and Lins 2002, Seppelt and Voinov 2002, Aerts and Heuvelink 2002, Aerts *et al.* 2003, Xiao *et al.* 2002, Armstrong *et al.* 2003, Kächele and Dabbert 2002, Stewart *et al.* 2004).

In addition to the classification of the articles into the GIS-MADA and GIS-MODA categories, it is useful to identify the algorithms or combination (decision) rules within each of the two groups. A decision rule is a procedure that allows for selecting one or more alternatives from a set of alternatives available to the decision-maker (see Malczewski 1999). Although a considerable number of decision rules have been proposed in the MCDA literature (e.g. Cohon 1978, Hwang and Yoon 1981, Goicoechea *et al.* 1982), the use of the combination rules in the GIS-MCDA studies has been limited to a few well-known approaches such as the weighted summation, ideal/reference point, and outranking methods (see table 4). The weighted summation and related procedures have been by far the most popular GIS-MCDA approaches. These methods were present in 143 articles or 39.3% of the total (e.g. Eastman *et al.* 1995, Gumbricht *et al.* 1996, Pettit and Pullar 1999, Robinson *et al.* 2002, Ceballos-Silva and López-Blanco 2003, Perez *et al.* 2003, Ayalew *et al.* 2004, Marinoni 2004). The weighted summation has typically been

Table 4. Classification of the GIS-MCDA articles according to the combination rule.

Combination rules		# of articles*	%
MADA	Weighted summation/Boolean overlay	143	39.3
	Ideal/reference point (TOPSIS, MOLA)	35	9.6
	Analytical Hierarchy Process (AHP)	34	9.4
	Outranking methods (ELECTRE, PROMETHEE)	17	4.7
	Other	30	8.3
	Total (GIS-MADA)	*259*	*71.3*
MODA	Multi-objectives programming algorithms (linear-integer programming)	57	15.7
	Heuristic search/evolutionary/genetic algorithms	29	8.0
	Goal programming/reference point algorithms	9	2.5
	Other	9	2.5
	Total (GIS-MODA)	*104*	*28.7*
	Total	363	100.0

Note: *some articles presented more than one combination rule.

used in conjunction with the Boolean operations (e.g. Eastman *et al.* 1995, Pettit and Pullar 1999, Perez *et al.* 2003). Many studies have used the weighted summation approach along with the linear transformation method for normalizing criteria and the pairwise comparison method for deriving the criterion weights (e.g. Eastman *et al.* 1995, Gumbricht 1996, Tseng *et al.* 2001, Basnet *et al.* 2001, Vlachopoulou *et al.* 2001, Wu *et al.* 2004, Marinoni 2004). The ordered weighted averaging (OWA) provides an extension and generalization of the Boolean operations and the weighted summation procedures. The OWA approach has been presented in Jiang and Eastman (2000), Rinner and Malczewski (2002), Makropoulos *et al.* (2003), Malczewski *et al.* (2003), and Rashed and Weeks (2003).

The Analytical Hierarchy Process (AHP) is another popular method which is based on the additive weighting model (e.g. Banai 1993, Wu 1998, Basnet *et al.* 2001, Zhu and Dale 2001). The AHP method has been used in two distinctive ways within the GIS environment. First, it can be employed to derive the weights associated with attribute map layers. Then, the weights can be combined with the attribute map layers in a way similar to the weighted additive combination methods. This approach is of particular importance for problems involving a large number of alternatives, when it is impossible to perform a pairwise comparison of the alternatives (Eastman *et al.* 1993). Second, the AHP principle can be used to aggregate the priority for all level of the hierarchy structure including the level representing alternatives. In this case, a relatively small number of alternatives can be evaluated (Jankowski and Richard 1994).

The primary reason for the popularity of the weighted summation and related methods is that the approaches are very easy to implement within the GIS environment using map algebra operations and cartographic modeling. The methods are also easy-to-understand and intuitively appealing to decision-makers. However, GIS implementations of the weighted summation procedures are often used without full understanding of the assumptions underlying this approach. In addition, the method is often applied without full insight into the meanings of two critical elements of the weighted summation model: the weights assigned to attribute maps and the procedures for deriving commensurate attribute maps. Hobbs (1980), Lai and Hopkins (1989), Heywood *et al.* (1995) and Malczewski (2000) provide discussions on some aspects of the incorrect use of the method.

Some of the difficulties associated with the weighted summation and AHP models can be avoided by using such MADA procedures as the ideal/reference point methods (Pereira and Duckstein 1993) and the outranking methods (Joerin *et al.* 2001). According to the survey (see table 4), the ideal/reference point method is the second most often-used GIS-MADA combination rule (e.g. Carver 1991, Pereira and Duckstein 1993, Malczewski *et al.* 1997, Tkach and Simonovic 1997, Lee *et al.* 2000, Jankowski *et al.* 2001). Over the years a considerable number of articles have presented the use of the outranking methods such as ELECTRE and related procedures (e.g. Carver 1991, Can 1992, Joerin 1995, Villa *et al.* 1996, Joerin and Musy 2000, Joerin *et al.* 2001, Schlaepfer *et al.* 2002, Morari *et al.* 2004) and PROMETHEE (e.g. Laaribi *et al.* 1996, Martin *et al.* 2003).

The GIS-MODA articles can be grouped into three main categories depending on the multiobjective algorithms: (i) multiobjective linear-integer programming, (ii) goal programming/reference point algorithms, and (iii) heuristic search/evolutionary/genetic algorithms (table 4). In general, the multiobjective models are often tackled by converting them to single objective problems and then by solving the problem using the standard linear-integer programming methods (e.g. Cohon 1978, Goicoechea *et al.* 1982). This approach is the most often used in the GIS-MODA research (e.g. Bowerman *et al.* 1995, Kao 1996, Cromley and Hanink 1999, Kächele and Dabbert 2002, Church *et al.* 2003). It accounts for 15.7% of all methods reported in the GIS-MCDA articles (table 4). Another group of GIS-MODA includes articles in which the goal programming/reference point algorithms are used (e.g. Antoine *et al.* 1997, Chang *et al.* 1997, Grabaum and Meyer 1998, Agrell *et al.* 2004, Stewart *et al.* 2004). These traditional approaches to MODA have some limitations (Malczewski and Ogryczak 1996, Zhou and Civco 1996, Xiao *et al.* 2002, Aerts *et al.* 2003). First, they can be applied in situations when it is possible to formulate decision problems in terms of mathematical programming models. Second, the methods are of limited applicability for very large and complex problems. Third, the methods may fail to find important solutions. Given these limitations, a number of heuristics approaches have been proposed. Notably, the evolutionary/genetic algorithms have recently been applied for solving complex spatial problems (e.g. Guimarães Pereira *et al.* 1994; Zhou and Civco 1996, Balling *et al.* 1999, Bennett *et al.* 1999, Feng and Lin 1999, Matthews *et al.* 1999, Seppelt and Voinov 2002, Xiao *et al.* 2002, Armstrong *et al.* 2003).

4.2.2 Individual and group decision-making. The GIS-MADA and GIS-MODA approaches can be further subdivided into two categories depending on the goal-preference structure of the decision-maker (see figure 2). If there is a single goal-preference structure, then the problem is referred to as a single decision-maker's problem, regardless of the number of individuals actually involved. On the other hand, if individuals (interest groups) are characterized by different goal-preference structures, then the problem becomes that of group decision-making. The group decision-making category includes the participatory decision making approaches (e.g. Jankowski and Nyerges 2001).

A majority of the GIS-MCDA articles represented the individual decision-maker's approaches (see figure 2 and table 5). These approaches were found in 63.8% of the GIS-MADA articles (e.g. Carver 1991, Banai 1993, Pereira and Duckstein 1993, Eastman *et al.* 1995, Jun 2000) and 36.2% of the GIS-MODA papers (e.g. Church *et al.* 1992, Xiang 1993, Kao 1996, Antoine *et al.* 1997, Kächele and Dabbert 2002, Aerts *et al.* 2003). The group/participatory approaches were presented in 70 articles (see figure 2 and table 6). They were found in 63 (90%) articles on GIS-MADA (e.g. Malczewski 1996, Feick and Hall 1999, 2002, Jankowski *et al.* 1997, 2001, Qureshi and Harrison 2001, Kyem 2004). There were only seven papers in the GIS-MODA-group decision-making category (e.g. Bennett *et al.* 1999, Seppelt and Voinov 2002, Bayliss *et al.* 2003).

Table 5. Classification of GIS-MCDA papers according to the type of multicriteria decision method for individual decision maker.

	Types of uncertainty			
Types of multicriteria analysis	Deterministic	Probabilistic	Fuzzy	Total
Multiattribute	119 (43.9)	17 (6.3)	37 (13.7)	173 (63.8)
Multiobjective	89 (32.8)	5 (1.8)	4 (1.5)	98 (36.2)
Total	208 (76.8)	22 (8.1)	41 (15.1)	271 (100.0)

Note: percentages of the total are given in brackets.

Table 6. Classification of GIS-MCDA papers according to the types of multicriteria decision methods for group decision-making.

	Types of uncertainty			
Types of multicriteria analysis	Deterministic	Probabilistic	Fuzzy	Total
Multiattribute	50 (71.4)	5 (7.2)	8 (11.4)	63 (90.0)
Multiobjective	5 (7.2)	1 (1.4)	1 (1.4)	7 (10.0)
Total	55 (78.6)	6 (8.6)	9 (12.8)	70 (100.0)

Note: percentages of the total are given in brackets.

4.2.3 Decisions under condition of certainty and uncertainty. Broadly speaking, decision problems can be categorized into decisions under certainty and decisions under uncertainty depending on the amount of information (knowledge) about the decision situation that is available to the decision-maker/analyst. If the decision-maker has perfect knowledge of the decision environment, then the decision is made under conditions of certainty (*deterministic* decision-making). Many real-world decisions involve some aspects that are unknowable or very difficult to predict. This type of decision-making is referred to as decisions under conditions of uncertainty. It should be recognized, however, that uncertainty may come from various sources. To this end, there are two basic types of uncertainty that may be present in a decision situation: (i) uncertainty associated with limited information about the decision situation, and (ii) uncertainty associated with fuzziness (imprecision) concerning the description of the semantic meaning of the events, phenomena or statements themselves. Consequently both multiattribute and multiobjective problems under uncertainty can be further subdivided into: *probabilistic* (stochastic) and *fuzzy* decision-making problems depending on the type of uncertainty involved (see figure 2).

Many analysts deliberately choose to model spatial decisions as occurring under a condition of certainty because of insufficient data or because the uncertainty is so remote that it can be disregarded as a factor (see Hwang and Yoon 1981, Malczewski 1999). Consequently, the majority of the GIS-MCDA articles fall into the deterministic category. The deterministic approaches were presented in 263 papers or approximately 77% of the total (e.g. Carver 1991, Church *et al.* 1992, Jankowski and Richard 1994, Malczewski 1996, Brookes 1997, Aerts *et al.* 2003, Marinoni 2004). A vast majority of these articles belonged to the individual decision-making category (see figure 2 and tables 5 and 6). The articles presenting the research on the GIS-MCDA under condition of uncertainty accounted for almost 23% of the total (e.g. Banai 1993, Klungboonkrong and Taylor 1998, Jiang and Eastman 2000, Noss *et al.* 2002, Seppelt and Voinov 2002, Rashed and Weeks 2003, Wang *et al.* 2004). Of the 78 articles on decision problems under condition of uncertainty, 35.9% fall into the probabilistic decision analysis category (e.g. Klungboonkrong and Taylor 1998, Noss *et al.* 2002, Seppelt and Voinov 2002, Wang *et al.* 2004) and 64.1% of the articles were found to represent the fuzzy decision-making (e.g. Banai 1993, Martin *et al.* 2003, Jiang and Eastman 2000, Joerin *et al.* 2001, Makropoulos *et al.* 2003, Rashed and Weeks 2003).

4.3 *Spatial Decision Support Systems (SDSS): integrating GIS and MCDA*

The surveyed articles have been classified according to (i) the extent of integration, and (ii) the direction of integration of GIS and MCDA. Four categories have been identified based on the extent of integration: (i) no integration, (ii) loose coupling, (iii) tight coupling, and (iv) full integration (Goodchild *et al.* 1992, Nyerges 1992, Jankowski 1995, Malczewski 1999, Jun 2000). In the loose-coupling approach, two systems (GIS and multicriteria modeling system) exchange files such that a system uses data from the other system as the input data. A tight-coupling strategy is based on a single data or model manager and a common user interface. Thus, the two systems share not only the communication files but also a common user interface. A more complete integration can be achieved by creating user-specified routines using generic programming languages. The routines can then be added to the existing set of commands or routines of the GIS package. This coupling strategy is referred to as a full integration approach.

The articles have also been classified in terms of the direction of integration. Five categories of articles have been identified: (i) no integration, (ii) one-direction integration with GIS as principle software, (iii) one-direction integration with MCDA system as principle software, (iv) bi-directional integration, and (v) dynamic integration (see (Nyerges 1992, Jun 2000). One-direction integration provides a mechanism for importing/exporting information via a single flow that originates either in the GIS or MCDA software. This type of integration can be based on GIS or MCDA as the principle software. In the bi-directional integration approach the flow of data/information can originate and end in the GIS and MCDA modules. While bi-directional integration involves one-time flow of information, dynamic integration allows for a flexible moving of information back and forth between the GIS and MCDA modules according to the user's needs (Jun 2000).

Table 7 shows a cross-classification of the articles according to the extent and direction of GIS-MCDA integration. It indicates that a considerable number of articles (26.0% of the total) do not provide any discussion on the integration of the two technologies (e.g. Balling *et al.* 1999, Noss *et al.* 2002). Of the 319 articles, 106 (33.2%) papers report the loose-coupling approach (e.g. Guimarães Pereira *et al.* 1994, Jankowski 1995), and 95 (29.8%) articles discuss research involving the tight-coupling approach (e.g. Bennett *et al.* 1999, Riedl *et al.* 2000). There are 35 (11.0%) articles presenting full integrated decision support systems (e.g. Eastman *et al.* 1995, Matthews *et al.* 1999). At the same time, almost half of the research has used GIS as the principle

Table 7. Classification of the GIS-MCDA articles according to the extent of integration and the direction of integration of GIS and MCDA.

		Extent of integration				
		No integration	Loose-coupling	Tight-coupling	Full integration	Total
Direction of integration	No integration	83 (26.0)	0 (0.0)	0 (0.0)	0 (0.0)	83 (26.0)
	One direction: GIS as principle software	0 (0.0)	99 (31.0)	40 (12.5)	14 (4.4)	153 (48.0)
	One direction: MCDA as principle software	0 (0.0)	7 (2.2)	26 (8.2)	7 (2.2)	40 (12.5)
	Bi-directional integration	0 (0.0)	0 (0.0)	21 (6.6)	8 (2.5)	29 (9.1)
	Dynamic integration	0 (0.0)	0 (0.0)	8 (2.5)	6 (1.9)	14 (4.4)
	Total	83 (26.0)	106 (33.2)	95 (29.8)	35 (11.0)	319 (100.0)

Note: the numbers in parentheses are the percentages of the total number of articles.

software for integrating MCDA and GIS (e.g. Jun 2000, Malczewski *et al.* 2003). The MCDA as the principle software strategy for integrating MCDA and GIS was used in 12.5% of the research (e.g. Antoine *et al.* 1997, Kächele and Dabbert 2002).

4.4 *Application domains and decision problems*

One of the most remarkable features of the GIS-MCDA approaches is the wide range of decision and management situations in which they have been applied over the last 15 years or so. Table 8 shows a cross-classification of the GIS-MCDA articles according to the type of decision (and management) problems and application domain. Major application areas were found to be in environmental planning/ecology and management (e.g. Pereira and Duckstein 1993, Villa *et al.* 1996, Bojórquez-Tapia *et al.* 2001, Qureshi and Harrison 2001, Noss *et al.* 2002, Seppelt and Voinov 2002, and Church *et al.* 2003), transportation (e.g. Church *et al.* 1992, Jankowski and Richard 1994, Bowerman *et al.* 1995, Weigel and Cao 1999, and Jha *et al.* 2001), urban and regional planning (e.g. Wu 1998, Feng and Lin 1999, Gomes and Lins 2002, and Ward *et al.* 2003), waste management (Carver 1991, Kao 1996, Kao and Lin 1996, MacDonald 1996, Charnpratheep *et al.* 1997, and Leão *et al.* 2004), hydrology and water resource (Langevin *et al.* 1991, Reitsma and Carron 1997, Tkach and Simonovic 1997, Giupponi *et al.* 1999, Lee *et al.* 2000, Makropoulos *et al.* 2003, Martin *et al.* 2003), agriculture (e.g. Matthews *et al.* 1999, Kächele and Dabbert 2002, Ceballos-Silva and Lopez-Blanco 2003, and Morari *et al.* 2004), and forestry (Vertinsky *et al.* 1994, Kangas *et al.* 2000, Riedl *et al.* 2000, Schlaepfer *et al.* 2002, Kyem 2004). These applications accounted for 72.4% of the total. The rest of the GIS-MCDA applications were found in areas such as natural hazard management (e.g. Rashed and Weeks 2003, Ayalew *et al.* 2004), recreation and tourism management (e.g. Feick and Hall 1999, 2004), housing and real estate (e.g. Can 1992, Johnson 2001), geology and geomorphology (e.g. de Araújo and Macedo 2002, Burton and Rosenbaum (2003), industrial facility management (e.g. Jun 2000, Vlachopoulou *et al.* 2001), and cartography (e.g. Huffman and Cromley 2002, Armstrong *et al.* 2003).

The survey showed that the GIS-MCDA approaches were most often used for tackling land suitability problems (table 8). Almost 30% of the articles were concerned with land suitability analysis. This type of analysis was most frequently used in such application domains as: ecology and environment (e.g. Pereira and Duckstein 1993, Bojórquez-Tapia *et al.* 2001), forestry (e.g. Riedl *et al.* 2000, Kyem 2004), agriculture (e.g. Ceballos-Silva and Lopez-Blanco 2003), waste management (e.g. Carver 1991, Charnpratheep *et al.* 1997), and natural hazard management (e.g. Rashed and Weeks 2003, Ayalew *et al.* 2004). Plan/scenario evaluation problems accounted for 15.4% of the total (e.g. Kangas *et al.* 2000, Martin *et al.* 2003). The types of problems were especially often tackled in the water resource application domain (e.g. Kächele and Dabbert 2002, Morari *et al.* 2004). In addition, the site search/selection problems (e.g. Aguilar-Manjarrez and Ross 1995, Cova and Church 2000, Rinner and Malczewski 2002) and the resource allocation problems (e.g. Aerts and Heuvelink 2002, Aerts *et al.* 2003, Stewart *et al.* 2004) were found in a substantial portion of the GIS-MCDA articles (approximately 14.5% and 11.0% of the total, respectively).

5. Conclusions

The last 15 years have evidenced remarkable progress in the quantity and quality of research in integrating GIS and MCDA. The multidisciplinary field of GIS-MCDA

Table 8. Classification of the GIS-MCDA articles according to the extent of integration and the application domain and decision problem.

		Decision/evaluation problems									
		Land suitability	Plan/scenario evaluation	Site search/ selection	Resources allocation	Transportation/ vehicle routing/ scheduling	Impact assessment	Location-allocation	Miscellaneous	Total	%
Application domains	Environment/ Ecology	19	8	3	10	0	5	0	10	55	17.2
	Transportation	3	2	0	0	13	2	0	9	34	10.7
	Urban/Regional planning	4	8	5	10	1	0	3	6	32	10.0
	Waste management	11	2	5	0	7	0	1	0	29	9.1
	Hydrology/Water resource	4	11	4	2	0	1	0	6	28	8.8
	Agriculture	8	3	4	7	0	2	0	2	27	8.5
	Forestry	12	2	8	3	3	0	0	2	26	8.2
	Natural hazard	9	4	0	0	1	0	0	1	15	4.7
	Recreation/Tourism	3	2	6	0	0	0	0	3	14	4.4
	Housing/Real estate	4	3	2	1	0	0	0	2	12	3.8
	Geology/ Geomorphology	3	0	0	0	0	1	0	5	9	2.8
	Manufacturing	3	0	4	0	0	0	0	0	7	2.2
	Cartography	0	0	0	0	0	0	0	5	5	1.6
	Miscellaneous	8	4	5	2	0	0	3	4	26	8.2
	Total	91	49	46	35	25	11	7	55	319	100.0
	%	28.5	15.4	14.5	11.0	7.8	3.4	2.2	17.2	100.0	

has been widely and strongly adopted within the GIS community. Quite correctly, the GIS community recognizes the great benefits to be gained by incorporating MCDA into a suite of GIS capabilities. This survey suggests that GIS-MCDA has generated a large enough literature allowing it to be considered as an essential subfield of research in GIScience. GIS-MCDA has been vital in advancing GIScience in two major areas: spatial decision support and participatory GIS.

The efforts to integrate MCDA into GIS has been instrumental for developing the paradigm of spatial decision support (Goodchild 1993), in which the geographic information technology is made available directly to decision-makers for policy or scenario development (Eastman *et al.* 1993, Malczewski 1999, Jankowski and Nyerges 2001, Ascough *et al.* 2002). The major advantage of incorporating MCDA techniques into GIS-based procedures is that the decision-makers can insert value judgments (their preferences with respect to evaluation criteria and/or alternatives) into GIS-based decision-making procedures, and receive feedback on their implications for policy evaluation. Such feedback can enhance the decision-maker's confidence in the results, consistent with general findings in the decision support system literature on the importance of feedback (e.g. Limayem and DeSanctis 2000). MCDA provides mechanisms for revealing decision-makers' preferences, and for identifying and exploring compromise alternatives. It can help users understand the results of GIS-based decision-making procedures, including tradeoffs among policy objectives, and use those results in a systematic, defensible way to develop policy recommendations.

The GIS-MCDA research has made considerable contribution to the participatory GIScience (Jankowski and Nyerges 2001). By their nature, the MCDA approaches integrate multiple views of decision problems. They may improve communication and understanding among multiple decision-makers and facilitate ways of building consensus and reaching policy compromises. Consequently, the GIS-MCDA support systems have the potential to improve collaborative decision making process by providing a flexible problem-solving environment where those involved in collaborative tasks can explore, understand, and redefine a decision problem (Feick and Hall 1999, Jankowski and Nyerges 2001, Kyem 2004). An integration of MCDA into GIS can support collaborative work by providing a tool for structuring group decision-making problems and organizing communication in a group setting. MCDA provides a framework for handling the debate on the identification of components of a decision problem, organizing the elements into a hierarchical structure, understanding the relationships between components of the problem, and stimulating communication among participants.

The survey has revealed several problems, challenges and trends in the GIS-MCDA research. They are related to the developments in geographic information technology and spatial analysis, as well as the developments in the area of conceptual and operational validation of the use of MCDA in real-world spatial problems. The development of GIS-MCDA has been paralleled by the evolution of geographic information technology. GIS systems have evolved from a 'close' expert-oriented to an 'open' user-oriented technology. This trend has stimulated a movement in the GIS community towards using the technology to increase the democratization of the decision-making process via public participation. Malczewski (2004) suggests that it is in the context of the debate on the interrelationship between GIS and society (Pickles 1995) that one can see the potential for advancing the role of GIS-MCDA in the participatory GIScience.

Specifically, GIS-MCDA should be constructed with two perspectives in mind: the techno-positivist perspective on GIS, and the socio-political, participatory GIS perspective. It is expected that the trend towards advancing public participatory approach to GIS-MCDA system design and application development will be of critical importance for a successful use of the GIS-MCDA approaches in the real-world decision situations (Jankowski and Nyerges 2001). Ascough *et al.* (2002) suggest that the development of GIS-MCDA must absorb new trends in geographical information technology including the Web-based applications (e.g. Zhu and Dale 2001, Rinner and Malczewski 2002, Hossack *et al.* 2004, Sakamoto and Fukui 2004) and location-based services. In the context of OpenGIS, the GIS-MCDA approaches could be made available as services rather than systems (Rinner 2003). Preliminary efforts to integrate MCDA into the location-based services have also been undertaken (e.g. Rinner and Raubal 2004).

Recent developments in spatial analysis show that geo-computation (computational intelligence) offers new opportunities for GIS-MCDA (Wu 1998, Zhou and Civco 1996, Bennett *et al.* 1999, Xiao *et al.* 2002). Geo-computational tools can potentially help in modeling and describing complex systems for inference and decision-making. An integration of MCDA and geo-computation can enhance the GIS-MCDA capabilities of handling larger and more diverse spatial data sets. Another significant trend has been associated with developing map-centered-exploratory approaches to GIS-MCDA (Armstrong *et al.* 1992, Jankowski *et al.* 2001, Andrienko and Andrienko 2003). The main purpose of these approaches is to provide the decision-maker with insights into the nature of spatial decision problems not readily obtained by conventional methods (such as tabular displays). The power of map-centered-exploratory analysis comes from the confidence in the GIS-based MCDA procedures that grows as decision-makers see the procedures confirm their understanding of the decision problem at hand.

The GIS-MCDA research has tended to concentrate on the technical questions of integrating MCDA into GIS. As a consequence, our understanding of the benefits of such integration is limited by the lack of research on conceptual and operational validation of the use of MCDA in solving real-world spatial problems. Very little empirical research has been undertaken to appreciate the dynamics of spatial decision making (Jankowski and Nyerges 2001). There are also other, more general, concerns surrounding the use of multicriteria decision methods in GIS that require careful consideration. In the MCDA community there has been much discussion focused on the theoretical foundations and operational validation of the MCDA methods (Bana e Costa *et al.* 1997). It is argued that some MCDA procedures are lacking a proper scientific foundation and some methods involve a set of stringent assumptions, which are difficult to substantiate in real-world situations (e.g. Hobbs 1980, Hwang and Yoon 1981, Bana e Costa *et al.* 1997). To a large extent, these problems have been ignored by the GIS-MCDA community. If a primary purpose of GIS-MCDA is to process and synthesize a large number of value judgments and spatial data sets, and to examine the implications of those value judgments for planning and policy-making, then more careful attention must be paid to the assumptions underlying the multicriteria procedures.

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Appendix 1

The following Web-based electronic libraries and databases were searched for relevant articles:

IEEE Xplore® (http://ieeexplore.ieee.org/Xplore),
Ingenta (http://www.ingentaconnect.com),
Inspec® (http://www.engineeringvillage2.org),
ISI Web of Knowledge™ (http://isi10.isiknowledge.com),
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Project MUSE® (http://muse.jhu.edu),
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