Chapter 3
Development of GIS-MCDA

3.1 Introduction

There are two main research traditions that influence methods and models of GIS-MCDA: Operations Research and Management Sciences (OR/MS) and landscape architecture/planning. OR/MS is typically associated with mathematical-based problem solving methods and approaches to decision making. Disciplines such as decision sciences, information sciences, behavioural sciences, and some aspects of systems analysis, are often included under the broad heading of OR/MS. Landscape architecture aims to apply scientific principles to the planning, designing, and managing of natural and built environments. It uses a systematic approach for analyzing social, ecological, geological, and geomorphologic conditions, and designing plans that will produce the desired outcome. The research interests of these two traditions, OR/MS and landscape architecture, meet at the application of their approaches to the land use planning and management. This common research interest resulted, *inter alia*, in establishing the GIS-MCDA paradigm.

This chapter traces the roots of GIS-MCDA and focuses on the recent developments in GIS-MCDA research. Specifically, we describe two research traditions underlying the development of GIS-MCDA: OR/MS and landscape architecture/planning. This is followed by an overview of the developments in GIS-MCDA research and applications for the last 20 years or so. The overview is based on a survey of relevant papers published in refereed journals.

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3.2 Historical Background

3.2.1 The Origins of GIS-MCDA

The roots of MCDA can be traced back to the eighteenth century works on ranked preferential voting systems, which was credited to J.C. Borda and N. Condorcet. However, it was not until the second half of the nineteenth century that the fundamental concepts of MCDA were established by F.Y. Edgeworth and V. Pareto. They proposed an approach for combining conflicting criteria into a single evaluation index. Pareto also introduced one of the fundamental elements of modern MCDA theory: the concept of efficiency (also known as Pareto optimality). Pareto's work has been instrumental for the development of MCDA within the broader field of OR/MS. Indeed, one of the precursors of today's GIS-MCDA was the introduction of systems analysis, first in OR/MS and then in such disciplines as regional science (Isard 1969), urban and regional planning (Chadwick 1973), and geography (Chorley and Haggett 1967). Within OR/MS, earlier theoretical work (e.g., Koopmans 1951; Gass and Saaty 1955) provided the basis for later algorithmic developments of multicriteria programming (Charnes and Cooper 1961). Neumann and Morgenstern (1944) introduced the expected utility theory and proposed axioms of rationality, thus setting the foundations of another MCDA approach. Their work formed the core of modern decision theory. Churchman et al. (1957) were among the earlier scholars to look at the multicriteria problem formally using a simple additive weighting method. In the mid-1960s, Roy and his colleagues at SEMA METRA International developed a MCDA approach based on the concept of outranking relations (Roy 1968).

A second and quite distinct history of GIS-MCDA stems from landscape architecture and spatial planning. This perspective has its roots in the application of hand-drawn map overlay techniques used by American landscape architects in the late nineteenth and early twentieth century (Steinitz et al. 1976; Collins et al. 2001). Such landscape architects as C. Eliot and W. Manning provided detailed descriptions of the overlay procedures, but neither of them gave explicit explanations of their underlying intellectual rationales (Steinitz et al. 1976). McHarg (1969) advanced the overlay techniques by proposing a procedure that involved mapping data on the natural and human-made attributes of the environment within a study area, and then presenting this information on individual, transparent maps using light to dark shading (high suitability to low suitability) and superimposing the individual transparent maps to construct the overall suitability maps for each land use. Although McHarg's approach is widely recognized as a precursor to the classic overlay procedures in GIS, some researchers credit C. Eliot (Miller 1993) and J. Tyrwhitt (Steinitz et al. 1976) as predecessors of the modern map overlay techniques. Tomlinson (1999) suggests that it was his company, Spartan Air Services of Ottawa, which first proposed computerizing the overlay method in 1962. The overlay method was perhaps the single most important precursor to later forms of complex GIS-MCDA methods.

3.2.2 Development of GIS-MCDA

The evolution of GIS-MCDA has been a function of the development of information technologies (including geographic information technologies) and the evolving perspectives of planning/decision making. The modern GIS era can be divided into three time periods: (i) the GIS research frontier period in the 1950s–1970s, which can be referred to as the innovation stage, (ii) the development of general-purpose GIS in the 1980s, or the integration stage, and (iii) the proliferation stage, which is characterized by the development of the user-oriented GIS technology over the last 20 years or so (Foresman 1998; Waters 1998). Accordingly, the development of GIS-MCDA follow three similar stages: (i) the innovation stage (the advancements in GIS and OR/MS), (ii) the integration stage (the integration of cartographic modeling and MCDA), and (iii) the proliferation stage (the user-oriented GIS-MCDA).

3.2.2.1 Innovation: GIS and OR/MS

Although the foundations of systems thinking were developed in the 1940s, it was not until a considerable increase in accessibility to computer-based mathematical programming software in the 1960s that systems thinking became a practical proposition for decision making and planning (Isard 1969; Chadwick 1973). This development coincided with advances in computer technology, allowing for the development of automated systems for storing, manipulating, and displaying geographic data. The first systems we now call GIS were emerging in the 1960s, just as computers were becoming accessible to large government and academic institutions. Taking full advantage of the improvements in computer hardware technology required advancements in theories of spatial analysis based on computer handling of geographic data. These advancements took place during the 'quantitative revolution' in the spatial sciences in the 1950s–1960s (Berry and Marble 1968; Thomas and Huggett 1980).

During the 1970s, the usefulness of quantitative methods, including the single-objective approaches to spatial optimization problems, was increasingly questioned. The criticism was part of a broader critique of the positivist paradigm that led to the adoption of a political perspective on planning and decision making. This perspective recognized that planning deals with socio-political systems that consists of interest groups with conflicting values and preferences, and therefore must include considerations of public participation, negotiation, compromise, consensus building, and conflict management and resolution (Couclelis 1991). The development of MCDA was one of the responses to the criticism of the classic system analysis and single-criterion (single-objective) approaches to spatial decision making and planning problems (Cohon 1978; Nijkamp 1979). Planners and regional scientists were among the first to advance the idea of combining multiobjective mathematical programming techniques with GIS/computer assisted mapping (see Diamond and Wright 1988).

The complexity of many spatial multiobjective optimization problems makes it impossible to solve them using the conventional mathematical programming methods. To solve such problems, heuristic and metaheuristics (artificial intelligence or AI methods) have been proposed. A. Turning was likely the first to use heuristic algorithms in the 1940s. His report on ‘Intelligent Machinery’ in 1948 (the National Physical Laboratory, UK) contained a number of innovative AI ideas, such as machine intelligence and learning, neural networks, and evolutionary algorithms (genetic algorithms). It was not, however, until the 1980s that significant advances in developing AI algorithms for solving multiobjective optimization problems were made. In 1985, J.D. Schaffer was presumably the first to use genetic algorithms to solve multiobjective optimization. Since then, many metaheuristic algorithms, such as simulated annealing, tabu search, ant colony, and particle swarm algorithms, have been proposed for solving multiobjective optimization problems (see Burke and Kendall 2005; Talbi 2009). This area of research has also been extended to GIS-based approaches for tackling complex spatial decision making and planning problems (Duh and Brown 2005; Xiao et al. 2002).

3.2.2.2 Integration: Cartographic Modeling and MCDA

Arguably, McHarg’s transparent map overlay approach to land-use suitability analysis has had a greater influence on the development of GIS-MCDA than any other single event in GIS history. The approach analyzes land-use suitability decision problems by representing each evaluation criterion as a transparent map with the darkest gradations of tones associated with the greatest value, and the lightest tones associated with the least significant value (McHarg 1969). All of the transparent criterion maps are then superimposed upon one another to identify the most suitable land for development. In the 1970s, McHarg’s approach has been used in several computer-assisted mapping and GIS applications (Murray et al. 1971; Turner and Miles 1971; Miller and Niemann 1972; Hobbs 1980).

The development of computer-assisted mapping coincided with a rapid change in availability of computer technologies in general, and geographic information technologies in particular. Although a couple of the major commercial GIS software companies (such as Environmental Systems Research Institute and Intergraph Corporation) were established at the end of the 1960s, it was not until the 1980s that numerous commercial GIS began to develop (e.g., ARC/INFO, MapInfo GIS, and TransCAD). At the same time, the scope of GIS applications in the 1980s widened by the range of related commercially available products of information technology including CAD (computer assisted design), DBMS (database management system), remote sensing, GPS (global positioning system), as well as an increase of digital data availability to private and public organizations. Further, as computing power increased and hardware prices plummeted in the 1980s, GIS became a viable technology for state and municipal planning, and academic departments. In this context, the development of low-cost raster-based GIS was critical. This development was inspired by work on cartographic modeling and map algebra (Tomlin 1990).

The development of cartographic modeling and map algebra was a pivotal step toward integrating GIS and MCDA. Broadly defined, cartographic modeling involves a set of related, ordered map operations that act on raw data, as well as derived and intermediate data, to simulate a spatial modeling process (Tomlin 1990). It is a generic method for organizing basic GIS operations into a complex spatial model. Map algebra techniques include fundamental methods of GIS-MCDA, such as Boolean screening and weighted map combination (overlay) procedures. The procedures play a central role in many GIS applications (O'Sullivan and Unwin 2010). They also form the basis of many approaches in GIS-MCDA (Eastman et al. 1993; Malczewski 2004; Duh and Brown 2005), including techniques that are at the forefront of advances in spatial decision analysis, such as artificial intelligence (geocomputation) (Sui 1993; Zhou and Civco 1996; Xiao et al. 2002), geosimulation (Benenson and Torrens 2004; Liu 2009), geovisualization (Jankowski et al. 2001; Andrienko et al. 2007), and Web-based GIS procedures (Carver 1999; Zhu and Dale 2001).

3.2.2.3 Proliferation: The User-Oriented GIS-MCDA

The notion of user-oriented GIS-MCDA stems from the view of planning as part of the larger socio-political system. A number of studies revealed that planning is more than the collection and provision of information that can improve the policy-making process (Harris 1989). It also involves a wide range of 'intangible' activities, attitudes, and values. While some elements of the planning process may be well defined, there are significant components of subjective knowledge involved in the process Klosterman (2001). Combining the objective and subjective elements of the planning process in a computer based system lies at the core of the concept of SDSS in general and GIS-MCDA in particular (see Sects. 1.3 and 1.4).

Although the advent of desktop computing and cartographic modeling in the 1980s was instrumental in stimulating the integration of GIS and MCDA, it was not until the 1990s that GIS-MCDA established itself as an identifiable area of research within the GIScience literature (e.g., Janssen and Rietveld 1990; Carver 1991; Church et al. 1992; Banai 1993; Jankowski 1995; Malczewski 1999; Thill 1999). Until the end of the 1980s, the use of GIS remained a highly specialized professional activity. This notion changed in the 1990s, with GIS becoming regarded as a routine software application within the grasp of lay individuals. At the same time, better awareness of the value of digital spatial data and GIS-based solutions to planning and management problems produced a large market for GIS. The technological progress has been accompanied by an explosion of digital data available to private and public sector organizations.

One of the more significant trends has been the evolution from individual stand-alone computers to the highly interconnected telecommunications network environments of today. The Internet and World Wide Web, more commonly known as the Web, created an environment with almost ubiquitous access to a world of information. At the same time, many organizational decisions migrated from individual decisions to ones made by small teams and to complex decisions made by large diverse groups of individuals. In this environment, several key technological developments occurred in the area of decision support. Various tools to support collaboration and group processes have been developed, implemented, evaluated, and refined (Nyerges and Jankowski 2010; Sugumaran and DeGroote 2011). Accordingly, GIS-MCDA has been applied as a collaborative decision support system allowing interest groups to interact with public or private planning agencies (see Carver 1999).

The increasing accessibility of GIS to the general public resulted in a greater recognition of the importance of decision analysis and support within the broader field of GIScience, as exemplified by a series of the NCGIA Initiatives (see NCGIA 2014). These Initiatives have stimulated the development of spatial decision support tools including GIS-MCDA (Jankowski and Nyerges 2001). Indeed, efforts to integrate MCDA into GIS have been instrumental for developing the paradigm of spatial decision support (Eastman 1997; Malczewski 1999; Thill 1999; Ascough et al. 2002; Li et al. 2012; Reynolds and Hessburg 2014).

3.3 Recent Progress

Malczewski (2006) surveyed the GIS-MCDA literature with a comprehensive review of over three hundred refereed articles published from 1990 through 2004 (a list of these articles can be found at http://publish.uwo.ca/~jmalczew/gis-mcda.htm). The list has been updated to include articles published from 2005 through 2010. In total, 805 articles have been published in the period between 1990 and 2010. Figure 3.1 shows that the development of GIS-MCDA was rather modest in the first half of the 1990s. The second half of the 1990s witnessed an increased growth in the number of the GIS-MCDA articles. This growth accelerated over the last decade such that almost 70 % of the total was published from 2005 through 2010 inclusive.

The rapid increase in the volume of GIS-MCDA research can be attributed to two main factors. First, during the 1990s, increasingly powerful personal computer-based GIS and decision analysis software was developed, refined, and utilized in applications. Second, there was a general recognition of the importance of decision analysis and support within the broader field of GIScience. Together these factors gave impetus to considerable progress in the quantity and quality of research on integrating GIS and MCDA. During this relatively short period, there was consolidation of previous research, as well as an expansion into new substantive and technical areas. It can be argued that GIS-MCDA research has generated enough literature for it to be regarded as a legitimate subfield of research within GIScience (Thill 1999; Malczewski 2006; Chakhar and Mousseau 2008; Sugumaran and DeGroote 2011).

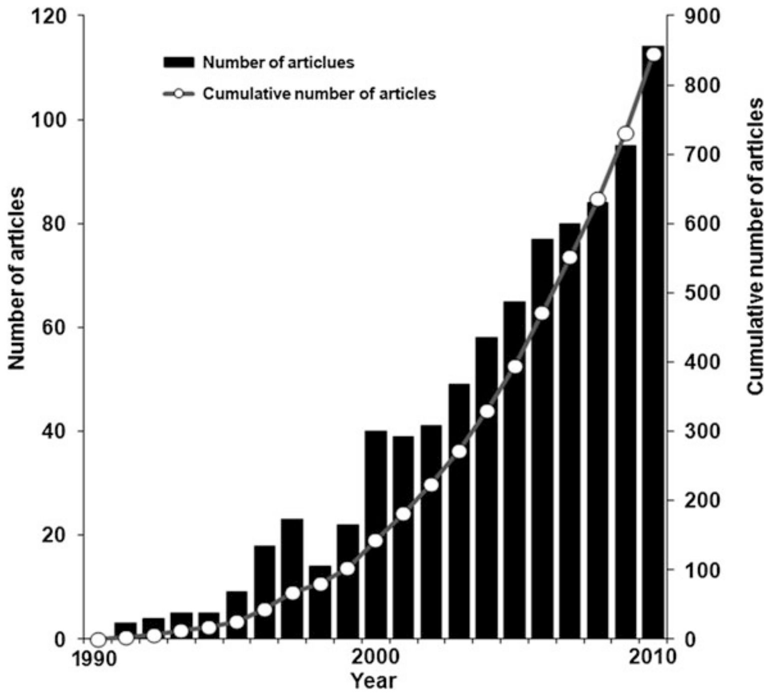

Fig. 3.1 The number of the GIS-MCDA articles published in refereed journals, 1990–2010 (*Note* the graph is based on the data for 1990–2004 taken from Malczewski (2006) and updated for 2005–2010)

3.3.1 Taxonomy of GIS-MCDA

Malczewski (2006) developed two classification schemes for the GIS-MCDA literature. First, all articles were classified based on the GIS components of GIS-MCDA methods. This classification involved the following considerations: (i) the geographic 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 elements of the MCDA methods. This taxonomy was based on the following considerations: (i) the nature of evaluation criteria, (ii) the number of individuals involved in the decision making process, and (iii) the nature of uncertainties.

3.3.2 GIS Components of GIS-MCDA

Figure 3.2 shows a classification of the GIS-MCDA approaches according to the GIS (spatial) components. There are two levels of the classification. First, the GIS-MCDA approaches can be subdivided into two groups: the raster-data-based

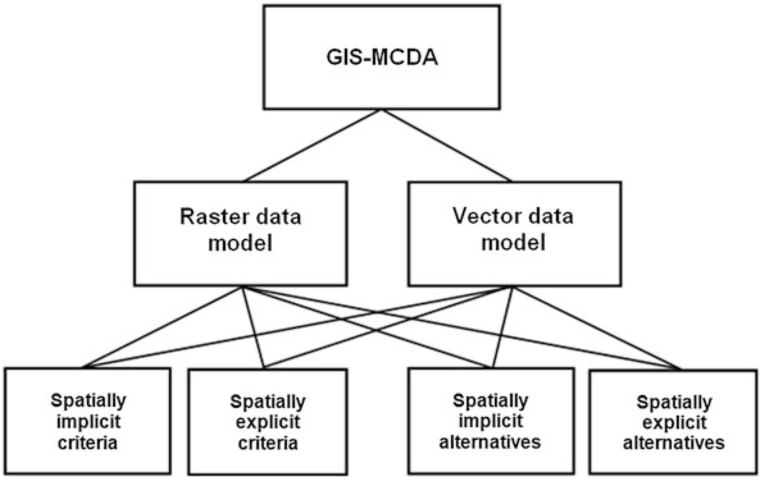

Fig. 3.2 Classification scheme for GIS components of GIS-MCDA

methods (e.g., Pereira and Duckstein 1993; Eastman et al. 1995; Malczewski 1996; Cromley and Hanink 1999; Church et al. 2003; Aerts et al. 2005), and the vector-data-based methods (e.g., Can 1992; Jankowski 1995; Laaribi et al. 1996; Rinner and Malczewski 2002; Feick and Hall 2004). It is important to note that some of the GIS-MCDA approaches have been based on the use of both the raster and vector data models. It was, however, the geographic data structure used in the multicriteria combination rules that provided the bases for classifying GIS-MCDA according to the geographic data model (Malczewski 2006). Thus, if the combination rules are performed using the raster data, then the study is categorized as the raster-based MCDA. Similarly, the vector-based multicriteria combination rules are categorized as the vector-based MCDA approaches, irrespectively 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).

Second, the raster- and vector-based GIS-MCDA approaches can further be categorized according to the nature of decision alternatives and evaluation criteria. Both alternatives and criteria can be classified into: spatially explicit and spatially implicitly categories (Herwijnen and Rietveld 1999; Malczewski 2006). These two categories are not mutually exclusive. According to Malczewski's (2006) survey, a majority of the GIS-MCDA studies (almost 70 %) involved a combination of spatially implicit and explicit criteria (e.g., Kao and Lin 1996; Antoine et al. 1997; Lin et al. 1997; Seppelt and Voinov 2002; Wu et al. 2004). Brookes (1997), Cromley and Hanink (1999, 2003), Church et al. (2003) and Malczewski (2011) provide examples of the raster-based GIS-MCDA involving a set of spatially explicit criteria. Examples of the raster-based spatially implicit criteria are given in

Brakewood and Grasso (2000), Fuller et al. (2003), Store and Jokimäki (2003), Feick and Hall (2004), and Ligmann-Zielinska and Jankowski (2012). The vector-based GIS-MCDA methods can also involve two categories of criteria: spatially explicit criteria (e.g., MacDonald 1996; Weigel and Cao 1999), and spatially implicit criteria (e.g., Vertinsky et al. 1994; Kächele and Dabbert 2002).

The spatial components of GIS-MCDA can also be examined in the context of the three categories of GIS-MCDA: the conventional MCDA, spatially explicit MCDA, and spatial multiobjective optimization (see Sect. 1.4). A vast majority of the GIS-MCDA approaches use the conventional (aspatial) MCDA methods for tackling spatial problems (e.g., Carver 1991; Banai 1993; Eastman et al. 1993; Malczewski 2000; Zhu and Dale 2001). The most popular MCDA methods include: the weighted linear combination and related procedures (e.g., Carver 1991; Eastman et al. 1993; Malczewski 2000), ideal/reference point methods (e.g., Pereira and Duckstein 1993; Malczewski 1996), the analytical hierarchy/network process (e.g., Banai 1993; Zhu and Dale 2001; Marinoni 2004), and outranking methods (e.g., Carver 1991; Joerin et al. 2001; Martin et al. 2003). Based on the criticism of the capabilities of conventional MCDA methods to tackle spatial problems, a number of approaches have been proposed to incorporate the spatial components of MCDA explicitly (e.g., Tkach and Simonovic 1997; Herwijnen and Rietveld 1999; Makropoulos and Butler 2006; Rinner and Heppleston 2006; Chakhar and Mousseau 2008; Ligmann-Zielinska and Jankowski 2008, 2012; Malczewski 2011; Carter and Rinner 2014). Spatial multiobjective optimization methods have been specifically designed for tackling spatial decision situations in which the decision/management alternatives have a geographic connotation such as location, distance, or connectivity. Examples of the spatial multiobjective optimization methods are given in Bennett et al. (1999), Huang et al. (2006), Li et al. (2009a, b), Meyer et al. (2009), Datta et al. (2012), Coutinho-Rodrigues et al. (2012), and Maliszewski et al. (2012). Many of those approaches involve metaheuristics for solving spatial multiobjective problems (e.g., Bennett et al. 1999; Huang et al. 2006; Li et al. 2009a, b; Datta et al. 2012).

3.3.3 MCDA Components of GIS-MCDA

Criterion is a generic term including both the concept of attribute and objective (see Sect. 2.2.2). Accordingly, GIS-MCDA can be classified into two categories: multi-attribute decision analysis (GIS-MADA) and multi-objective decision analysis (GIS-MODA) (see Fig. 3.3). A majority of the GIS-MCDA approaches falls into the GIS-MADA category (see Malczewski 2006). Banai (1993), Pereira and Duckstein (1993), Jankowski (1995), Eastman et al. (1995) and Jun (2000) provide examples of GIS-MADA. The GIS-MODA approaches are presented in Antoine et al. (1997), Seppelt and Voinov (2002), Aerts et al. (2003), Xiao et al. (2002), Armstrong et al. (2003), Stewart et al. (2004), Ligmann-Zielinska et al. (2008), and Maliszewski et al. (2012), to mention a few.

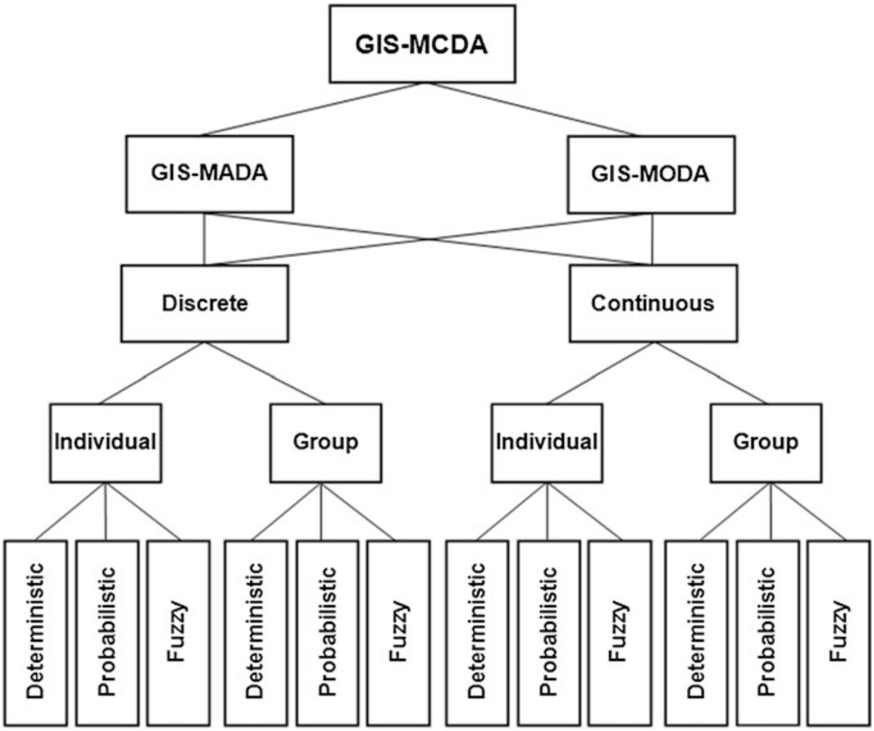

Fig. 3.3 Classification scheme for MCDA components of GIS-MCDA

GIS-MCDA approaches can also be categorized into discrete and continuous methods, depending on the definition of decision alternatives (decision variables) (see Sect. 2.2.3). The survey of GIS-MCDA shows there is an overlap between GIS-MADA and discrete multicriteria analysis on the one hand, and between GIS-MODA and continuous multicriteria analysis on the other (see Malczewski 2006). A vast majority of the GIS-MADA approaches have been used for tackling talking discrete spatial decision problems (e.g., Carver 1991; Banai 1993; Pereira and Duckstein 1993). There have been a few studies representing the GIS-continuous MADA (e.g., Varma et al. 2000; Prato 2008). This type of approaches typically involves a multiattribute utility mathematical programming based on an assessment of utility functions (see Goicoechea et al. 1982). In addition, there have been several GIS-MADA studies involving the mixed-integer mathematical programming models (e.g., Lin and Kao 2005; Wu and Murray 2005; Eiselt 2007; Ligmann-Zielinska et al. 2008). The continuous models have typically been used in the context of multiobjective mathematical programming (e.g., Lanta et al. 2005; Roetter et al. 2005; Santé-Riveira et al. 2008).

The GIS-MADA and GIS-MODA approaches can be further subdivided into two categories: individual and group decision making. This classification is based on the goal-preference structure of the decision maker. 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 (see Sect. 2.2.1). On the other hand, if the individuals involved in the decision making process are characterized by different goal-preference structures, then the problem becomes that of group decision making. A majority of the GIS-MCDA articles represented the individual decision maker's approaches (Malczewski 2006). These approaches can be found in both GIS-MADA (e.g., Carver 1991; Banai 1993; Pereira and Duckstein 1993; Eastman et al. 1995; Jun 2000) and GIS-MODA (e.g., Church et al. 1992; Xiang 1993; Kao 1996; Antoine et al. 1997; Aerts et al. 2003). The group/participatory approaches are presented in Malczewski (1996), Feick and Hall (2002), Bailey et al. (2003), Jankowski et al. (2008), and Boroushaki and Malczewski (2010b). These studies are based on the GIS-MADA methods. There is a relatively small number of applications using GIS-MODA for group decision making (e.g., Bennett et al. 1999; Seppelt and Voinov 2002; Bayliss et al. 2003). The group decision making category includes the participatory decision making approaches (Jankowski and Nyerges 2001). Participatory GIS-MCDA is a general concept that includes Group GIS-MCDA and Public Participation GIS-MCDA. This distinction is based on the size of group involved in the decision making process (Balram and Dragićević 2006). The Group GIS-MCDA applications typically involve a small group of participants (e.g., Feick and Hall 2004; Norese and Toso 2004). The Public Participation GIS-MCDA applications are based on the involvement of a large group of participants (e.g., Bojorquez-Tapia et al. 2004; Jankowski and Nyerges 2001; Boroushaki and Malczewski 2010a).

The GIS-MCDA studies can also be categorized according to the amount of information about the decision situation that is available to the decision maker/analyst. To this end, one can distinguish three categories of decision problems: deterministic, probabilistic, and fuzzy. If the decision maker has perfect knowledge of the decision environment, then the decision is made under conditions of certainty (deterministic decision making). 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, majority of the GIS-MCDA studies fall into the deterministic category (e.g., Carver 1991; Jankowski and Richard 1994; Brookes 1997; Marinoni 2004).

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 (Malczewski 1999). Consequently, both multiattribute and multiobjective problems under uncertainty can be further subdivided into: *probabilistic* (or stochastic) (e.g., Klungboonkrong and Taylor 1998; Seppelt and Voinov 2002; Prato 2008) and *fuzzy* decision making problems depending on the type of uncertainty involved (e.g., Banai 1993; Jiang and Eastman 2000; Joerin et al. 2001; Bailey et al. 2003; Makropoulos et al. 2003; Chen et al. 2010; Qiu et al. 2014).

3.3.4 Integration of GIS and MCDA

From the perspective of MC-SDSS (see Sect. 1.3.2), it is useful to identify the different approaches for integrating GIS and MCDA. These approaches can be categorized according to: the extent of integration and the direction of integration of GIS and MCDA. Three categories can be identified based on the extent of integration: (i) loose-coupling, (ii) tight-coupling, and (iii) full integration (Goodchild 1992; Nyerges 1992; Jankowski 1995; 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 (e.g., Guimarães Pereira et al. 1994; Jankowski 1995). 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 common user-interface (e.g., Bennett et al. 1999; Riedl et al. 2000). A more complete integration can be achieved by creating user-specified routines using generic programming languages. The routines then can 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 (e.g., Eastman et al. 1995; Matthews et al. 1999; Yatsalo et al. 2010).

The GIS-MCDA approaches can also be classified in terms of the direction of integration. This type of classification includes four categories: (i) one-directional integration with GIS as principal software, (ii) one-directional integration with MCDA system as principal software, (iii) bi-directional integration, and (iv) dynamic integration (see Nyerges 1992; Jun 2000). One-directional integration provides mechanisms 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 principal software. Jun (2000) and Malczewski et al. (2003) provide examples of the one-directional integration with GIS as the principal software. MCDA as the principal software for integrating MCDA and GIS was used in Antoine et al. (1997), and Kächele and Dabbert (2002). 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; Yatsalo et al. 2010).

3.3.5 Application Domains

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. Table 3.1 shows the major areas of the GIS-MCDA applications and a sample of relevant studies. According to Malczewski's (2006) survey, the major application areas include: environmental planning/management, transportation, urban and regional planning, waste management, hydrology and water resource, agriculture,

Table 3.1 Application domains of GIS-MCDA

Application domain	References
Environmental planning/ management	Pereira and Duckstein (1993), Bojórquez-Tapia et al. (2001), Noss et al. (2002), Seppelt and Voinov, 2002, Geneletti (2007), Lesslie et al. (2008), Çelik and Türk (2011) and Hessburg et al. (2013)
Transportation planning/ management	Church et al. (1992), Weigel and Cao (1999), Jha et al. (2001), Farhan and Murray (2008), Alçada-Almeida et al. (2009), Coutinho-Rodrigues et al. (2012) and Maliszewski et al. (2012)
Urban/regional planning	Wu (1998), Feng and Lin (1999), Gomes and Lins (2002), Ward et al. (2003), Ligmann-Zielinska et al. (2008) and Plata-Rocha et al. (2011)
Waste management	Carver (1991), Kao (1996), Kao and Lin (1996), MacDonald (1996), Charnpratheep et al. (1997), Leão et al. (2004) and Ferretti (2011)
Hydrology and water resource management	Reitsma and Carron (1997), Tkach and Simonovic (1997), Giupponi et al. (1999), Lee et al. (2000), Makropoulos et al. (2003), Martin et al. (2003), Chen et al. (2011)
Natural hazard	Rashed and Weeks (2003), Ayalew et al. (2004), Gorsevski et al. (2006), Ozturk and Batuk (2011) and Lai et al. (2013)
Agriculture	Matthews et al. (1999), Kächele and Dabbert (2002), Ceballos-Silva and Lopez-Blanco (2003), Meyer et al. (2009), Chen et al. (2010) and Cisneros et al. (2011)
Forestry	Vertinsky et al. (1994), Kangas et al. (2000), Riedl et al. (2000), Schlaepfer et al. (2002), Gilliams et al. (2005) and Zeng et al. (2007)

and forestry. These domains account for more than 70 % of all GIS-MCDA applications (Malczewski 2006). In addition, the GIS-MCDA methods have found their applications in such diverse domains as: recreation and tourism management (e.g., Feick and Hall 1999, 2004), housing and real estate (e.g., Can 1992; Johnson 2001; Malczewski and Rinner 2005), geology and geomorphology (e.g., 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).

Some decisions are more important than others in terms of their immediate impact or significance. Therefore, it is instructive to look at the GIS-MCDA applications from the perspective of the decision levels. One can identify three levels of decision: *operational*, *tactical,* and *strategic*. The operational (or routine) decision problems are those that occur frequently and they are almost identical (a high degree of replication). The vehicle routing and scheduling problems are examples of this type of spatial optimization (e.g., Bowerman et al. 1995; Chang and Wei 1999; Lopes et al. 2008; Choi et al. 2009). The tactical level decisions tend to be medium range, medium significance, and with moderate consequences. Districting problems provide an example of a spatial optimization problem at the tactical level (e.g., November et al. 1996; Bong and Wang 2004). Strategic decisions are concerned with general direction, long-term goals, and values. These decisions are the least structured with the most uncertain outcome, partly because they reach far into the future and partly because they are of great significance. There are a number GIS-MCDA applications that are concerned with strategic decisions, such as locating major facilities (e.g., Carver 1991; Negi and Jain 2008; Zucca et al. 2008), land allocation (e.g., Aerts et al. 2005; Duh and Brown 2005), choice of environmental strategies (e.g., Martin et al. 2003; Bryan and Crossman 2008), and urban/regional development (e.g., Wu and Webster 1998; Plata-Rocha et al. 2011).

3.4 Conclusion

The multidisciplinary field of GIS-MCDA has been widely and strongly adopted within the GIScience community. The decision analysis community has also recognized it as an important area of application. The chapter overviewed recent development in GIS-MCDA, and also provided a brief historical background of the research traditions that have influenced the evolution of GIS-MCDA. Based on the survey of relevant publications, this chapter has presented taxonomy of GIS-MCDA research and applications. The survey suggests that the research and applications have focused on relatively small number of multiattribute methods including the weighted linear combination, ideal point methods, the AHP/ANP, and outranking methods. Also, a few multiobjective programming methods have been used for tackling spatial problems within the GIS environment. Another finding of the survey suggests that artificial intelligence approaches have increasingly been employed for solving complex spatial multiobjective problems. Part II of this book will discuss the most often used GIS-MCDA methods.

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