

Enhancing Geographical Information Systems Capabilities with Multi-Criteria Evaluation Functions

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ABSTRACT The essence of this paper is to present a strategy for integrating geographical information systems (GIS) and multicriteria analysis (MCA), a family of operations research/management science (OR/MS) tools that have experienced very successful applications in different domains since the 1960s. In fact, GIS has several limitations in the domain of spatial decision-aid. The remedy to these limitations is to integrate GIS technology with

OR/MS tools and especially with MCA. The long-term aim of such integration is to develop the so-called spatial decision support system (SDSS), which is devoted to help decision makers in spatial problems. Thus, a design of a SDSS is also presented in this paper.

KEYWORDS: Geographical information system, Multicriteria analysis, Spatial decision-aid, Spatial decision support system.

1. Introduction

A fully functional GIS is an integration of several components and different subsystems (see e.g., Maguire et al. 1991; Burrough and McDonnell 1998; Longley et al. 1999). It is devoted especially to collect, store, retrieve and analyze spatially-referenced data. Even though numerous practical applications have shown that GIS is a powerful tool of acquisition, management and analysis of spatially-referenced data, most of current OR/MS specialists (e.g. Janssen and Rietveld 1990; Carver 1991; Fischer and Nijkamp 1993; Laaribi et al. 1993, 1996; Malczewski 1999; Laaribi 2000) share the impression that the GIS is a limited tool in spatial decision-aid domain. This is due essentially to its lack of more powerful analytical tools enabling it to deal with spatial problems involving several parties with conflicting objectives/criteria.

Among the criticisms that have been addressed to GIS technology, we enumerate the following ones (Burrough 1990; Janssen and Rietveld 1990; Carver 1991; Goodchild 1992; Laaribi et al. 1993; Laaribi 2000):

- decision maker's preferences (e.g. criteria weights) are not taken into account by current GIS. Some raster-based GIS, however, allow ratios for criteria (e.g. starting with Version 4.1, the IDRISI GIS supports the AHP (Analytic Hierarchy Process) method of (Saaty 1980) for computing criteria weights) but these ratios are usually introduced prior to the solution(s) generation process, i.e., in a non-interactive manner;
- in most GIS packages spatial analytical functionalities lie mainly in the ability to perform deterministic overlay and buffer operations, which are of limited use when multiple and conflicting criteria are concerned;
- current GIS do not permit the assessment and comparison of different scenarios. They identify only solutions satisfying all criteria simultaneously;
- analytical functionalities found in most GIS are oriented towards the management of data not towards an effective analysis of them;
- overlaying technique that is found in nearly all standard GIS becomes difficult to comprehend when the number of layers increases. Moreover, overlaying methods consider that all features are of equal importance.

The remedy suggested by some researchers is to integrate the GIS with different OR/MS tools. Practically, the idea of integrating GIS with several OR/MS tools seems to be a long-term solution. In fact, this requires the development of a coherent theory of spatial analysis parallel to a theory of spatial data (Laaribi 2000). A more realistic solution is, however, to incorporate only a family of analytical methods into the GIS. Intuitively, the most suitable family is that of MCA, which is a family of OR/MS tools that have experienced very successful applications in different domains since the 1960s (Section 2 provides a brief description of MCA; more information on the subject are available in e.g.,

Hwang and Yoon 1981; Vincke 1992; Pomerol and Barba-Romero 1993; Roy and Bouyssou 1993; Roy 1996; Belton and Stewart 2002).

Perhaps, the most convincing argument that supports the idea of GIS-MCA integration is related to the complementarity of the two tools. In fact, the former is a powerful tool for managing spatially-referenced data, while the latter is an efficient tool for modeling spatial problems. Another important argument consists of the ability of MCA to support efficiently the different phases of the (Simon 1960)'s decision-making process phases (i.e. *intelligence*, *design* and *selection*).

The remaining of this paper is structured as follows. Section 2 presents the MCA paradigm. Then, Section 3 provides two solutions for extending the capabilities of GIS. The first long-term perspective solution looks at the development of the SDSS. The second short-term perspective solution focuses on the GIS-MCA integration. The proposed short-term strategy for integrating GIS and MCA is then discussed in Section 4. Some concluding remarks are given in Section 5.

2. Multicriteria analysis paradigm

It is quite difficult to define precisely MCA. However, various definitions appear in literature. One common definition is that of Roy (1996). Roy (1996) postulates that MCA is '*a decision-aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often contradictory, in order to guide the decision maker(s) towards a judicious choice*'.

Whatever the definition, it is generally assumed in MCA that the decision maker has to choose among several options or *alternatives*. The *set of alternatives* is the collection of all alternatives. Selecting an alternative among this set depends on many characteristics, often contradictory, called *criteria*. Accordingly, the decision maker will generally have to be contented with a *compromising solution*.

The multicriteria problems are commonly categorized as *continuous* or *discrete*, depending on the domain of alternatives (Zanakis et al. 1998). (Hwang and Yoon 1981) classify them as (i) multiple attribute decision-making (MADM), and (ii) multiple objective decision-making (MODM). According to Zanakis et al. (1998), the former deals with discrete, usually limited, number of pre-specified alternatives. The latter deals with variable decision values to be determined in a continuous or integer domain of infinite or large number of choices.

Different MCA models have been developed during the second half of the 20-th century (see Vincke 1992; Pomerol and Barba-Romero 1993; Roy and Bouyssou 1993; Maystre et al. 1994; Zanakis et al. 1998; Belton and Stewart 2002). They essentially differ from each other in the nature of the aggregation¹ procedure, i.e., the manner in which different alternatives are globally evaluated.

¹ The term 'aggregation' is used both in GIS and MCA literatures. In GIS community, this term implies spatial aggregation (e.g. aggregating spatial units). It is a combination function that 'aggregate' different map layers. In MCA community, this term implies functional aggregation of partial evaluations of alternatives (using, for e.g., weighed sum technique) into one global evaluation.

However, they may be categorized into two general models of MADM and MODM (Figure 1). These models, which will be detailed in the two next Sections, illustrate how the different elements of the decision problem are linked to each other. They are inspired from MADM general model of (Jankowski 1995).

2.1 Multiple attribute decision-making general model

The first requirement of nearly all MADM techniques is a *performance table* containing the evaluations or *criteria scores* of a *set of alternatives* on the basis of a *set of criteria*. Generally, the two sets are separately defined. A more adequate conception of the decision problem necessitates, however, that criteria and alternatives are jointly defined.

The next step in MADM consists of the *aggregation* of the different criteria scores using a specific *aggregation procedure* and taking into account the decision maker *preferences*, generally represented in terms of *weights* that are assigned to different criteria. The aggregation of criteria scores permits the decision maker to make comparison between the different alternatives on the basis of these scores. Aggregation procedures are somehow the identities of the MCA techniques. In MADM, they are usually categorized into two families: (i) outranking relation-based family, and (ii) utility function-based family (see Vincke 1992).

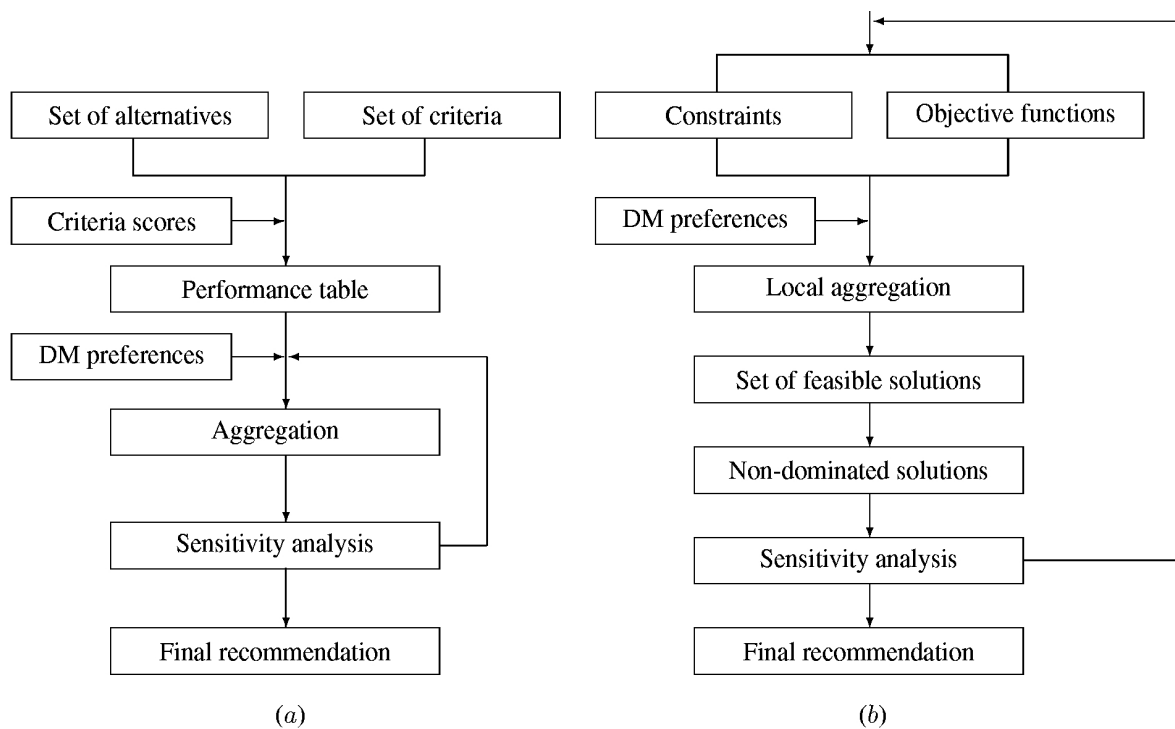


Figure 1. The MADM (a) and MODM (b) general models

In addition to weights, the decision maker's preferences may also take the form of *aspiration levels* or *cut-of values*. The aspiration level represents the degree of performance according to a given

criterion making the decision maker fully satisfied with an alternative in regard to the considered criterion, while the cut-of value represents the degree of performance which ought to be attained (or exceeded) by an alternative; otherwise, it is rejected.

The uncertainty and the fuzziness generally associated with any decision situation require a *sensitivity analysis* enabling the decision maker(s) to test the consistency of a given decision or its variation in response to any modification in the input data and/or in the decision maker preferences.

The aim of any decision model is to help the decision maker to make decisions. The *final recommendation* in MCA may take different forms, according to the manner in which a problem is stated. Roy (1996) identifies four types of results corresponding to four ways for stating a problem: (i) *choice* - selecting a restricted set of alternatives, (ii) *sorting* - assigning alternatives to different pre-defined categories, (iii) *raking* - classifying alternatives from best to worst with eventually equal positions or (iv) *description* - describing the alternatives and their follow-up results.

2.2 Multiple objective decision-making general model

The start point of any MODM technique is a set of *constraints* and a set of *objective functions*. The former set contains inequalities which reflect natural or artificial restrictions on the values of the input data. This means that feasible solutions are *implicitly* fixed in terms of these constraints.

In MODM, the decision maker preferences generally take the form of weights that are assigned to different objective functions. They may also be represented as *target values* that should be satisfied with any feasible solution. The decision maker should also indicate the nature of optimization for each objective function, i.e., maximization or minimization. No other information than the weights and the nature of optimization are required to define the set of *non-dominated solutions*. This set contains solutions that are not *dominated* by any other one. The set of non-dominated solutions is generally of a reduced size compared to the initial feasible solutions one. However, its generation usually requires a computer. This is explained by the high number of the initial feasible solutions to be evaluated.

Generally, *local and interactive aggregation algorithms* are used to define the feasible solutions set. This permits to combine the decision maker preferences and the computer to solve the decision problem, using methods that alternate calculation steps and dialogue steps. In reality, the local and interactive algorithms require the decision maker preferences to be expressed *progressively* during all the resolution process. The decision maker preferences, however, may be expressed *a priori* (i.e. before the resolution process) or *posteriori* (i.e. after the resolution process).

In many practical situations, the decision maker is called for to relax some of its constraints in order to guarantee that the set of feasible solutions is not empty or, simply, to test the stability of the results. Finally, we note that most of MODM problems are choice-oriented ones. Their aim is to find a 'best' solution (Vincke 1992). Table 1 shows some corresponding points between the MADM and MODM general models.

Table 1. Some characteristics of MADM and MODM general models

Multiple Attribute Decision-Making	Multiple Objective Decision-Making
Restricted set of alternatives	High or infinite number of feasible solutions
Explicitly defined set of alternatives	Implicitly defined set of feasible solutions
Aggregation function is based upon an outranking relation or a utility function	Uses a local and an interactive aggregation algorithms
Requires a priori information on the decision maker's preferences	Requires much less a priori information on the decision maker's preferences

3. Extending the capabilities of the GIS

As mentioned in the introduction, GIS technology is a limited tool in spatial decision-aid and an important question has emerged during the 1990s: *is the GIS a complete decision-aid tool?* Many recent works raise the crucial question of decision-aid within GIS (e.g. Janssen and Rietveld 1990; Carver 1991; Laaribi et al. 1993, 1996; Malczewski 1999). Most if not all of these works have come to the conclusion that GIS by itself can not be an efficient decision-aid tool and they have recommended the *marry* between GIS and OR/MS and computing tools. The long-term objective of such integration is to develop the so-called SDSS. The development of SDSS is an ambitious project that goes beyond the objective of this research. Instead, a design of a SDSS is proposed in the following section.

3.1 Long-term solution: Developing a SDSS

What really makes the difference between a SDSS and a traditional decision support system (DSS) is the particular nature of the geographic data considered in different spatial problems. In addition, traditional DSS are designed primarily for solving structured and simple problems which make them non practicable for complex spatial problems. Since the end of the 1980s, several researchers have oriented their works towards the extension of traditional DSS to SDSS that support spatially-related problems (e.g. Densham and Goodchild 1989; Densham 1991; Ryan 1992; Chevallier 1994; Jankowski and Ewart 1996; Leung 1997; Malczewski 1999). This requires to add to conventional DSS a range of specific techniques and functionalities used especially to manage spatial data,. These additional capacities enable the SDSS to (Densham 1991):

- acquire and manage the spatial data,
- represent the structure of geographical objects and their spatial relations,
- diffuse the results of the user queries and SDSS analysis according to different spatial forms including maps, graphs, etc., and

- perform an effective spatial analysis by the use of specific techniques.

In spite of their power in handling the first three operations, GIS are particularly limited tools in the fourth one. Moreover, even if the GIS can be used in spatial problem definition, they fail to support the ultimate and most important phase of the general decision-making process concerning the selection of an appropriate alternative. To achieve this requirement, other evaluation techniques instead of optimization or cost-benefit analysis ones are needed. Undoubtedly, these evaluation techniques should be based on MCA.

As has already been indicated, the GIS-MCA integration constitutes an intermediate solution towards the development of SDSS. Hence, to complete this integration successfully, it must be seen as an essential but not the only phase of a more general project that aims at developing the so-called SDSS. This project is beyond the scope of this research. However, a brief description of a design of a SDSS is provided hereafter.

The proposed design is conceived of in such a way that it supports GIS-MCA integration and is also open to incorporate any other OR/MS tool into the GIS. Figure 2 shows the components of the SDSS. These components are extensions of those of conventional DSS which are here enriched with other elements required: (i) to acquire, manage and store the spatially-referenced data, (ii) to perform the analysis of spatial problems, and (iii) to provide to the decision maker and/or analysts an interactive, convivial and adequate environment for performing an effective visual decision-aid activity. These components are briefly discussed hereafter.

Spatial data base management system The spatial data base management system (SDBMS) is an extension of the conventional database base management system (DBMS). It is used specially to manage spatial data.

Geographic data base The geographic data base (GDB) is an extended GIS database. It constitutes the repository for both (i) the spatial and descriptive data, and (ii) the parameters required for the different OR/MS tools.

Model base The model base (MB) is the repository of different analytical models and functions. Among these functions, there are surely the basic GIS ones (e.g. statistical analysis, overlaying, spatial interaction analysis, network analysis, etc.). MB contains also other OR/MS models. Perhaps the most important ones are those of MCA. Nevertheless, the system is opened to include any other OR/MS tool (e.g. mathematical models, simulation and prediction models, etc.), or any other ad hoc model developed by the model construction block (MCB) (see later in this Section).

Model management system The role of this component is to manage the different analysis models and functions. Figure 2 shows the model management system (MMS) which contains four elements: the meta-model (MM), the model base management system (MBMS), the MCB and the knowledge base (KB).

Meta-model The meta-model serves as a guide tool that helps the decision maker (and/or analyst) to select an appropriate model or function for the problem under consideration (Lévine and Pomerol

1989, 1995) (see Figure 3). This element is normally an Expert System used by the decision maker to explore the MB. This exploration enables the decision maker to perform a 'what-if' analysis and/or to apply different analytical functions. The meta-model uses a base of rules and a base of facts incorporated into the KB.

The notion of meta-model is of great importance in the sense that it makes the system open for the addition of any OR/MS analysis tool. This requires the addition of the characteristics of the analytical tool to the base of rules, and, of course, the addition of this model to the MB.

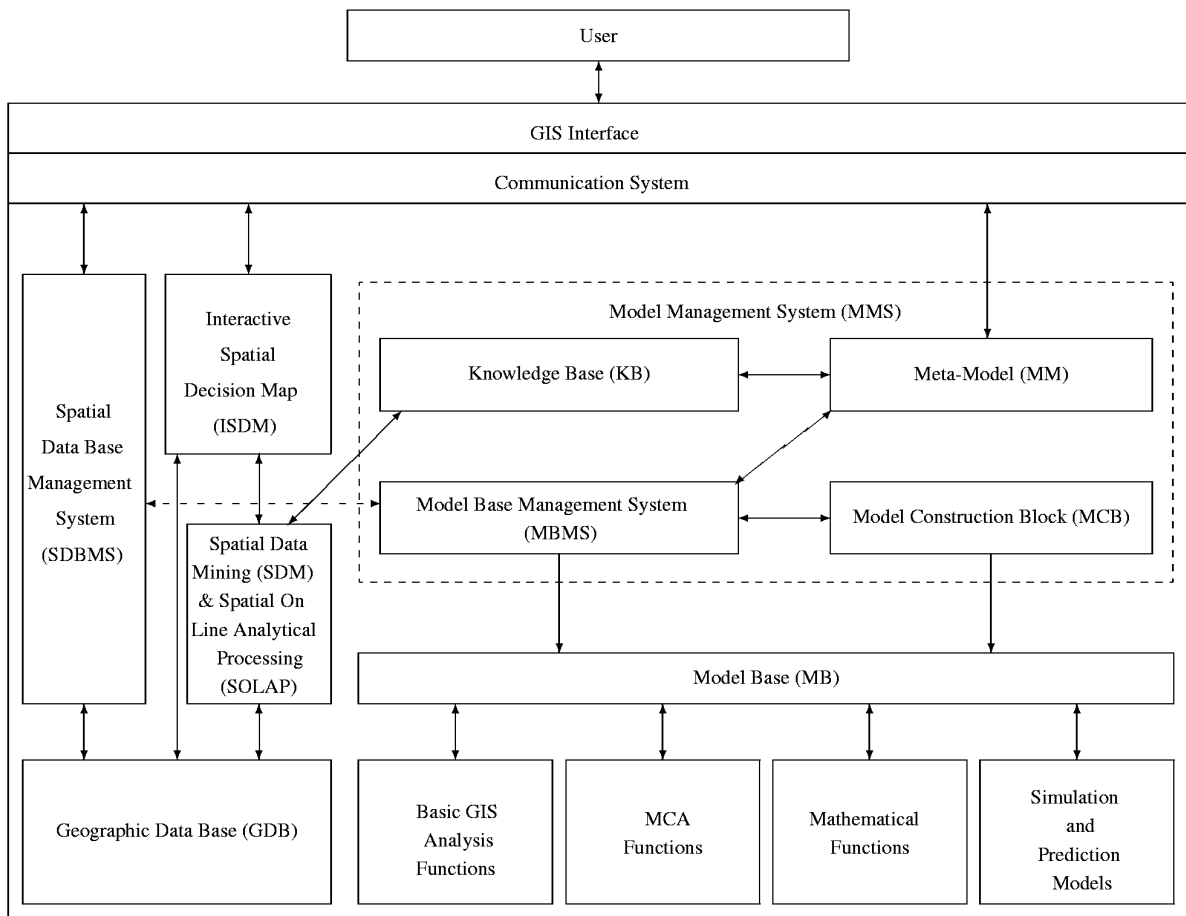


Figure 2. A design of a SDSS

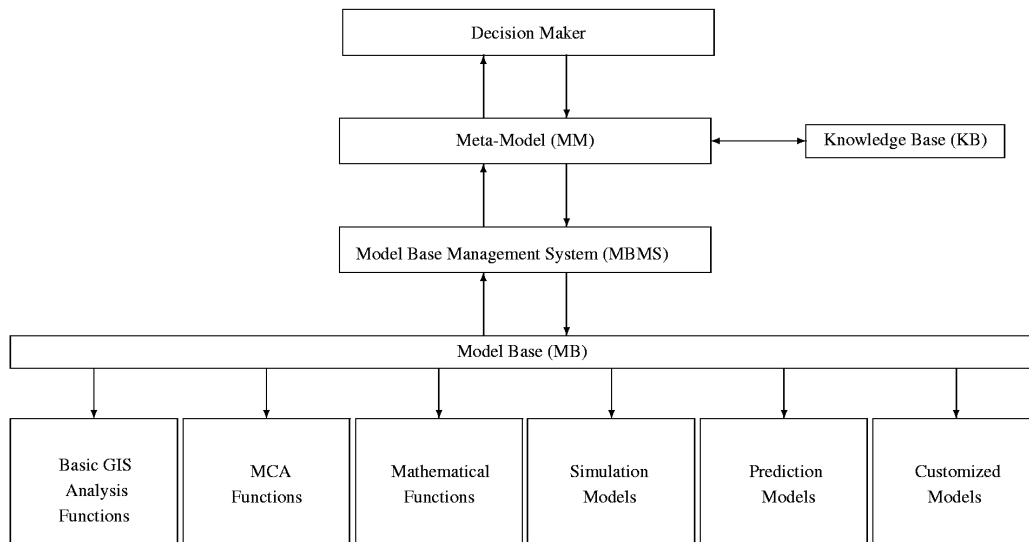


Figure 3. The role of the Meta-Model [inspired from (Lévine and Pomerol 1989)]

Knowledge base The knowledge base is the repository for different pieces of knowledge used by the meta-model to explore the model base. Practically, the KB is divided into a base of facts and a base of rules. The base of facts contains the facts generated from the model base. It also contains other information concerning the uses of different models, the number and the problems to which each model is applied, etc. The base of rules contains different rules of decision which are obtained from different experts, or automatically derived by the system from past experiences. This base may, for instance, contain the following rule: *'If the problem under study is the concern of many parties having different objective functions then the more appropriate tool is that of MCA'*.

Model base management system The role of the model base management system (MBMS) is to manage, execute and integrate different models that have been previously selected by the decision maker through the use of the meta-model.

Model construction block This component gives the user the possibility to develop different ad hoc analysis models for some specific problems. The developed ad hoc model is directly added to the model base and its characteristics are introduced into the base of rules of the KB.

Spatial data mining and spatial on line analytical processing Data mining and on line analytical processing (OLAP) have been used successfully to extract relevant pieces of knowledge from huge traditional databases. Recently, several authors have been interested in the extension of these tools in order to deal with huge and complex spatial databases (e.g. Ester et al. 1997; Koperski et al. 1999; Zeitouni and Yeh 1999; Faiz 2000). In particular, spatial data mining (SDM) is a very demanding field that refers to the extraction of implicit knowledge and spatial relationships which are not explicitly stored in geographical databases (Faiz 2000). According to Faiz (2000) spatial OLAP technology uses multidimensional views of aggregated, pre-packaged and structured spatial data to give quick access to

information. Incorporating SDM and spatial OLAP into the SDSS will undoubtedly ameliorate the decision-making process.

Interactive spatial decision map Interactive decision map (IDM) is a new concept in decision-aid area (see, for e.g., Lotov et al. 1997; Andrienko and Andrienko 1999; Jankowski et al. 2001; Lotov et al. 2003). Its basic idea is to use map-based structures in order to provide an on-line visualization of the decision space, enabling the decision maker(s) to appreciate visually how the feasibility frontiers and criterion trade-offs evolve when one or several decision parameters change. The interactive spatial decision map (ISDM) component that we propose to integrate into the SDSS is an extension of this concept. It is an electronic map representing an advanced version of a classical geographic map, with which the decision maker is quite accustomed, and which becomes a powerful visual spatial decision-aid tool, where the decision maker uses a representation very similar to real-world to dialogue with the database, explicit his/her preferences, manipulate spatial objects and modify their descriptive attributes, add/delete other spatial objects, simulate the adoption of a given scenario without alerting the original data, appreciate the effects of any modification affecting any preference parameters, order a decision, modify the decision space representation, use different spatial data exploration tools, etc.

It is important to note that the decision map does not subtract the utility of SDBMS. Rather, it constitutes another facet for managing spatial data. In fact, a SDBMS is exclusively oriented towards data management, while the decision map is oriented towards visual spatial decision-aid. They are two complementary tools requiring a maximum of coordination for their implementation.

Communication system The communication system represents the interface and the equipments used to achieve the dialogue between the user and the SDSS. It permits the decision maker to enter his/her queries and to retrieve the results.

As it is underlined above, the development of the proposed design is an ambitious project that requires the collaboration of researchers from different disciplines and can be envisaged only in a long-term perspective. Instead, a more realistic solution that consists in the integration of GIS technology with MCA is provided in the following section.

3.2 Short-term solution: GIS and MCA integration

To avoid the limitations of GIS in spatial decision-aid, different researchers support the idea of integrating GIS with different OR/MS modeling and computing tools (e.g. Janssen and Rietveld 1990; Carver 1991; Fischer and Nijkamp 1993; Laaribi et al. 1996; Malczewski 1999; Laaribi 2000). In fact, there are several concrete tentatives to integrate OR/MS and computing tools (such as linear programming, statistical analysis tools, neural networks, genetic algorithms, fuzzy sets, Expert Systems, etc.) and GIS in the literature (e.g. Waters 1989; Chuvieco 1993; Altman 1994; Arthur and Nalle 1997; Bennett et al. 1999; Armstrong et al. 2003). However, many of these contributions ignore the multidimensional nature of territory-related problems. Moreover, in these works, modeling is usually achieved within an independent package and the GIS is used only as a visualization tool (Brown et al. 1994). In addition and as it is stated by (Laaribi et al. 1996), in almost all these works the

integration of GIS and OR/MS tools is achieved in a bottom-up way without any coherent framework. One possible path that has been supported by many authors and can be used to achieve the promise of GIS is to build a coherent theory of spatial analysis parallel to a theory of spatial data. Laaribi et al. (1996) believe that such an idea is foreseeable only in the long-term and they have proposed an intermediate solution consisting of integrating GIS with only a family of analysis methods. Perhaps the most convenient family is that of MCA. The role of the GIS in such an integrated system is to manage the spatially-referenced data associated with different spatial problems, while the role of MCA is to model these problems.

There is a large literature on GIS-MCA integration (e.g. Janssen and Rietveld 1990; Carver 1991; Eastman et al. 1993; Pereira and Duckstein 1993; Jankowski and Richard 1994; Jankowski 1995; Laaribi et al. 1996; Malczewski 1996; Janssen and Herwijnen 1998; Malczewski 1999; Laaribi 2000; Jankowski et al. 2001; Sharifi et al. 2002; Armstrong et al. 2003). The conceptual idea on which most of past works are based is the use of the GIS capabilities to prepare an adequate platform for using multicriteria models. Operationally, the GIS-MCA integrated system starts with the problem identification, where the capabilities of the GIS are used to define the set of feasible alternatives and the set of criteria. Then, the overlay analysis procedures are used in order to reduce an initially rich set of alternatives into a small number of alternatives which are easily evaluated by using a multicriteria model. Finally, the drawing and presenting capabilities of the GIS are used to present results.

Physically, there are three possible modes to integrate GIS and MCA tools. Our formulation of these modes is illustrated in Figure 4 and described in the following paragraphs. This formulation is inspired from the works of (Goodchild 1991), (Laaribi et al. 1993) and (Jankowski 1995).

An indirect GIS-MCA integration mode The integration of GIS software and a stand-alone MCA software is made possible by the use of an *intermediate system*. The intermediate system permits to reformulate and restructure the data obtained from the overlay analysis which is performed through the GIS into a form that is convenient to the MCA software. The other parameters required for the analysis are introduced directly via the MCA software interface. The results of the analysis (made in the MCA part) may be visualized by using the presentation capabilities of the MCA package, or feedback to the GIS part, via the intermediate system, for display and for further manipulation. It should be noted that each part has its own database and its own interface, which makes the interactivity a non-convivial operation.

A built-in GIS-MCA integration mode In this mode, a particular MCA model is directly added to the GIS software. The MCA model constitutes an integrated but autonomous part with its own database. The use of the interface of the GIS part alone increases the interactivity of the system. Here, there is no need for an intermediate system because the MCA model is reformulated in such a way that the exchange of data and analysis results between the two parts is performed directly. This mode is the first step towards a complete GIS-MCA integrated system. Yet, with the autonomy of the MCA model, the interactivity remains a problem.

Full GIS-MCA integration mode The third mode yields itself to a fully GIS-MCA integrated system that has a unique interface and a unique database. Here, the MCA model is activated directly from the GIS interface as any GIS basic function. The GIS database is extended so as to support both the geographical and descriptive data, on the one hand, and the parameters required for the multicriteria evaluation techniques, on the other hand. The common graphical interface makes the global system a convivial single tool.

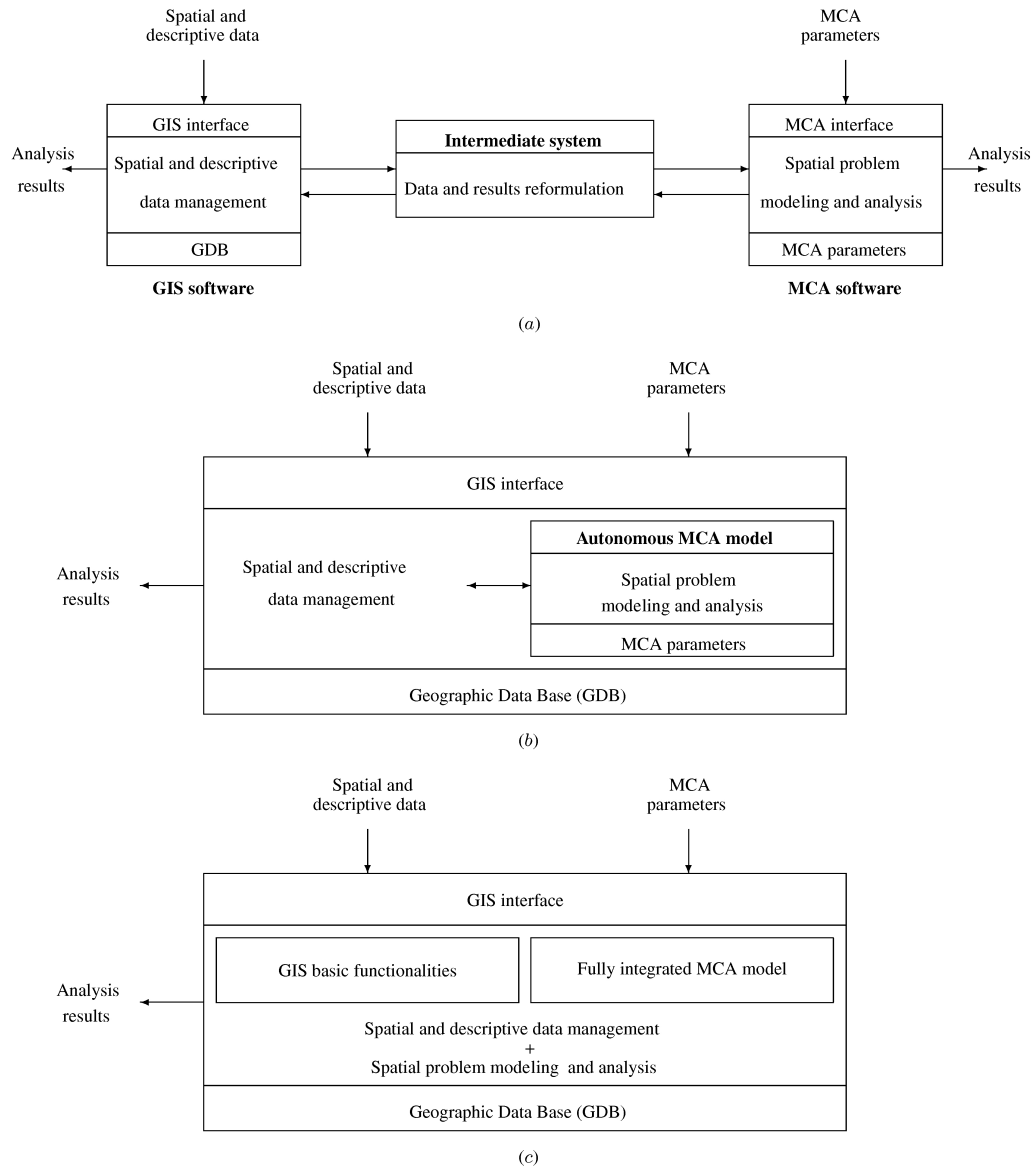


Figure 4. The three GIS-MCA integration modes: (a) An indirect GIS-MCA integration mode, (b) A built-in GIS-MCA integration mode, and (c) A full GIS-MCA integration mode.

Clearly, the third way is the most efficient one for a powerful GIS-MCA integrated system. Consequently, it has been followed by several researchers (e.g. Jankowski 1995; Laaribi et al. 1996). Their works have, however, a major limitation is that they integrate only one model (or a limited number of models), which makes the obtained system a rigid tool. Two possible ways to remedy this

limitation are (i) to integrate as many different MCA models as possible, or (ii) to integrate different multicriteria evaluation functions. Nevertheless, neither the first nor the second way would be able to solve the problem by itself. In fact, the first way generates a new problem relative to the selection of the appropriate MCA model in a given spatial problem, while the second way has no tool to choose the appropriate aggregation procedure. To take advantages of both ways and to avoid their respective limitations, an integration strategy is developed in the following section.

4. A strategy for GIS-MCA integration

The strategy developed in this section consists of the combination and extension of two past works. In fact, the idea of our strategy is to integrate (i) different multicriteria evaluation (MCE) functions, and (ii) a model for multicriteria aggregation procedure (MCAP) selection into the GIS. This new system uses a MCAP selection process of Laaribi et al. (1996), a general model of MADM proposed by Jankowski (1995) and illustrated in Figure 1(a), and the MODM general model illustrated in Figure 1(b).

Instead of integrating complete MCA models as was the case of almost all past works, this new strategy proposes the integration of only multicriteria evaluation functions. The idea is not totally new. It was proposed by Jankowski (1995) for incorporating MADM common functions into a GIS. Nonetheless, this idea is here enriched with other functions and extended to include both MADM and MODM techniques.

4.1 Multicriteria evaluation functions

The MCE functions considered in the strategy are illustrated in Figure 1 and summed up in Table 2. The next paragraphs provide brief descriptions of these functions.

#	Function
F1	Alternatives\Criteria definition and generation
F2	Constraints definition
F3	Non-dominated solutions generation
F4	Objective functions definition
F5	Performance table generation
F6	Performance table normalization
F7	Weights assignment
F8	Aggregation procedure selection\definition
F9	Preferences definition
F10	Aggregation
F11	Sensitivity analysis
F12	Final recommendation

Table 2. Multicriteria evaluation functions

Alternatives\Criteria definition and generation This function permits the user to explicitly define and then generate discrete sets of alternatives and criteria. Two important remarks arise at this level. First, the two sets are here defined jointly and not separately as in (Jankowski 1995), which leads to a more realistic problem formulation. Second, the generation of the two sets should be normally handled by using the GIS overlay capabilities. However, the intervention of the decision maker and/or analyst for updating or may be a definition of both criteria and alternatives sets is a necessity. This is due to the fact that the overlays defined through the GIS are not true criteria. Rather, they are *admissibility criteria* or constraints. Nevertheless, a possibility of generating the two sets automatically by using the capabilities of the GIS in use should be offered to the user via this function.

Constraints definition 'Constraints definition' function is used when the problem has very high or infinite number of feasible solutions, i.e., MODM problem. These constraints are used to generate the feasible solutions set. They can be defined explicitly by the decision maker or automatically through the overlay operations of the GIS. In fact and as noted in the preceding paragraph, the overlay analysis of GIS is a powerful tool to define admissibility criteria.

Non-dominated solutions generation Once this function is activated, it generates the non-dominated solutions set on the basis of the decision maker preferences represented in terms of target values, objective functions weights, etc.

Objective functions definition This function offers the user the possibility to define his/her objective functions in a context of a MODM problem. The user should define the sense of the optimization and the structure of each objective function. Of course, the variables used in the different functions are those used to define the set of constraints and consequently the set of feasible solutions.

Performance table generation The function 'performance table generation' is required by almost all MADM techniques. Here, the decision maker is called for to articulate his/her preferences in terms of criteria scores.

Performance table normalization Criteria scores can be quantitative or qualitative and can be expressed according to different measurement scales (ordinal, interval or ratio). Thus, this function is used to re-scale (when it is necessary) the different criteria scores between 0 and 1. Different methods of normalization are offered to the user. The selection of the appropriate method depends greatly on the nature of the available data.

Weights assignment The criteria\ objective weights are a necessity for almost all MCA methods. The role of this function is to define a vector of weights assigned to different criteria or objective functions. Several techniques for weighing criteria are available. The selection of the appropriate one depends heavily on the aggregation procedure used.

Aggregation procedure selection\definition This function is the most important one in an integrated GIS-MCA system. It permits the decision maker and/or the analyst to choose the manner by which different criteria or objective functions are aggregated together. The selection of the appropriate

aggregation technique is a very important step in MCA. In fact, there is a large number of methods; each of which has its advantages and disadvantages. In this sense, one method may be useful in some problems but not in others. The applicability of a given method depends on the way the problem is stated and on the data available and the instant when these data are provided by the decision maker. Laaribi et al. (1996) propose a three phases-based model for selecting the more appropriate aggregation procedure. This model will be adopted in our strategy of integration and will be presented in details later in this Section.

Preferences definition As mentioned, in addition to weights, the decision maker's preferences may also take the form of aspiration levels, cut-of values, or the form of target values. Contrary to weights which are required by almost all MCA models and to which we have associated a specific function, the aspiration levels, cut-of values and target values may or not be required in a given problem. This depends on the type of the aggregation procedure used. However, to make the system more flexible, this function should propose to the decision maker and/or analyst different possible ways for defining preferences and he/she should select the relevant ones. We note that in MODM problems, decision maker's preferences are usually expressed progressively during the resolution process. In this case, they are better defined through the 'Non-dominated solutions generation' function. Nevertheless, 'Preferences definition' function remains useful for MODM problems in which the preferences are expressed *a priori* or *posteriori* to the resolution process.

Aggregation As mentioned above; there are three families of aggregation procedures: (i) outranking relation-based family, (ii) utility function-based family, and (iii) local aggregation-based family. The two first ones are used in MADM problems and require that all the elements of the decision problem (i.e. alternatives, criteria, preferences) are defined. The third one is used in MODM problems within an interactive manner. Accordingly, aggregation for the methods of the two first families is handled through this function but local aggregation required by interactive methods is handled through the 'Non-dominated solutions generation' function.

Sensitivity analysis Almost all decision problems require a sensitivity analysis, enabling the decision maker to test the consistency of a given decision or its variation in response to any modification in the input data.

Final recommendation One of the basic concepts of decision-aid tools is that the final decision should never be taken by the system, i.e., the intervention of the decision maker in the selection and validation of a final recommendation is an inevitable phase (Lévine and Pomerol 1995). Thus, the role of this function is only to provide the results of the analysis, via the capabilities of the GIS, to the decision maker to choose and, then, validate.

4.2 Aggregation procedure selection model

According to Jankowski (1995), the selection of the appropriate aggregation procedure is guided only by the creativity of the decision maker (and/or analyst) and his/her knowledge in the domain of MCA,

which may be very limited. A remedy to this consists of incorporating a model that will be used to guide the decision maker during the process of aggregation procedure selection. We note that the model that will be detailed hereafter is an implementation of the MCAP selection process that was proposed by Laaribi et al. (1996), and can be considered as a first version of the meta-model discussed in Section 3.1.

The principal idea beyond this model is stated as follows: the characteristics² of the spatially-referenced decision problem (SRDP) largely determine the characteristics of the MCAP that are appropriate to the problem under consideration. Knowing the characteristics of the SRDP and the operating conditions of the MCAP, one can identify the characteristics³ of the MCAP that are suitable to the problem under focus.

Operationally, the model proceeds by elimination until the most convenient MCAP is identified. It starts with the identification of the characteristics of SRDP under focus. Then, these characteristics are used along with the operating conditions of the MCAP in order to identify the characteristics of the MCAP which are appropriate to the problem under study. Once these characteristics are identified, they are superposed on a MCAP classification tree (see Figure 6) to select a subset of suitable MCAP, from which the decision maker can select the appropriate method. More formally, the steps of this model are (see Figure 5):

1. *Identification of the characteristics of the SRDP.* The decision maker and/or analyst is called for to provide the characteristics of the SRDP.
2. *Identification of the characteristics of the MCAP.* The characteristics of the SRDP, along with the operating conditions of MCAP, are used to identify the characteristics of the appropriate MCAP.
3. *Selection of a subset of MCAP.* The characteristics of the appropriate MCAP are superposed on the classification tree in order to select a subset of suitable MCAP.
4. *Selection of a MCAP.* Finally, the decision maker uses some intrinsic characteristics related to the use of MCAP to identify the most suitable MCAP.

² In terms of the type of the problematic (choice, sorting, ranking or description), the nature of the set of alternatives (finite or infinite), the nature of the required information [measurement scale (ordinal, interval or ratio) and availability], and the type of the evaluation results [type of impacts (punctual or dispersed) and level of reliability]; see §6.2.3 in (Laaribi 2000, pp.107-110).

³ In terms of the type of the problematic (choice, sorting or ranking), the nature of the set of alternatives (discrete or continuous), the nature of the required information [concerning criteria (ordinal or cardinal), and intra and intercriteria information], and the type of the evaluation results [type of result (punctual or dispersed) and the presence or absence of imprecision]; see Appendix 3 in (Laaribi 2000, pp.162-164).

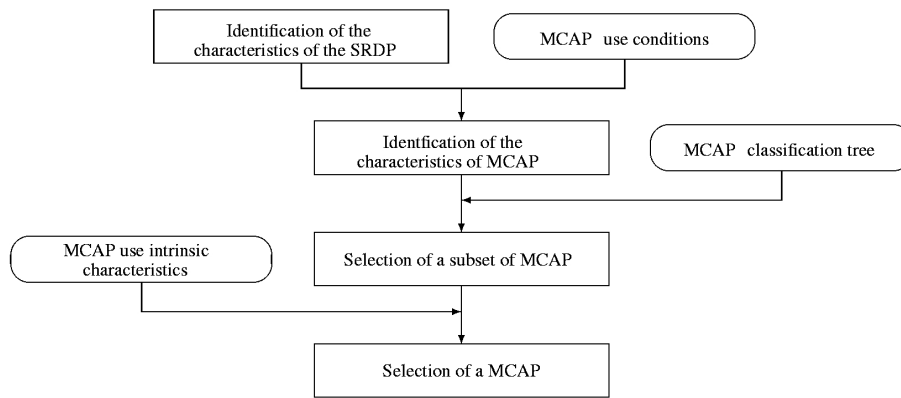


Figure 5. MCAP selection model

This model, which is largely controlled by the decision maker, will guarantee him/her the selection of the most adequate aggregation procedure to the problem under consideration.

Two other simple models which can be used by the decision maker and/or analysts to select respectively the appropriate weighting technique or the normalization procedure are added to the system. As it is underlined above, the selection of the appropriate weighting technique depends mainly on the nature of the aggregation procedure to be used, while the selection of the normalization procedure depends essentially on the nature of the available information.

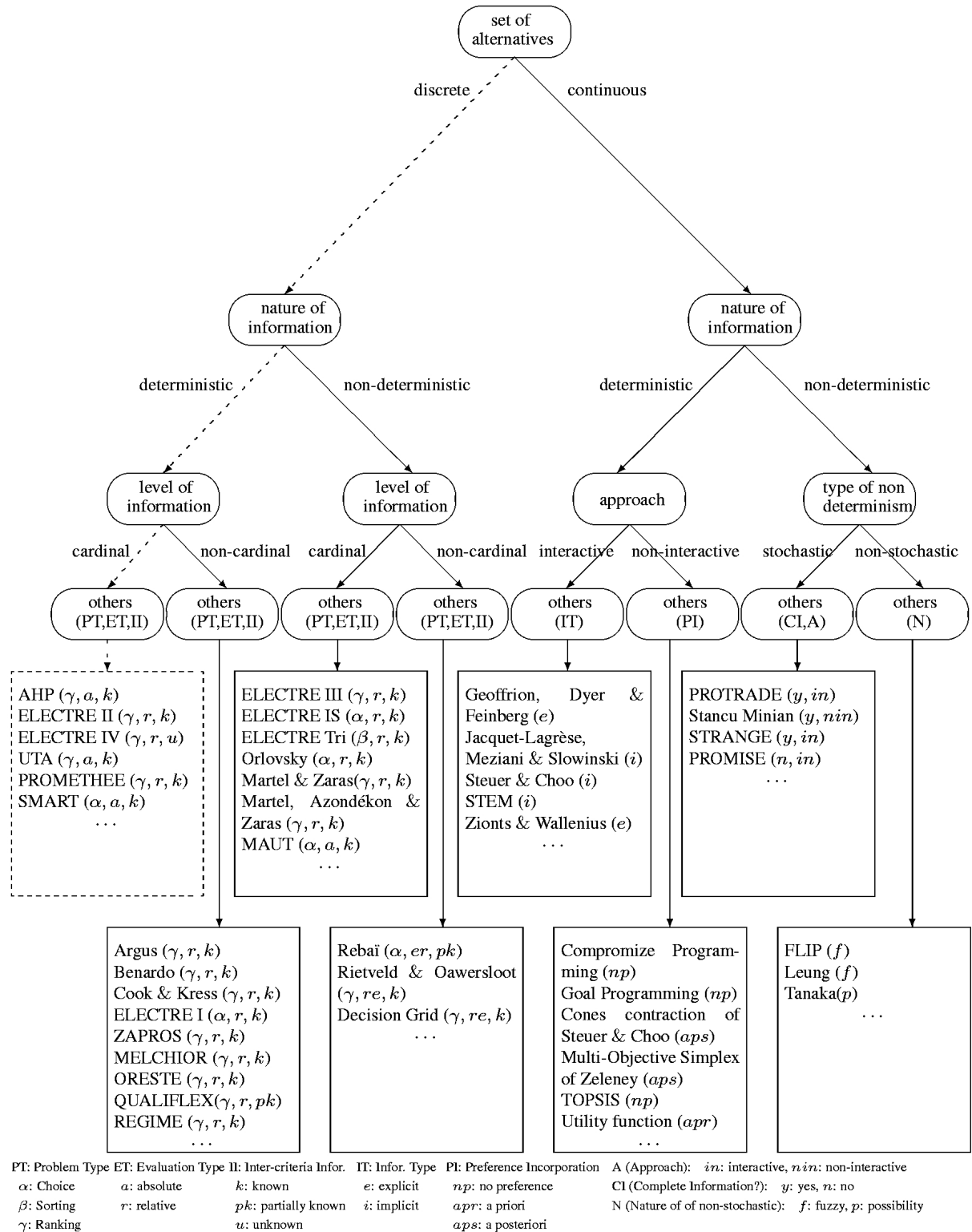


Figure 6. MCAP classification tree [reproduced from (Laaribi 2000, pp.114-115)]

4.3 Advantages of the strategy

The combination of GIS, MCE functions and MCAP selection model in a single tool yields a new system (Figure 7) that gathers the power of GIS in data management and presentation, the potentiality

of MCA in spatial problems modeling, and the efficiency of the MCAP selection model for choosing the aggregation procedure.

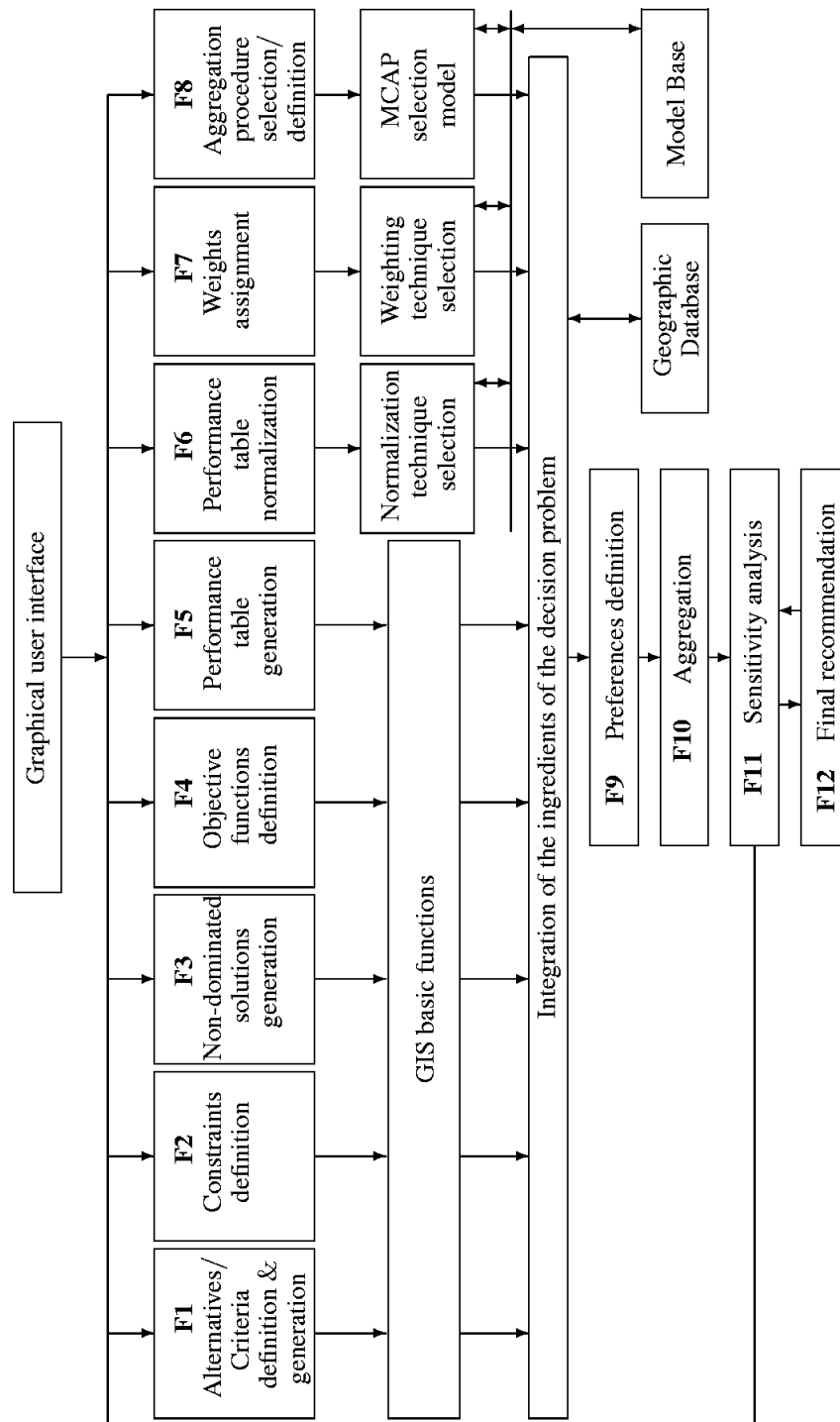


Figure 7. Schematic representation of the strategy

The proposed strategy of integration gathers the advantages of both Jankowski (1995) and Laaribi et al. (1996) approaches. Perhaps the most important ones are:

- the achievement of a basic characteristic of SDSS which is *flexibility*, i.e., the capability of the system to be applied to a large spectrum of spatial problems. Using different and independent

functions, the decision maker has the possibility to freely integrate different ingredients of MCA techniques in order to 'create' a new and customized model adapted to the problem under focus.

- the ability of the decision maker to interact constantly during all the decision-making process phases. In fact, each step in the resolution of any problem is directly controlled by the decision maker.
- the ability to carry out the different steps of the decision-making process in a 'non-sequential' schema.
- the strategy guarantees the decision maker to select the most appropriate MCAP for the problem under study.

4.4 Illustrative example

To better appreciate the proposed strategy considering the following hypothetical facility location problem illustrated in Figure 8. The company involved in this illustrative example distributes petroleum products to different gas stations located throughout a given national market. The aim of this company is to determine the 'optimal' location for a new depot in order to avoid deliverance delay problems.

The responsible of the company has identified two sitting factors which must be verified:

- the site must be within an area having a population greater than 50 thousands, and
- the new depot can not be located in an area where a depot already exists.

The first step is to use basic GIS functions to identify all the feasible sites. The inputs of this step are two layers representing the two factors cited above. These layers are then superposed upon each other and a logical addition operation is applied to them in order to identify areas that verify simultaneously the two factors.

In the next step one should apply function F1 ('Alternatives/Criteria definition and generation') to define the set of evaluation criteria. We suppose that the following evaluation criteria are considered in our example:

- distance from different pre-existing depots,
- number of potential customers in the rayon of 150km,
- implementation cost, and
- proximity to routes

Once criteria are defined, the function F7 ('Weights assignment') is activated in order to define a vector of weights $\mathbf{w} = (w_1, w_2, w_3, w_4)$. In the next step, we may use function F5 ('Performance table generation') to calculate criteria scores for each feasible alternative. The first distance criterion can be easily performed through GIS basic functions. For each feasible location, the score of the second criterion can be obtained by summing the number of customers in all sites which are located no more than 150km from this location. The implementation cost criterion can be directly provided by the

decision maker and/or analyst. The proximity criterion may be calculated as the number of routes which are no more than 100m far from the site.

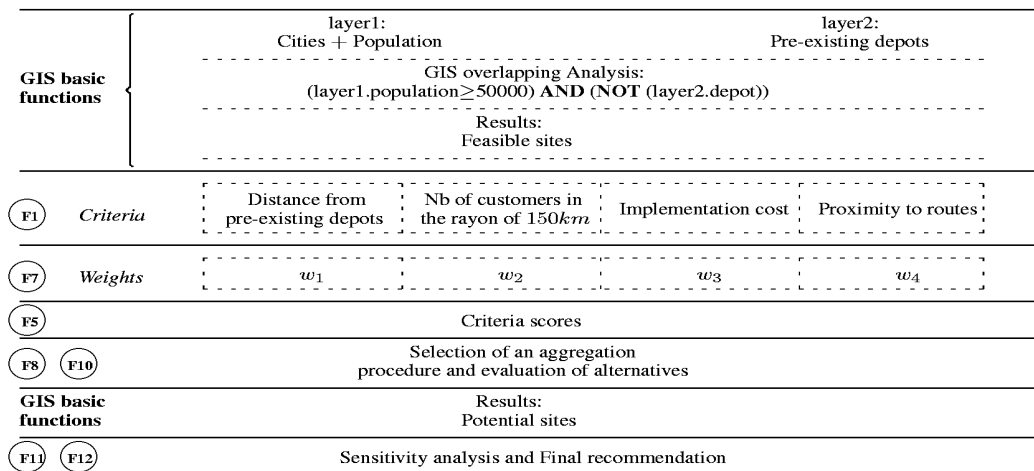


Figure 8. Illustrative facility location example

Once all criteria scores are calculated, we may use the F8 function ('Aggregation procedure selection/definition') to select an aggregation procedure. This function will activate the MCAP selection model in order to identify the most appropriate aggregation procedure(s). The progress of selection⁴ is shown in dashed arrows in Figure 6, which indicate that the decision maker and/or analyst should select one procedure from the left-side dashed box of Figure 6. Then, we may apply the F10 function ('Aggregation') in order to globally evaluate the different feasible alternatives.

Then, the result of aggregation and evaluation steps is visualized using the capabilities of the GIS. The decision maker and/or analyst may then use the F11 function ('Sensitivity analysis') as many as necessary to see the effects of any modification on the input data. Finally, F12 ('Final recommendation') is used to adopt a given alternative.

5. Concluding remarks

In this paper we have proposed a strategy for integrating GIS and MCA. The idea of our strategy is to integrate: (i) different MCE functions, and (ii) a model for MCAP selection into the GIS. Depending on the two general models of MCA that are illustrated in Section 2, twelve different MCE functions are identified. These functions represent the different operations required to perform MCA modeling. The separation of these functions allows for achieving an important characteristic of any SDSS which is flexibility. In fact, this will offer the decision maker the possibility to integrate different ingredients of MCA techniques in order to 'create' a new and customized model adapted to the problem under

⁴ In this example, the set of alternatives is *discrete*, the nature of information is *deterministic* and the level of information is *cardinal*.

focus. Moreover, this will lead the decision maker to interact constantly during all the decision-making process phases.

Given the fact that the MCAP is the most important ingredient of any MCA model, the selected procedure will largely influence the final recommendation. Thus, the strategy proposes the incorporation of a specific model to aid the decision maker to select the most appropriate procedure for the problem under focus.

The combination of GIS, MCE functions and MCAP selection model in a single tool yields a new system that gathers the power of GIS in data management and presentation, the potentiality of MCA in spatial problems modeling and the efficiency of the MCAP selection model in selecting the aggregation procedure.

Currently, the proposed strategy is being implemented in the GIS ArcView environment. An immediate perspective of our strategy is to add to GIS other OR/MS tools in addition to MCA. The first candidates are prediction tools including time series, forecasting techniques, and so on. This relies on the fact that spatial objects and phenomena are subject to numerous spatio-temporal changes. Thus, the predictions tools will serve to model these changes and will make the system a powerful planning tool. A long-term possible extension of this research consist of the implementation of the design of the SDSS detailed in Section3.1.

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