

Towards a Spatial Decision Support System: Multi-Criteria Evaluation Functions Inside Geographical Information Systems

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Résumé

L'objectif de cet article est de présenter une stratégie d'intégration des systèmes d'information géographiques (SIG) et de l'analyse multicritère (AMC), une famille d'outils de la recherche opérationnelle/science de management (RO/SM) qui connaît des applications réussies dans différents domaines depuis les années 1960. En effet, le SIG présente plusieurs limites dans le domaine d'aide à la décision spatiale. La solution à ces limites consiste à intégrer le SIG avec différents outils de la RO/SM et spécialement avec l'AMC. Le but à long terme de cette intégration vise le développement d'un système informatique d'aide à la décision (SIAD) spatiale. A cet effet, un design d'un SIAD spatiale est également proposé dans ce papier.

Mots-clefs : Système d'information géographique, Analyse multicritère, Aide à la décision spatiale, Système informatique d'aide à la décision spatiale.

Abstract

The essence of this paper is to present a strategy for integrating geographical information systems (GIS) and multicriteria analysis (MCA), a family of operational 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 an integration is to develop the so-called spatial decision support system (SDSS), which is devoted to help deciders in spatially-related problems. Thus, a design of a SDSS is also presented in this paper.

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

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1 Introduction

A fully functional GIS is a smooth integration of several components and different subsystems (for more information concerning GIS technology, see, for e.g., Burrough and McDonnell (1998)). 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, the impression shared by 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) and decision-makers sets the GIS to be a limited tool in spatial decision-aid domain. This due essentially to its lack in more powerful analytic tools enabling it to deal with spatial problems, where it is usually several parties having conflicting objectives are involved in the decision-making process.

Among the critics 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 are not taken into account by current GISs. Some raster-based GISs, however, allow ratios for criteria (e.g. the models GRID Arc/Info of ESRI and MGE Grid Analyst d'Intergraph) 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,
- analytic functionalities found in most GIS are oriented towards the management of data but not towards an effective analysis of them,
- overlapping technique that is found in nearly all standard GIS becomes difficult to comprehend when the number of layers is more than four or five. Moreover, overlapping methods consider that all features are of equal importance.

The remedy that has been supported by different researchers consists in integrating 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 analyze 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, for e.g., Roy 1985; Vincke, 1992; Pomerol and Barba-Romero, 1993; Roy and Bouyssou, 1993; 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 modelling spatial problems. Another important argument consists of the ability of MCA to support efficiently the different phases of the Simon's (1960) decision-making process phases.

The remaining of this paper is structured as follows. Section 2 presents MCA paradigm. Then, section 3 provides two solutions for extending the capabilities of GIS. The first long-term perspective solution looks to the development of the SDSS. The second short-term perspective solution focalizes on GIS-MCA integration. The proposed short-term strategy for integrating GIS and MCA is then detailed in section 4. Lastly, 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 (1985). Roy 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 decider(s) towards a judicious choice*'.

Whatever the definition, it is generally assumed in MCA that the decider-maker (DM) has to choose among several possibilities, called *actions* or *alternatives*¹. 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 content 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.

¹The two terms 'action' and 'alternative' are slightly different. In fact, the term 'alternative' applies when actions are mutually exclusive, i.e., selecting an action excludes any other one. In practice, however, we may be called to choose a combination of several actions, which violates the exclusion hypothesis. In this paper, we adopt the term 'alternative'.

Different MCA models have been developed during the second half of the 20th century (see Vincke (1992), Pomerol and Barba-Romero (1993), Roy and Bouyssou (1993), Maystre *et al.* (1994) and Belton and Stewart (2002) for some MCA models). They essentially differ from each other in the nature of the aggregation procedure, i.e., the manner in which different alternatives are globally evaluated. However, they may be categorized into two general models of MADM (a) and MODM (b) (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 the MADM general model of Jankowski (1995).

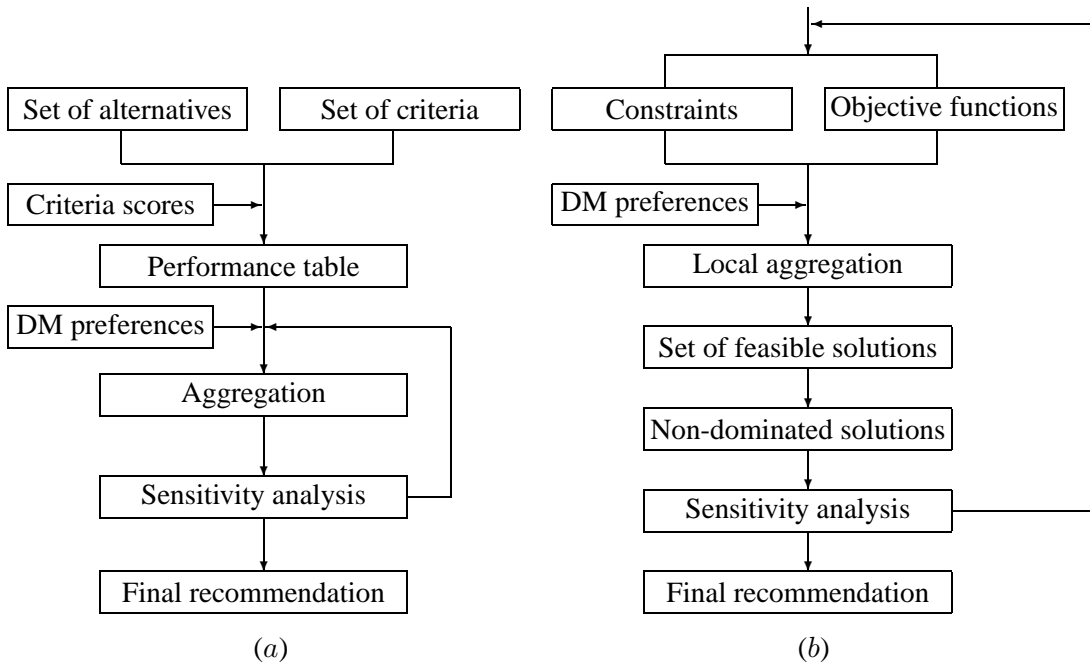


Figure 1: The MADM (a) and MODM (b) general models

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. An efficient conception of the decision problem necessitates, however, that criteria and alternatives are jointly defined. The next step in MADM consists in the *aggregation* of the different criteria scores using a specific *aggregation procedure* and taking into account the *DM preferences*, generally represented in terms of *weights* that are assigned to different criteria. The aggregation of criteria scores permits the DM 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 great families (*i*) outranking relation-based family, and (*ii*) utility function-based family (see Vincke (1992)).

In addition to the weights, the DM'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 DM 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 decider(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 DM preferences.

The aim of any decision model is to help the decider take decisions. The *final recommendation* in MCA may take different forms, according to the manner in which a problem is formulated. Roy (1985) identifies four objectives corresponding to four various problem formulations: choice, sorting, raking or description (see Table 1). Along with the nature of the decision problem, one formulation may be more efficient than an other. Lastly, we note that practical problems may require more than one formulation.

<i>Problematic</i>	<i>Objective</i>
Choice-oriented (P_α)	Selecting a restricted set of alternatives
Sorting-oriented (P_β)	Assigning alternatives to different pre-defined categories
Ranking-oriented (P_γ)	Classifying alternatives from best to worst with eventually equal positions
Description-oriented (P_δ)	Describing the alternatives and their follow-up results

Table 1: Decision-aid problematics

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 DM 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 DM should also indicates, for each objective function, its sense of optimization, i.e., maximization or minimization. No other information than the weights and these senses 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 DM 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 DM preferences to be expressed *progressively* during all the resolution process. The DM 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 DM 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, aiming to find a 'best' solution (Vincke, 1992).

Table 2 below presents some corresponding points between the MADM and MODM general models.

<i>MADM</i>	<i>MODM</i>
Restricted set of alternatives	High or infinite number of feasible solutions
Explicitly defined set of alternatives	Implicitly defined set of feasible solutions
Different problem formulations	Choice-oriented formulation
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 DM's preferences	Requires much less a priori information on the DM's preferences

Table 2: Some characteristics of MADM and MODM general models

3 Extending the capabilities of the GIS

As it is underlined 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 the OR/MS and computing tools. The long-term objective of such an integration is to develop the so-called SDSS. The development of such a tool is an ambitious project that goes beyond the objective of this research. Instead, a design of a SDSS

is proposed in the following section. Then, a more realistic solution is introduced in §3.2 and then implemented in §4.

3.1 Long-term solution: Developing a SDSS

What really makes the difference between a SDSS and a traditional DSS is the particular nature of the geographic data considered in different spatial problems. In addition, traditional DSSs are devoted almost only to solve 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 DSSs to SDSSs that support territory-related problems (Densham and Goodchild, 1989; Densham, 1991; Ryan, 1992; Chevallier, 1994; Malczewski, 1999). This requires the addition of a range of specific techniques and functionalities used especially to manage spatial data, to conventional DSSs. 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 to
- perform an effective spatial analysis by the use of specific techniques.

In spite of their power in handling the three first operations, GISs are particularly limited tools in the fourth one, which is relative to spatial analysis. Moreover, even if the GISs can be used in spatial problem definition, they fail to support the ultimate and most important phase of the general decision-making process relative to 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 a SDSS. Hence, to complete this integration successfully, it must be seen as an essential but not the only phase of a more general project aiming to build the so-called SDSS. A such 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 DSSs 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 decider and/or analysts an interactive, convivial and adequate environment for performing an effective visual decision-aid activity. These components are briefly depicted hereafter.

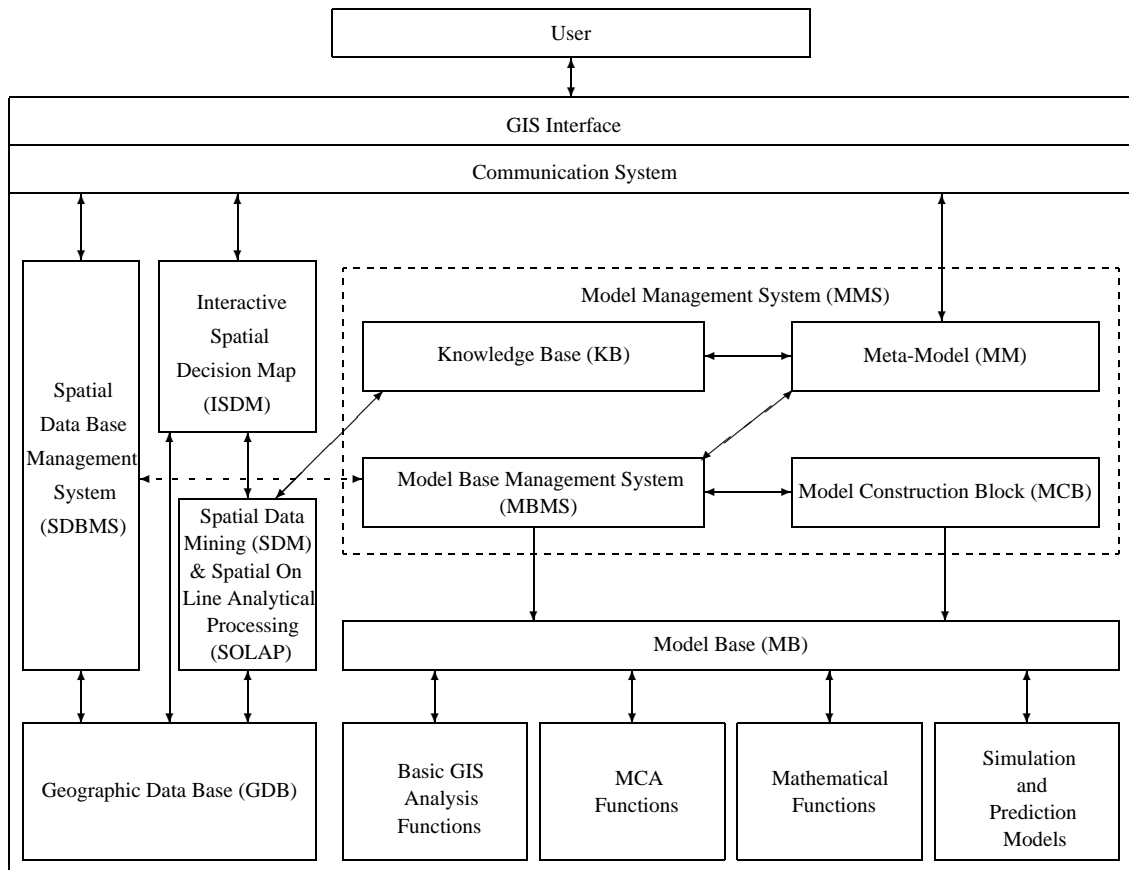


Figure 2: A design of a SDSS

Spatial Data Base Management System Spatial Data Base Management System (SDBMS) corresponds to the DBMS part of the GIS used specially to manage and store the spatial data. In fact, spatial data management is one of the powers of GISs.

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 analysis models and functions. Among these functions, there are surely the basic GIS ones (e.g. statistical analysis, overlapping, spatial interactions analysis, network analysis, etc.). This 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. As it is shown in Figure 2, the Model Management System (MMS) contains four elements: the Meta-Model, 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 DM and/or analyst to select an appropriate model or function for the problem under study (Lévine and Pomerol, 1989, 1995) (see Figure 3). This element is normally an Expert System used by the DM to explore the MB. This exploration enables the DM to perform a 'what-if' analysis and/or to apply different analysis functions. The selection of the appropriate function depends on a base of rules and a base of facts continued in the KB. Lévine and Pomerol (1995) advocate the fact that the Meta-Model is necessarily incomplete because a part of it resides in the decision-maker's mind. This enhances the role of the DM as an integral and indispensable component in the decision-making process. Finally, we note that 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 analysis tool to the base rules, and, of course, the addition of this model to the MB.

Knowledge Base 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, contains: *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 DM 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.

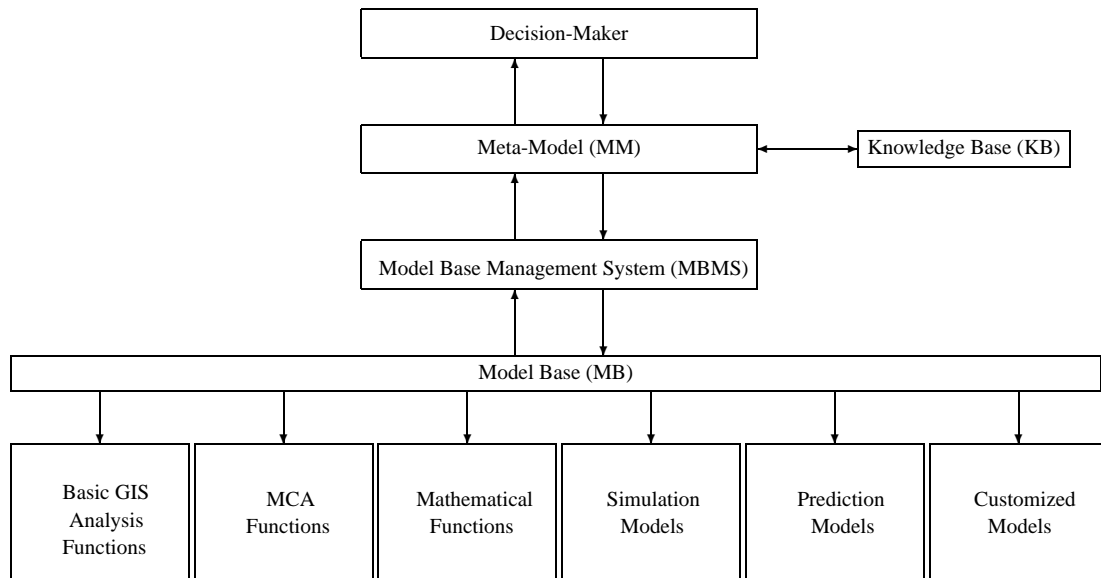


Figure 3: The role of the Meta-Model (inspired from Lévine and Pomerol (1989))

Spatial Data Mining and Spatial On Line Analytical Processing Data mining and On Line Analytical Processing (OLAP) have been used successfully to extract relevant 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. In particular, Faiz (2000) underlines that 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. The same author adds that spatial OLAP technology uses multidimensional views of aggregated, pre-packaged and structured spatial data to give quick access to information. Incorporating SDM and SOLAP into the SDSS will undoubtedly ameliorate the quality of data and, consequently, add value to 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

decider-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 decider-maker is quite accustomed, and which becomes a powerful visual spatial decision-aid tool, where the decider 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 parameter, 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 spatially-referenced 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 DM 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 require 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 GISs with different OR/MS modelling 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, fuzzy sets, Expert Systems, etc.) and GIS in the literature. However, these first contributions ignore the multidimensional nature of territory-related problems. Equally, in these works the aspirations of decision-makers are completely neglected, which increases the gaps between GIS and SDSS. Moreover, in these works, modelling is usually achieved within an independent package and the GIS is served 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 GISs 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.

Several past works concerning GIS-MCA integration are available in the literature (e.g. Janssen and Rietveld, 1990; Carver, 1991; Eastman et *al.*, 1993; Pereira and Ducstein, 1993; Jankowski and Richard, 1994; Jankowski, 1995; Laaribi et *al.*, 1996; Janssen and Herwijnen, 1998; Laaribi, 2000; Sharifi et *al.*, 2002). What remain now is a consistent methodology for integrating efficiently the two tools.

The conceptual idea on which 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 ways to integrate GIS and MCA tools. Our formulation of these three integration modes is illustrated in Figure 4 and described in the three 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 a 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 overlapping 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 (totally 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, eventually, 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

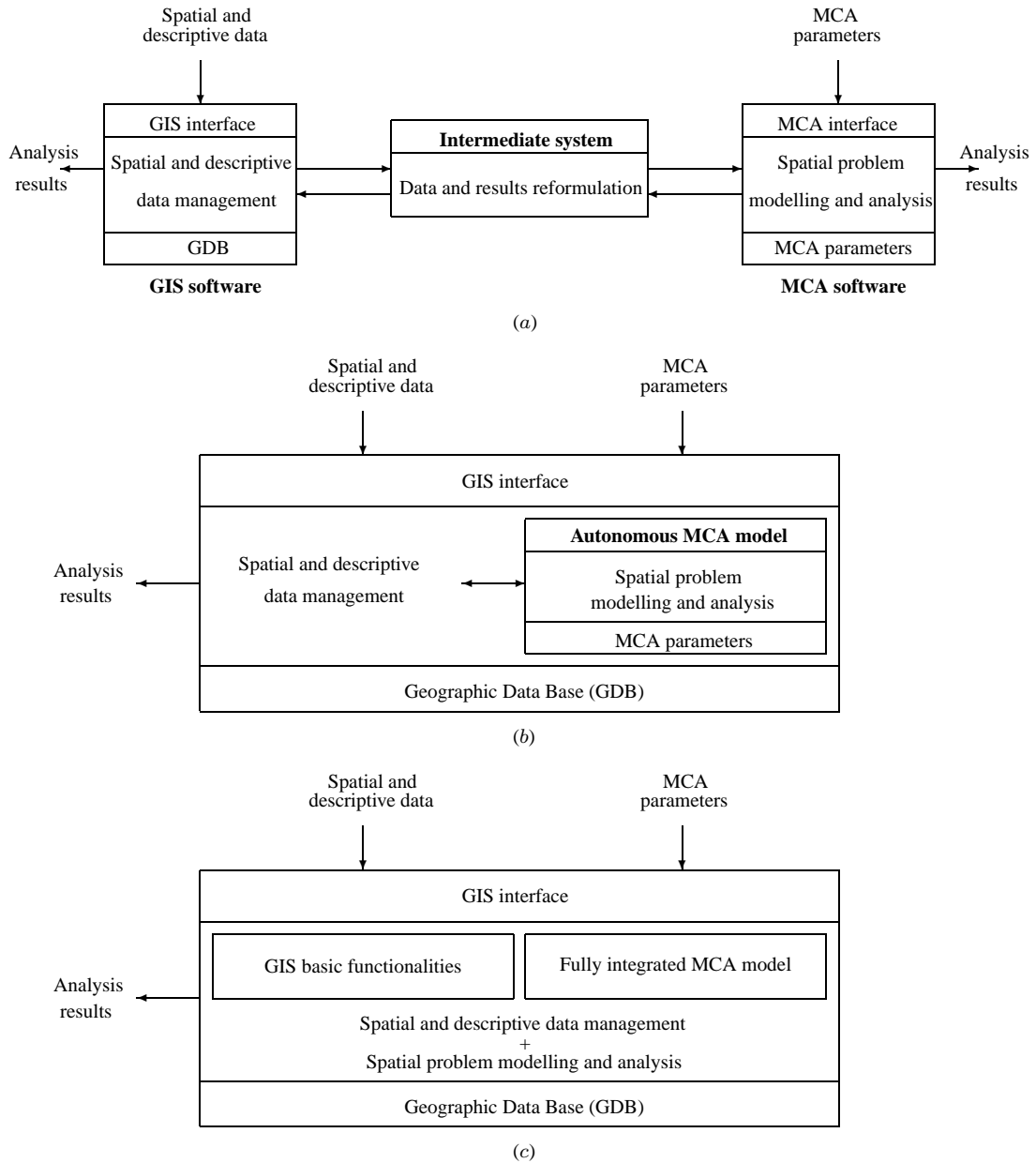


Figure 4: The three GIS-MCA integration modes: (a) An indirect GIS-MCA integration mode, (b) A built-in GIS-MCA integration mode, and (c) A full GIS-MCA integration mode

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 analyzed 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 complete 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.

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 problem 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 MCA functions considered in the strategy are illustrated in Figure 1 and summed up in Table 3. The following paragraphs provide brief descriptions of the considered MCA common functions that are meant to be integrated into a GIS.

#	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 3: MCA common functions

Alternatives\criteria definition and generation This function permits the user to explicitly define and then generate discrete sets of alternatives and criteria. There are two important remarks to 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 DM 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 is 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 DM or automatically through the overlapping capabilities of the GIS. In fact and as it is noticed in the preceding paragraph, the overlay analysis of GISs 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 DM 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 DM 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, 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 w 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 DM and 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 high 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 aim of the problem formulation and on the data

available, and the instant when these data are provided by the DM. 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 more details later in this section.

Preferences definition As it is underlined in §2 and in addition to weights, the DM'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, these ones (i.e. 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 will propose to the decider\analyst different possible ways for defining preferences and he\she should select the relevant ones. We note that in MODM problems, DM'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 it is 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 Nearly, all decision problems require a sensitivity analysis, enabling the DM 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 DM 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 DM to choose and, then, validate.

4.2 Aggregation procedure selection model

In Jankowski (1995), the selection of the appropriate aggregation procedure is guided only by the creativity of the DM (and/or analyst) and his/her knowledge in the domain of MCA, which may be very limited. A remedy to this consists in incorporating a model that will be used to guide the DM 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 §3.1.

The principal idea beyond this model is stated as follows: the characteristics [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] of the spatially-referenced decision problem (SRDP) largely determine the characteristics of the MCAPs that are appropriate to the problem in question. Knowing the characteristics of the SRDP and the operating conditions of the MCAPs, one can identify the characteristics [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] of the MCAPs 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 MCAPs which are appropriate to the problem in consideration. Once these characteristics are identified, they are superposed on a MCAPs classification tree (see Figure 5) to select a subset of suitable MCAPs, from which the DM can select the appropriate method. More formally, the steps of this model are (see Figure 6):

1. *Identification of the characteristics of the SRDP.* The decision-makers and/or analysts are 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 MCAPs, are used to identify the characteristics of the appropriate MCAP.
3. *Selection of a subset of MCAPs.* The characteristics of the appropriate MCAP are superposed on the classification tree in order to select a subset of suitable MCAPs.

4. *Selection of a MCAP*. Finally, the DM uses some intrinsic characteristics related to the use of MCAP to identify the most suitable MCAP.

This model, which is largely controlled by the DM, will guarantee him/her the selection of the most efficient aggregation procedure to the problem in consideration. Two other simple models which can be used by the DM and/or analysts to respectively select the appropriate weighting technique and 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 (if it is necessary), depends essentially on the nature of the available information.

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 modelling, and the efficiency of the MCAP selection model for choosing the aggregation procedure.

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 tenet of any 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 DM has the possibility to freely integrate different ingredients of MCA techniques in order to 'create' a new and customized model adapted to the problem in question.
- the ability of the DM 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 DM.
- the ability to carry out the different steps of the decision-making process in a 'non-sequential' schema.
- the strategy guarantees the DM 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, which is illustrated in Figure 8. The company involved in this il-

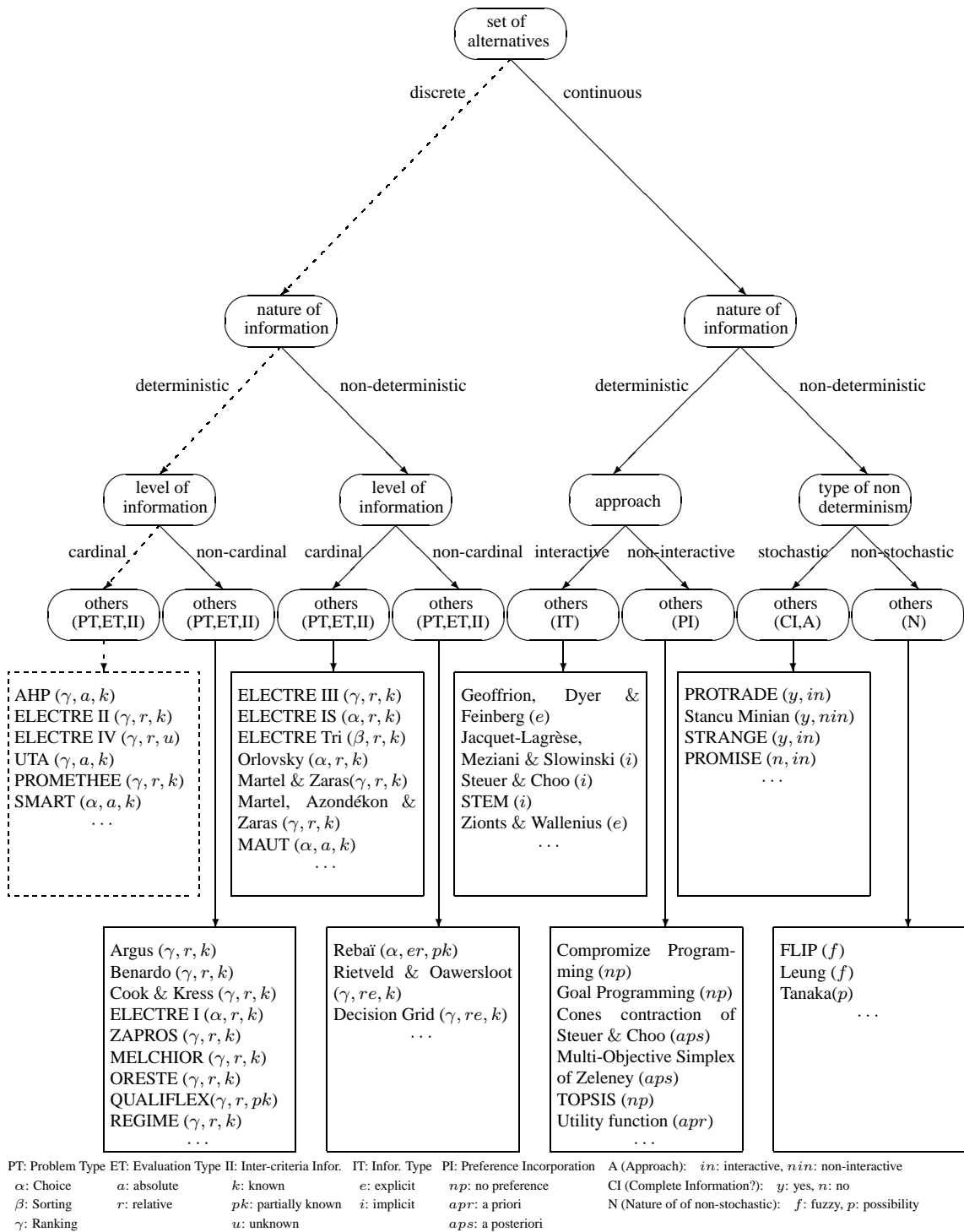


Figure 5: MCAPs classification tree [reproduced from Laaribi (2000), pp.114-115]

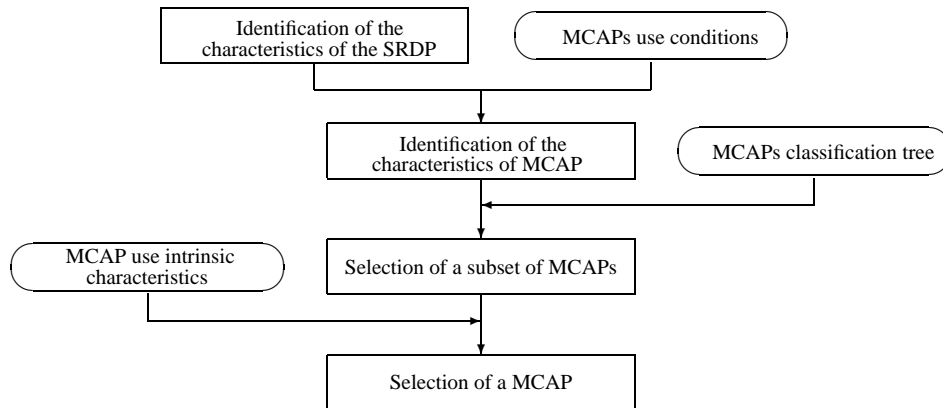


Figure 6: MCAP selection model

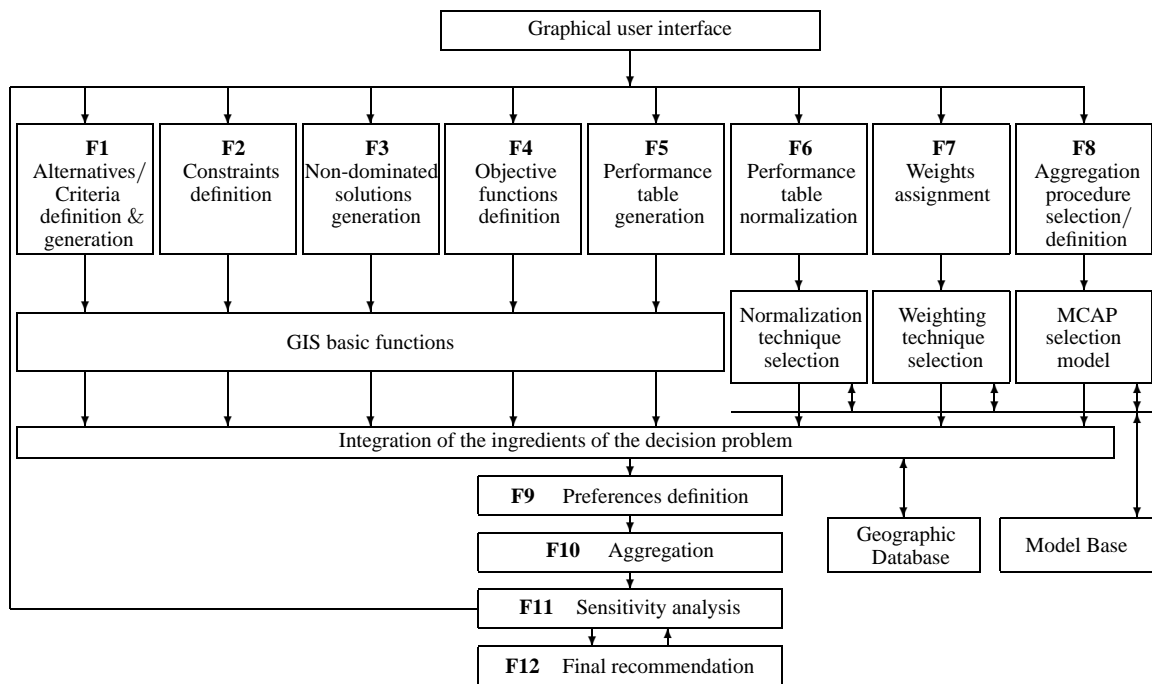


Figure 7: Schematic representation of the strategy

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 siting factors which must be verified:

- the site must be within an area having a population greater than 50 thousand, 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 is 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 150 km,
- 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 $w = \langle w_1, w_2, w_3, w_4 \rangle$. 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 decider 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.

Once all criteria scores are calculated, we may use function F8 ('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 selection² is shown in dashed arrows in Figure 5, which indicates that the decider and/or analyst should select one procedure from the left-side dashed box of Figure 5. Then, we may apply function F10 ('Aggregation') in order to globally evaluate the different feasible alternatives.

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

²In this example, the set of alternatives is *discrete*, the nature of information is *deterministic* and the level of information is *cardinal*.

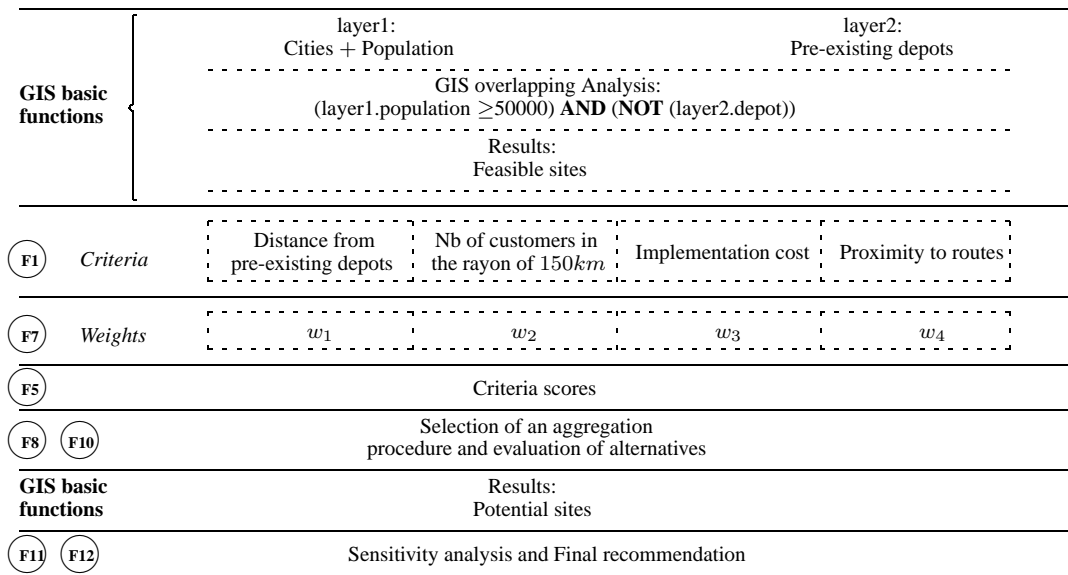


Figure 8: Illustrative facility location example

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 isolated. These functions represent the different operations required to perform any MCA model. The separation of these functions permits to achieve an important characteristics of any SDSS which is flexibility. In reality, this will offer the DM the possibility to integrate different ingredients of MCA techniques in order to 'create' a new and customized model adapted to the problem in question. Moreover, this will lead the DM 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 DM 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 modelling and the efficiency of the MCAP selection model to choose the aggregation procedure.

Currently, the proposed strategy is being implemented by using the GIS ArcView. 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 tech-

niques, 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 in the conception and the implementation of the design of the SDSS detailed in §3.1.

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