Enhancing ArcGIS Decision Making Capabilities Using an Intelligent Multicriteria Decision Analysis Toolbox

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ABSTRACT. Spatial decision making problems are multi-facetted challenges. Not only they often involve numerous technical requirements, but may also contain economic, social, environmental and political dimensions that may have conflicting values. Solutions for these problems involve highly complex spatial data analysis processes and frequently require advanced means to address physical suitability conditions while considering the multiple socio-economic variables. Geographic Information Systems (GIS) and Multicriteria Decision Making (MCDM) techniques are the most common tools employed to solve these problems, each of these tools has its own shortcoming and could not be used alone to reach an optimum solution. The need for combining the strengths of these techniques has prompted researchers to seek integration of GIS and MCDM. Most GIS software packages do not support MCDM such as ArcGIS ® which is a great tool for handling spatial analysis. However, it has limited capabilities of handling multicriteria decision problems. In the same time, decision makers need intelligent guidance for selecting a suitable MCDM technique for their decision situation because different MCDM techniques suit different kinds of decision situation. In this study, an intelligent ArcGIS extension (MCDM Analyst) is developed to enhance ArcGIS decision making capabilities and to help the GIS analysts to select and implement the suitable MCDM techniques for their problems. The component object model (COM) technology is used in designing and integrating this extension with ArcGIS to achieve software interoperability. A typical case study is presented to demonstrate the application of this extension.

Keywords: GIS, ArcGIS, MCDM, COM, Spatial Decision Making

1. Introduction

Spatial decision making is a routine activity that is common to individuals and to organizations. People make decisions influenced by location when they choose a store to shop, a route to drive, or a neighborhood for a place to live, to name but a few. Organizations are not much different in this respect. They take into account the realities of spatial organization when selecting a site, choosing a land development strategy, allocating resources for public health, and managing infrastructures for transportation or public utilities (Jankowski and Nyerges, 2001). Spatial decision making is a highly complex process of choosing among alternatives to attain an objective or a set of objectives under constraints. It can be a structured process involving problems with standard solution procedures, or an unstructured process consisting of problems with no clear-cut solution procedures, or even semi-structured problems for which combinations of standard procedures and individual judgments have to be used to find a solution. All these

processes generally involve voluminous spatial and aspatial information, structured and unstructured knowledge, and human valuation and judgment (Leung, 1997). Spatial decision-making problems are multi-facetted challenges. Not only do they often involve numerous technical requirements, but they may also contain economical, social, environmental and political dimensions that could have conflicting objectives.

Solutions for these problems involve highly complex spatial data analysis processes and frequently require advanced means to address physical suitability conditions while considering the multiple socio-economic variables. Geographic information systems (GIS) and multicriteria decision making techniques (MCDM) are the most common tools employed to solve these problems. However, each suffers from serious shortcomings. Most available GIS software packages do not support MCDM. For example, ArcGIS is a great tool for handling physical suitability analysis. However, it has limited capabilities of incorporating the decision maker's preferences into the problem solving process. MCDM is the proper tool for analyzing decision problems and evaluating alternatives based on a decision maker's values and preferences. However, it lacks the capability of handling spatial data (e.g., buffering and overlay) that are crucial to spatial analysis. Accordingly, many real-world spatial planning and management problems give rise to GIS-based multicriteria decision making (Malc-

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zewski, 1999). The need for combining the strengths of these techniques has prompted researchers to seek integration of GIS and MCDM (Eldrandaly et al., 2003).

There is now a well-established body of literature on GIS-MCDM (e.g., Diamond and Wright, 1988; Janssen and Rietveld, 1990; Carver, 1991; Church et al., 1992; Banai, 1993, Pereira and Duckstein, 1993; Eastman et al., 1995; Heywood et al., 1995; Jankowski, 1995; Laaribi et al., 1996; Malczewski, 1999; Thill, 1999; Laaribi, 2000; Chakhar and Martel, 2003; Eldrandaly et al., 2003, Feick and Hall, 2004; Eldin and Eldrandaly, 2005; Marinoni, 2004; Eldrandaly et al., 2005; Malczewski, 2006b; Boroushaki and Malczewski, 2008; Chang et al., 2008; Vahidnia et al., 2009; Boroushaki and Malczewski, 2010; Farahani et al., 2010; Eldrandaly, 2010). Most of these studies give considerable interest in integrating GIS with a specific MCDM technique to meet the requirements of a particular problem such as Eldrandaly (2003) who integrated Analytical Hierarchy Process (AHP) with ArcGIS for solving industrial site selection problems, and few of them has implemented a specific MCDM technique as an extension to one of the available GIS software packages such as Boroushaki and Malczewski (2008) who implemented a multicriteria combination operator (Analytical Hierarchy Process-Ordered Weighted Averaging, AHP-OWA) as an extension to ArcGIS. However, there is no implementation of a complete MCDM toolbox that contains several techniques and can be used for solving different problems.

Over the past 20 years there has been a plethora of MCDM techniques which suit different kinds of decision situations. Many inexperienced users have difficulty in deciding which kind of MCDM techniques will be the most suitable for their decision situations. Therefore, decision makers need intelligent guidance for selecting and using a suitable MCDM technique for their decision situations.

In this study, an intelligent ArcGIS extension (MCDM Analyst) is developed to enhance ArcGIS decision making capabilities and to help the GIS analysts to select and implement the suitable MCDM techniques for their problems. The component object model (COM) technology is used in designing and integrating this extension with ArcGIS to achieve software interoperability. A typical case study is presented to demonstrate the application of this extension.

2. Geographic Information Systems

Geographic Information Systems (GIS), a promising branch of Information Systems (IS), have achieved considerable success in recent years. This area of IS has concentrated on the construction of computer-based information systems that enable capture, modeling, storage, retrieval, sharing, manipulation, analysis, and presentation of geographically referenced data (Worboys and Duckham, 2004).

2.1. GIS and Decision Making

Malczewski (1999) analyzed the GIS capabilities for supporting spatial decisions in the context of Simon's decision

making process framework which divides any decision making process into three major phases: intelligence (is there a problem or opportunity for change?), design (what are the alternatives?), and Choice (which alternative is best?). Malczewski mentioned the following conclusions: (1) commercially available GIS systems tend to focus on supporting the first phase of the decision-making process through its ability to integrate, explore, and effectively present information in a comprehensive form to the decision makers, (2) these available GIS systems have limited capabilities of supporting the design and choice phases of the decision-making process, and (3) these systems provide a very static modeling environment and thus reduce their scope as decision support tools-especially in the context of problems involving collaborative decision-making.

Today, GIS provide decision makers with powerful tools for the processing, management and analysis of spatially referenced data. However, they lack mechanisms enabling them to incorporate the decision makers' preferences and to make a choice in a context of conflicting objectives and multiple criteria evaluation (Jankowski, 1995; Malczewski, 2006a; Eldrandaly, 2007).

2.2. ArcGIS Desktop

In the last few years, the GIS software market has undergone a remarkable change. The number of GIS software packages has increased significantly and prices have declined dramatically. Many of these packages were developed to fit different user needs and were designed to execute on a variety of hardware platforms. The GIS marketplace has four key vendors that deliver generic platforms: ESRI, Intergraph, Autodesk, and GE Energy (Longley et al., 2005). MCDM techniques are implemented only in two GIS software packages, including IDRISI and CommonGIS. The other GIS software packages don't support MCDM such as ESRI ArcGIS Desktop which is a great tool for handling spatial analysis. However, it has limited capabilities of handling multicriteria decision problems (Nyerges and Jankowski, 2010).

ArcGIS Desktop is a scalable set of state-of-the-art software for geographic data creation, management, integration, analysis, and presentation. ArcGIS Desktop includes a suite of integrated applications: ArcMap, ArcCatalog, and ArcToolbox. Detailed descriptions of ArcGIS are reported elsewhere (ESRI, 2001; ESRI, 2006).

ArcGIS Desktop is built on a technology framework known as ArcObjects. ArcObjects is a set of platform-independent software components, written in C++, which provides services to support geographic information system (GIS) applications on the desktop in the form of thick and thin clients and on the server. ArcObjects makes use of the Microsoft Component Object Model (COM). COM is a standard that enhances software interoperability. Interoperability is the ability of two or more software components to directly cooperate /communicate despite of their differences in programming language, interface, and execution platform (Finkelstein, 1998). COM specifies an object model and programming require-
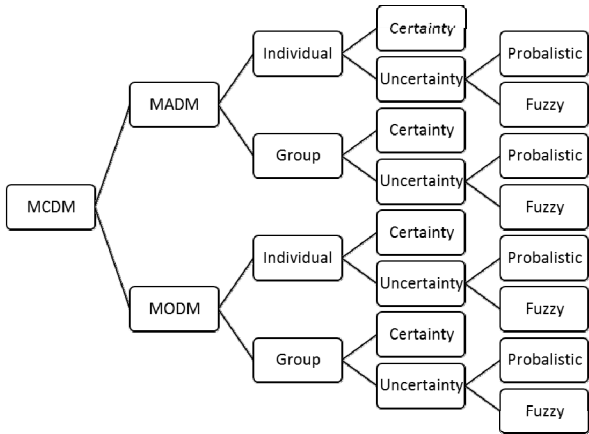
Figure 1. Classification of multicriteria decision problems (adapted from Malczewski, 1999).

ments that enable COM objects to interact with other COM objects. These objects can coexist in a single procedure/process, in independent procedures/processes, or even on remote machines. COM allows these objects to be reused at a binary level and thus third-party developers do not require access to source code, header files, or object libraries in order to extend the system (Vckovski, 1998). Code running under the control of the .NET Framework is called managed code; conversely, code executing outside the .NET Framework is called unmanaged code. Component Object Model (COM) is one example of unmanaged code. The .NET Framework interacts with COM via a technology known as COM Interop. For COM Interop to work, the Common Language Runtime (CLR) requires metadata for all the COM types. This means that the COM type definitions normally stored in the type libraries need to be converted to .NET metadata. This is easily accomplished with the Type Library Importer utility (tlbimp.exe) that ships with the .NET Framework Software Developer Kit (SDK). This utility generates interop assemblies containing the metadata for all the COM definitions in a type library. Once metadata is available, .NET clients can seamlessly create instances of COM types and call its methods as though they were native .NET instances (ESRI, 2004).

3. Multicriteria Decision Making

Multicriteria problems with conflicting objectives have encountered in several applications, such as facility location. The development of multicriteria methods is actually relatively recent. Over the past 20 years there has been a plethora of tools and techniques developed for solving these problems. MCDM techniques are decision support tools designed to analyze decision problems, generate useful alternative solutions, and evaluate alternatives based on the decision maker's values and preferences. The general objective of these methods is to assist the decision-maker in selecting the best alternative from the number of feasible alternatives under the presence of multiple choice criteria and diverse criteria priorities (Eldrandaly et al., 2009). A literature review suggests that a number of approaches have been used in formulating MCDM tools. The underlying theory of multi-criteria decision making and algo-

rithms have been summarized in a variety of operations research, management science, and decision sciences literatures (Mollaghasemi and Pet-Edwards, 1997).

3.1. MCDM Problems

MCDM problems can be broadly categorized into two groups (Malczewski, 1999; Laskar, 2003), namely, (1) Multi Attribute Decision Making (MADM), and (2) Multi Objective Decision Making (MODM). MADM is concerned with choice from a moderate/small size set of discrete actions (feasible solutions) while MODM deals with problem of design (finding near optimal solutions) in a feasible space bounded by the set of constraints. Both MADM and MODM problems can be further categorized into single decision making problem and group decision making problem, which in turn subdivided into deterministic, probabilistic, and fuzzy decisions as shown in Figure 1.

3.2. MCDM Methods

Almost all methods for solving multiple criteria problems (whether multiobjective or multiattribute) involve two general sub processes (Evans, 1984): (1) articulation of the decision maker's preference structure over the multiple criteria, and (2) optimization of the preference structure. According to the timing of these two sub processes relative to one another, the methods for solving multiple-criteria problems can be categorized into the following three classes (Mollaghasemi and Pet-Edwards, 1997; Eldrandaly, 2010):

(1) Methods based on the prior articulation of preferences: In these methods the decision maker's preferences are obtained through detailed interviews between the decision maker and the analyst prior to the start of the optimization process. The major disadvantage of this approach is the difficulty facing the decision maker in giving the required preference information. The optimization process, however, is usually relatively simple because the multicriteria problem has typically been reduced to a single-objective problem. Some of these approaches are suitable for solving only multiattribute problems (for example, scoring methods, the analytic hierarchy process, and outranking methods), some are suitable only for multiobjective programming problems (such as goal programmming), while others can be used for both multiattribute and multiobjective programming problems (for example, utility-based methods). The majority of these approaches are designed for problems with known (deterministic) outcomes.

(2) Methods based on the progressive articulation of preferences: The techniques that relay on progressive articulation of preferences (interactive methods) follow a common pattern. The decision maker is presented with a subset of the nondominated alternatives and is asked to provide some local preference information of these alternatives. This information allows the formulation of a single-criterion sub problem, which is then solved. The new nondominated solution and the outcome are then presented to the decision maker to provide new local information and the process is repeated until the decision maker either converges toward a best-compromise

Table 1. MCDM Methods Used in Building the Proposed System

MCDM Methods	Problem	Method
Analytic Hierarchy Process (AHP)	Multiattribute	Prior
Analytic Network Process (ANP)	Multiattribute	Prior
Ordered Weighted Averaging (OWA)	Multiattribute	Prior
Value Based Function	Multiattribute, Multiobjective	Prior
Utility Based Function	Multiattribute, Multiobjective	Prior
Goal Programming	Multiobjective	Prior
Interactive Goal Programming	Multiobjective	Progressive
Data Envelopment Analysis (DEA)	Multiobjective	Posterior
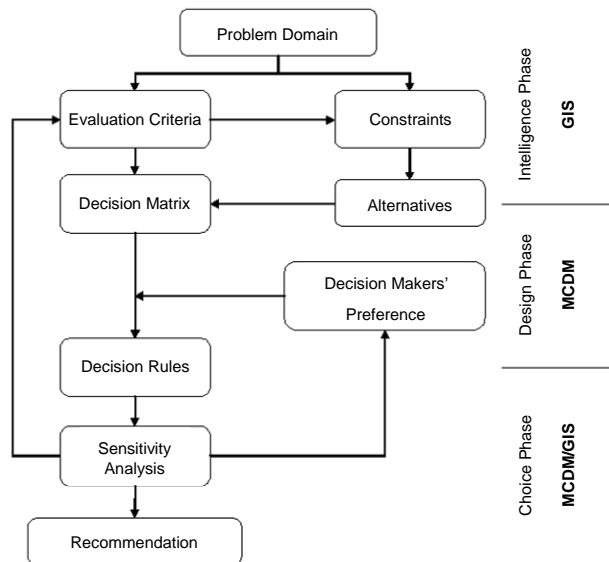
Figure 2. Framework for spatial multicriteria decision analysis (adapted from Malczewski, 1999).

solution or terminates the process prior to reaching that point. The objective is to find a satisfactory solution after a reasonable number of iterations and within a reasonable amount of time. When compared to the prior articulation of preferences methods, interactive methods are, in general, more complicated and difficult for the decision maker to understand. These methods tend to involve a higher degree of mathematical sophistication and, consequently, are less transparent to the user. However, they require less information from the decision maker in terms of implementation. An advantage of these methods is that they are interactive in nature and require the information to be obtained incrementally. This means that the decision maker is involved throughout the process.

(3) Methods based on the posterior articulation of preferences: The techniques that relay on posterior articulation of preferences are the least commonly used of the multicriteria

approaches. The majority of the methods in this category are applied to multiple-objective mathematical programming problems. These methods try first to find all or almost all of the nondominated solutions to the problem. The nondominated solutions are then presented to the decision maker to select the preferred one through elicitation of preference information. There are several disadvantages to this class of methods. First, the algorithms are often very complex and difficult for the analyst and the decision maker to understand and use. Second, many real-world problems, particularly multiobjective programming problems, are to large to be solved using this approach. Finally, posterior methods can lead to a very large number of efficient (nondominated) solutions. Choosing a single preferred solution from a large efficient set can be a very difficult task for the decision maker. Because of the level of complexity of these methods, the most widely used method in this category is the data envelopment analysis (DEA). Although DEA doesn't explicitly use preference information from the decision maker, Mollaghasemi and Pet-Edwards (1997) classified it as a posterior method because it is used to analyze the efficiency of sets of alternatives. After applying DEA, the decision maker will often use the information generated by the method in making more informed choices about the alternatives.

Table 1 summarizes the eight MCDM methods used in building the proposed system. Detailed descriptions of the different MCDM methods are reported elsewhere (Mollaghasemi and Pet-Edwards, 1997; Malczewski, 1999; Triantaphyllou, 2000; Forman and Selly, 2001; Jankowski and Nyerges, 2001; Saaty, 2004; Figueira et al., 2006; Saaty, 2008; Chu and Lin, 2009).

3.3. MCDM Methods and Spatial Decision Making

MCDM techniques were designed to analyze decision problems, generate useful alternative solutions, and to evaluate the alternatives based on a decision maker's values and preferences. The general objective of these methods is to assist the decision-maker in selecting the best alternative from a number of feasible alternatives under the presence of multiple choice criteria and diverse criterion priorities (Mollaghasemi and Pet-Edwards, 1997; Jankowski, 1995). These techniques, however, assume homogeneity within the study area, which is unrealistic in many spatial decision making situations such as site selection problems. It also, lacks the capability of handling spatial data (e.g., buffering and overlay) that are crucial to spatial analysis. Malczewski (1999) suggested that there is a need for an explicit representation of geographical dimension in MCDM techniques. The combination of GIS and MCDM capabilities could effectively solve this problem.

Malczewski (1999) has proposed a framework for spatial multicriteria decision analysis, as shown in Figure 2.

3.4. Data Standardization

Central to spatial multicriteria decision making is the fact that an attribute can be represented in a GIS database as an attribute (criterion) map layer. A criterion map represents the spatial distribution of an attribute that measures the degree to

which its associated objective is achieved. The procedure for generating criterion maps is based on GIS functions. Given a variety of scales on which each criterion can be measured, Multicriteria evaluation requires that values contained in the various criterion map layers be transformed to comparable units (standardized to a common scale). Two common approaches to standardizations are linear and nonlinear. The simplest formula for linear standardization is called the maximum score procedure. The formula divides each raw criterion value by the maximum criterion value as shown in equation (1):

$$x'_{ij} = \frac{x_{ij}}{x_j^{\max}} \qquad (1)$$

where x'_{ij} is the standardized score for the ith decision alternative and the jth criterion, x_{ij} is the raw data value, and $x_j^{\max}$ is the maximum score for the jth criterion. The values of standardized scores can range from 0 to 1 and are linearly related to the raw data values. In the nonlinear standardization procedure, the standardized criterion value is computed by dividing the difference between a given criterion's raw data value and the minimum value of the value range as shown in equation (2):

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \qquad (2)$$

Detailed descriptions of standardization approaches are reported elsewhere (Malczewski, 1999; Boroushaki and Malczewski, 2008; Nyerges and Jankowski, 2010).

3.5. Selecting MCDM Method

There is a great diversity of MCDM methods; each of them has its own advantages and disadvantages. Identifying the most suitable method for solving a given problem is a difficult task because different decision problems have distinct characteristics (Mollaghasemi and Pet-Edwards, 1997) and decision makers, who must provide the preference information, differ in their decision making styles and preferences. Care and judgment must be used in selecting an appropriate method for solving a specific problem because the use of an inappropriate method can lead to decisions that cannot be justified even if the problem has been structured perfectly (Ozernoy, 1992). The selection of the suitable MCDM methods have been discussed and analyzed by many researchers (e.g., Ozernoy 1992; AI-Shemmeri et al., 1997; Gilliams et al., 2005; Li , 2007; Eldrandaly et al., 2009).

There are several factors that should be considered when selecting a MCDM method. These factors can be classified as shown in Figure 3 as follows (Evans, 1984; Mollaghasemi and Pet-Edwards, 1997; Li, 2007; Eldrandaly et al., 2009): (1) characteristics of the decision problem such as the size, complexity and the amount of uncertainty of the problem, (2) Characteristics of the decision maker such as the ability and/or desire of the decision maker to articulate various amounts and type of preference information, and (3) characteristics of the
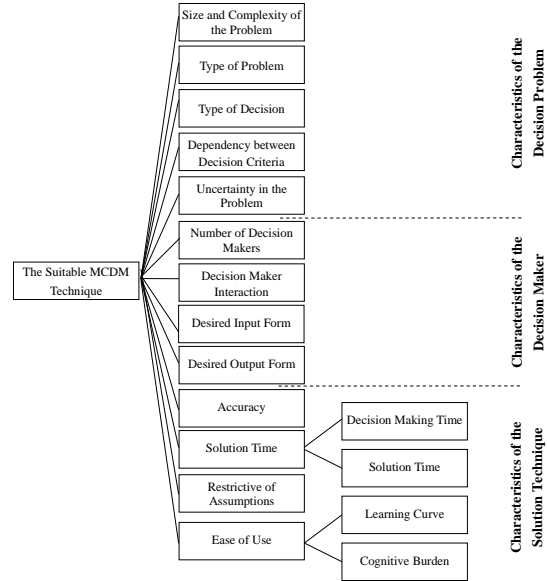

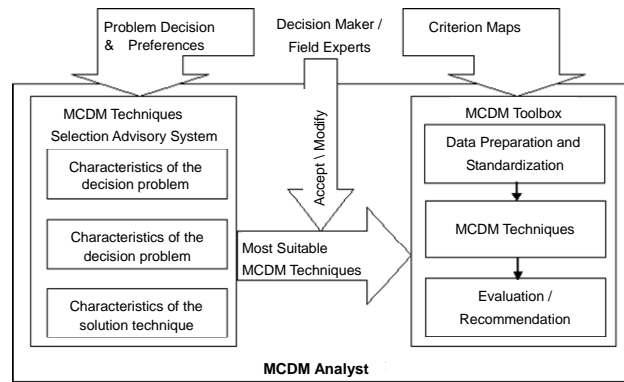**Figure 3**. Factors used in selecting the most suitable MCDM method.

Figure 4. Framework of the proposed system.

solution technique such as ease of use, total time required to solve the problem, accuracy, and restrictiveness of the underlying assumptions.

In order to select an appropriate technique, the characteristics of both the decision problem and the decision maker must be studied against the characteristics of the solution technique so that the best match can be identified.

4. Development of the Proposed System (MCDM Analyst)

MCDM Analyst is developed as an ArcGIS extension to help the GIS analysts to select and implement the suitable MCDM methods for their problems. The component object model (COM) technology is used in designing and integrating this extension with ArcGIS to achieve software interoperability. MCDM Analyst consists of two basic modules which can be invoked separately as shown in Figure 4.

1. MCDM Techniques Selection Advisory System: a prototype expert system for selecting the suitable MCDM techni-

ques based on a set of characteristics that describe the decision problem, decision maker and solution technique (see section 3.5).

2. MCDM Toolbox: This toolbox provides two functions: (1) data standardization (see section 3.4), and (2) multicriteria evaluation using eight MCDM methods (Table 1).

4.1. MCDM Techniques Selection Advisory System

A prototype expert system is developed to assist the Decision makers in selecting a suitable MCDM technique for their problem. The output of the proposed system is a set of recommended MCDM techniques that are suitable for spatial decision making problem under consideration. Using Visual Rule Studio® (an object-oriented expert systems development environment for windows) the proposed expert system is developed as an ActiveX DLL to achieve the required software interoperability.

Visual Rule Studio solves the problem of software interoperability by allowing the developers to package rules into component reusable objects called RuleSets. By fully utilizing OLE and COM technologies, RuleSets act as COM Automation Servers, exposing RuleSet objects in a natural COM fashion to any COM compatible client. Visual Rule Studio installs as an integral part of MS Visual Basic 6.0, Professional or Enterprise Editions, and appears within the Visual Basic as an ActiveX Designer. This allows the developers to add rule objects to their existing or new Visual Basic application in much the same manner they would extend their application with a new form or ActiveX control. RuleSets can be complied within Visual Basic, EXE, OCX, or DLL executables and used in any of the ways the developers normally use such executables (RuleMachines, 2002).

The RuleSet of the proposed system consists of four Classes and 72 Rules based on the different selection criteria mentioned in section 3.5. The inference engine of Visual Rule Studio's production system acts as the unseen hand or executor which causes processing to take place. Processing here is defined as the combining of supplied data with rules to create inferred data. It is the inferred data that is the desired end result of the production system processing. The Visual Rule-Studio inference engine provides two primary problem- solving engines relevant to production systems: the forward chaining engine and the backward chaining engine (RuleMachines, 2002). In the proposed expert system forward chaining engine is used. Starting from an initial or current set of data, the forward chaining inference engine makes a chain of inferences until a goal is reached.

4.1.1. Verification and Validation of Expert System

Verification determines correctness of the system, i.e. whether the product satisfies the specification standards set at the beginning of the project. In the expert system's context, verification ensures that the compile time and runtime errors are eliminated. The debugging utilities of the Visual Basic 6.0 and Visual Rule Studio are utilized throughout the development cycle to ensure error-free execution of the system. Different modules are evaluated individually by executing a series
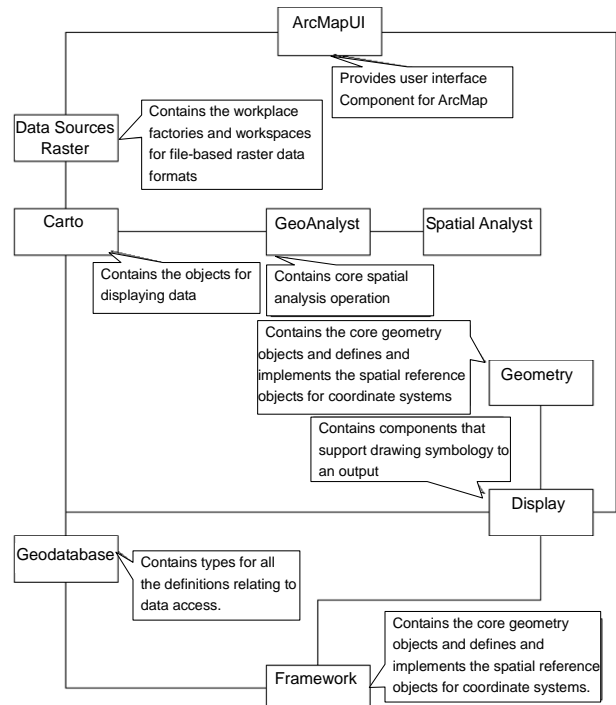

Figure 5. The used ArcObjects libraries (adapted from ESRI, 2004).

of predetermined test cases (Laudon and Laudon, 2001). The complete system is then verified to ensure that the integrated modules behaved as expected. Verification aspects common to knowledge-based processing, as noted by Medsker and Liebowitz (1994), is also applied.

Validation is the process of determining that the system completely and accurately represents the problem domain, and that it achieves acceptable performance levels (Libertore and Stylianou, 1993). Based upon their research methods approach, Ayel and Laurent (1991) as well as Libetore and Stylianou (1993) present a common procedure for establishing content validity. These guidelines are utilized throughout the development of the expert system. According to Medsker and Leibowitz (1994), validation using independent experts reduces potential bias in the results, and lends credibility to the validation process. Content validity is established through face validation by several external experts. These experts are selected for their in-depth knowledge and experience in the field of MCDM. All of the domain experts considered the system to be satisfactory, and that only some minor modifications are required. Any disparities between the evaluators' opinions are resolved, and their suggestions for modification are incorporated into the final version.

4.2. MCDM Toolbox

The MCDM Toolbox has been implemented within ESRI ArcGIS 9.2 Desktop as an extension to extend its decision making capabilities. Extensions are a collection of toolbars and commands. Commands are components that implement the ICommand interface of ArcObjects, ArcGIS development pla-