Korean Journal of Geomatics
Vol. 2, No. 2 / December 2002
pp. 115~122

Integration Issues in the GIS and Decision Support Systems

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Abstract

Since geographic information systems (GIS) began to emerge as an effective spatial information processing technology, there also has been growing interest in integrated use of GIS with other decision support systems. As various spatial-related problems such as urban development planning and natural resource management require more analytical and interpretive solutions, it is viewed that the supportive role of GIS to complement or reinforce the counterpart decision tools will be increased. This study examines the major situations that have needed the integration methodologies in the past decade to derive research trends relating to this integration agenda and, hence, to elicit the possible underlying principles from those experiences. According to the kinds of decision tools linked with GIS, alternative methodologies and viewpoints are categorized and compared.

Keywords : *GIS, Integration, DSS, Expert Systems, Mathematical Models*

1. Introduction

Geographic information systems (GIS) have been recognized as powerful tools in a variety of academic and practical areas for their capabilities of managing, analyzing and displaying spatial data. On top of the basic characteristics as computer-based tools—fast, correct, large, consistent, durable, and reproducible—GIS provides unique capabilities that can replace traditional manual techniques. Strengths of GIS are mentioned frequently in the voluminous GIS literature. Broadly the advantages include: (i) spatial data layers are combined with non-spatial data that describe corresponding spatial features, a great advantage over using separate computer systems such as cartographic systems and database systems; (ii) spatial data and their non-spatial portion can be stored, related, and manipulated; and (iii) different applications can share the same GIS database.

Although these capabilities have proved their usability in a multitude of applications, there also has been increasing interest in coupling GIS with other decision support systems. This implies that current GIS has basic weaknesses presenting their use as complete tools to meet different needs from different fields and that, from a positive viewpoint, GIS and the information generated by GIS are useful for many specialist systems. Since most proprietary GIS packages do not, (or, practically, can not) provide sufficient capabilities to satisfy various specific requirements, it is viewed that the use of GIS as the supportive tools to complement the needs demanded by using other decision models will inevitably be increased. However, due to the relatively short period of experiences and insufficient understanding on both the needs and the technical capabilities, the proper integrated use of GIS with other decision tools has been limited. Also the fact that these different decision support systems are generally originated from or used in different backgrounds and user communities has discouraged most researchers and practitioners from obtaining their integrative potential.

With these issues in mind, this study seeks to clarify the kinds and the methodologies of integration of GIS by investigating the major situations that have needed the integration methodologies. In this study, the previous research approaches are examined and alternative methodologies and viewpoints are categorized and compared. First, the different frameworks used in other literature in classifying the integration approaches

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The manuscript for this paper was submitted for review on December 5, 2002.

are discussed and the classification scheme employed in this study is presented. Based on this scheme, is an analysis of the previous applications on integration. As the concluding remarks, some relevant facts found in the previous approaches are described along with suggestions for improvements.

2. Classifications of Systems Integration

Some of the discussion on this topic has presented different viewpoints by which the methods of linkage between a GIS and other decision tool can be identified. The most frequently cited classification scheme is the architectural basis for integration, where the integration is expressed in terms of the closeness or the extents to which two separate systems are interfaced (Nyerges 1992, Goodchild *et al.* 1992, Fedra 1993). Examples of this classification include loose coupling, tight coupling and full integration (Fig. 1). In loose coupling, two systems exchange files such that a system uses the data from the other system as the input data. Actually, at this level of integration, two systems run independently and no system modification or programming takes place except that the data of a system needs to be edited as necessary for the proper format to the other system. Although this technique is found in most approaches that involve integration of systems due to its simplicity, manipulating the exchange files tend to be cumbersome and error prone. Tight coupling involves writing some form of programs to automate or facilitate the integration process between the components. Two systems share not only the communication files but also the common user interface. This is achieved by using macro languages such as AML (Arc Macro Language) that is provided by the Arc/Info GIS package. Although AML is not suited to perform complex numerical manipulations, relatively simple forms of calculations can be formulated inside AML codes and it can invoke external programs, which enables the user to interact with both systems through a user interface without having to quit either system. In full integration more complete integration can be achieved by creating user-specified routines through generic programming languages such as FORTRAN or C and adding them into the existing set of commands or routines of the GIS package. This technique requires such resources as source codes or command libraries and relatively complicated programming knowledge, which is not available to most GIS users.

Anselin *et al.* (1993) classified the integration approaches based on the direction of interaction between the systems into three broad types—one-directional integration, two-directional integration and dynamic integration (Fig. 2). One-directional integration moves information via a single flow which originates in either the GIS or in the decision support tool of interest. In the movement of information from the GIS to the other decision support module, the data generated in the GIS serves as the input data to the second module while the flow in the opposite direction involves using the data from the decision tool in the GIS for direct visualization or further analyses. Two-directional inte-

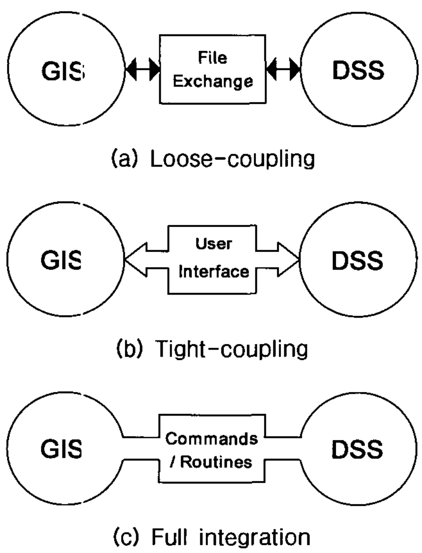

Fig. 1. Classification of GIS-integration methods in terms of the extent of integration.

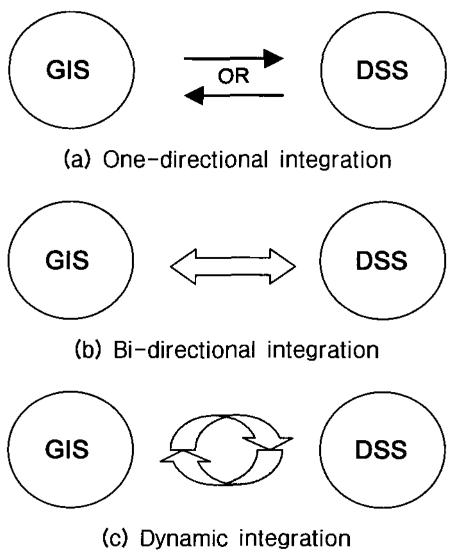

Fig. 2. Classification of GIS-integration methods in terms of the direction of interaction.

gration links the systems in a form that simply combines the two aspects of the one-directional integration. Most approaches that employ this method start from the GIS module generating the appropriate data for the counterpart decision support module, perform the required operations in the second module, and ultimately use the resultant data to add to the existing attribute data set and to visualize based on this newly created information. While two-directional integration involves one time flow of information, dynamic integration enables the data flow between the decision tool and the GIS to move back and forth flexibly based on the user's needs. Such dynamic iteration can be performed by developing the user interface that allows the user to interact with either system through graphical menu-based tools. This type of integration may be especially useful in cases where the decisionmaker wants to revise the data or the decision scenarios after examining the results obtained from an intermediate iteration.

While broadly agreeing with the above categorization framework by Anselin (1993), this study employs an alternative analysis scheme in classifying previous approaches to diverse integration methodologies. This scheme categorizes the applications that play a role as counterpart decision support modules of the GIS in the integration into the expert systems, statistical data analysis tools and a variety of mathematical models. The different kinds of applications that have appeared in wide range of literature on the integration with the GIS are categorized and compared based on this classification scheme. For examining an integrated system, the previous two classification schemes, that is, the extent of integration and the direction of integration can be also applied along with the kind of decision support systems. For example, an integrated system can be classified as a loosely coupled, one-directional integrated system of a GIS and an expert system.

Although the categories—expert systems, statistical analysis tools and mathematical models—may not represent all possible cases for linked uses, the previous approaches in the past decade have shown some sort of characteristics that can be grouped by one of these categories. Expert systems (often called knowledge-based systems) are used in storing the expert's knowledge and decision logic, making inferences about a given fact and generating the expert's advice and explanations. A GIS can be used as the information provider or the receiver based on the problem's requirements. Various statistical analysis tools are used in analyzing and explaining the properties of data. The attribute data that describes the spatial features in the GIS are analyzed and interpreted by the statistical tools and, in case of two-directional or dynamic integration, the newly created information are sent back to the GIS for visualization. Mathematical modeling can be regarded as a special class of decision support system and range from rigid mathematical optimization models to descriptive or heuristic solution techniques. Modeling techniques use the GIS data in defining various constants, solve the formulated problems, and, if necessary, visualize the results in the GIS. Recent literature includes 'quasi-mathematical' modeling approaches using multiple criteria decision making (MCDM) tools in the effort to solve the trade-offs between multiple and conflicting decision elements.

The following sections present the examination of the research literature on integrated use with GIS based on these three categories. Rather than an exhaustive analysis, the efforts are focused on identifying the approaches that are viewed to be relatively representative and relevant to the research purpose for eliciting the research trends and principles.

3. Integration with Expert Systems

Expert Systems (ES) comprise a software technology that can replicate certain aspects of expertise, and can manipulate both qualitative and quantitative knowledge. This technology offers planners new ways of organizing, formalizing, and manipulating context-specific knowledge and problems (Masri *et al.* 1993). Such systems have been somewhat hopefully viewed as a means of overcoming the limitations found in current deterministic model-based approaches to problem solving (Han and Kim 1989).

Numerous expert systems developed for spatial problems without involving GIS had already implied the promising possibilities of incorporating spatial information into expert reasoning processes. Davis and Grant (1987) developed an expert system (ADAPT) designed to assist local planners in producing zoning schemes. This expert system is a typical example that aids the decisionmaker by means of interactions for relevant data and knowledge. Another managerial information system (SITE CODE) was developed by Shaw *et al.* (1993) to apply municipal regulations to particular building site plans. The rules in this system represent the logic of regulation, the facts about the ordinances, and the locations of particular site. Although these two systems demonstrated that an expert system can embody planning regulations adequately, they could not represent the relationship between spatial location and non-spatial regulation, which is crucial especially when decision rules depends strongly on a geographic location.

Other cases that revealed limitations in utilizing standalone expert systems for solving spatial problems include those applications in site selection and suitability analysis problems (e.g. Suh *et al.* 1988, Amha *et al.* 1994). Although those applications incorporated experts' judgmental decision factors as well as quantifiable factors, they did not include the means to use, analyze and visualize spatial data. Since most planning activities such as site selection include spatial analysis and delineation on maps to facilitate the decision process, the standalone expert systems applied in planning areas that do not involve spatial data access or visualization contained fundamental weaknesses for practical uses.

The expert systems in spatial problem solving became more sophisticated as they began to associate GIS data into the system processes. Ideas and research efforts to fix the deficiencies of GIS utilizing expert system techniques have increased since the mid 1980's (e.g. Peuquet 1984, Robinson et al 1987, Fisher 1989, Wright 1990, Lu *et al.* 1992, Maidment *et al.* 1993, Cowen *et al.* 1994). An integrated expert system and GIS have been referred to as an expert GIS or, interchangeably, a knowledge-based GIS when focusing on the stored facts or rules. The uses of expert GIS have shown such benefits as enabling a novice GIS user to carry out some range of GIS operations similarly to an experienced user by making user interaction with GIS easier.

The first category of expert GIS contains those applications that mainly address spatial entities of GIS data for spatial feature extraction or classification. An early example of such applications was a study by Peuquet (1984) that suggested solutions to several problems found in current GIS by means of using a knowledge-based GIS (KBGIS). A prototype expert system was developed to remedy incomplete and error-prone characteristics of geographic data. The stored facts and logical rules were used as a self-checking mechanism to detect and correct data errors. A heuristic search procedure was employed to increase the speed of data search and retrieval by eliminating large portions of the database from consideration at an early stage of search process. Another similar study was done by Leung *et al.* (1993). In this study, the expert system was used for spatial data classification with remotely-sensed data and regular GIS data layers. A notable aspect was that they employed fuzzy logic to correct the unrealistic regional classification by which the borders of a region are sharply defined based on Boolean logic.

Another broad category of expert GIS includes those applications that incorporate GIS data and operating capabilities into an expert system to form a geographic decision support system for resource management, territorial planning or land suitability analysis. Djokic (1991) linked the Arc/Info GIS with an expert system to create a drainage network assessment system that checks for completeness and connectivity of network elements of GIS data. Evans *et al.* (1993) stated in his study that the improved version of SITE CODE (Shaw *et al.* 1993) can provide regulatory information to the user by linking regulatory facts stored in a data base to sites located in a GIS through an expert system query interface. A study by Miller (1994) illustrated an increased utility of integrated decision tools by showing how the GIS can be coupled not only to the knowledge-base but also to the environmental model to address vegetation change problems.

The review of expert system efforts related to GIS indicates that, from the expert system's viewpoint, a better decision system that relies on spatial information is likely to involve accessing and visualizing spatial data. Although experience in the integration issues of expert systems and GIS has not been yet sufficiently accumulated due to the relatively short history of research efforts, those planning-related areas such as site suitability analysis or resource management evidently belong to a problem domain suitable for the integration approaches using expert system-GIS combined system.

4. Integration with Statistical Analysis Tools

Statistics is the study of making sense of data. The objective of statistics is to make inferences about a population based on information contained in a sample (Ott 1993). In other words, we can rephrase that statistical analysis deals with the issues of what property can be inferred from the given data. Geography's domain of data is the surface of earth composed of different types of spatial entities—points, lines, and areas. Although there is no common definition of what constitutes spatial analysis, the statistical analysis of spatial data, as a research area, has always played a central role in the quantitative scientific tradition in geography, largely addressing identification of properties from those spatial entities as data.

Individual spatial features on the space have some attributes respectively. For example, a piece of land, which is expressed as an area or a polygon on a map, may be characterized by such attributes as land price, vegetation cover, soil type, slope percentage, temperature, or population density. With the advent of GIS, storing and manipulating both spatial features and their corresponding information data have become facilitated. Such advantages along with various analytical capabilities that the GIS provides have expanded the research topics in statistical-spatial data analysis from traditional pattern detection and description (Boots and Getis 1988, Odland 1988) to a wider range of methodological issues in spatial statistics (Fischer and Nijkamp 1992, O'Kelly 1994, Batty and Xie 1994).

Anselin *et al.* (1993) classified different issues of integration between GIS and spatial analysis as follows: (i) the construction of linkages between data in a GIS and statistical packages; (ii) the addition of specialized spatial data analysis functions to a GIS by using macro languages or external software module; and (iii) the inclusion of visualization capabilities for exploratory data analysis in a dynamically linked integration.

The most frequently observed type of integration has been that between a GIS and an existing statistical package, where the GIS play the role of non-spatial data provider. These applications have not fully taken advantage of GIS's spatial analysis component relying on using a GIS only in the initial data gathering step rather than for visualization or spatial data manipulations. Moreover, such loosely coupled integrations require the user to export GIS data to a statistical package for statistical analysis because most commercial packages operate outside the GIS environment. Some efforts have been made to incorporate spatial techniques into the GIS environments so that the user can utilize spatial data analytical techniques with GIS visual techniques in the same environment (Ding and Fotheringham 1992, Bao *et al.* 1995). The integration in these applications was done within the Arc/Info environment by programming statistical formulations and Arc/Info commands in AML.

More researchers are becoming interested in developing closely integrated GIS-spatial analysis system utilizing macro languages to be able to perform spatial analysis and visual analysis in a flexible and user-friendly environment. Considering this trend, improvement of current macro languages (e.g., AML) is called for to satisfy diverse programming needs from diverse user communities who want to combine GIS visualization with their specialized decision tools.

5. Integration with Mathematical Models

Although many researchers see using mathematical models as a trend of spatial data analysis research, this study distinguished mathematical modeling techniques into a different group considering their origins and problems that are addressed. While spatial data analysis concerns the properties that can be inferred from spatial data, models deal with simplification of an observed relation or process. There is no universally accepted classification scheme for models but some views will serve (Burrough 1988, Wheeler *et al.* 1988). Although a model can be viewed, inclusively, as an attempt to generalize or simplify the relationships observed in nature, this examination concerns the scope of mathematical models as external decision support tools from GIS's viewpoint. Rather than examining the components or types of models, primary efforts were made to elicit how the GIS were used for models.

The most frequently observed research topic is uses of GIS as the data provider for establishing some sort of constants of a model (e.g., Fisher 1991, Chuvieco 1993, Campbell *et al.* 1992, Haddock and Jankowski 1993, Cromley 1994; Warwick and Haness 1994, Xiang 1993). Campbell *et al.* (1992) and Chuvieco (1993) presented the application of linear programming (LP) in combination with a GIS in planning land use strategies. Basically, the LP model is a mathematical model that maximizes or minimizes some objective function subject to a set of constraints. Chuvieco (1993) designed a test application of the LP-GIS integrated system to maximize the most labor-intensive organization of land use. This objective was constrained by limited resources and the GIS was used in demarcating resource availability by means of overlay map analysis. The optimal solution indicates the maximum number of new jobs from the new organization of land use that can be reached after satisfying all the constraints. The number of hectares for optimal land use allocations was then passed to the GIS for mapping and comparison with existing situations.

A similar study was done by Xiang (1993) employing a multiobjective linear programming technique. In many practical situations it would be desirable to achieve a solution that is "best" with respect to multiple different criteria rather than one criterion as in Chuvieco (1993) i.e. maximizing labor productivity. In multiobjective LP, all the objectives are assigned target levels for achievement and a relative priority on achieving these levels. It then attempts to find an optimal solution that comes "as close as possible" to the targets in the order of specified priorities. However, the major drawback of multiobjective LP is that it requires the user to formulate the model by specifying constraints and variables and to quantify the priorities in advance, which is difficult in reality.

By contrast, preference-oriented methods generally interact with the decisionmaker for the preference setting during the analysis. The multiple criteria decision making (MCDM) techniques has been proved useful in those situations that require the decisionmaker to select the best alternative from the number of feasible choice alternatives in the presence of multiple decision criteria and diverse criterion priorities. Some applications of MCDM techniques coupled with the GIS are found in recent research approaches (e.g., Carver 1991, Jankowski and Richard 1994, Hickey and Jankowski 1997). Jankowski and Richard (1994) illustrated how the land suitability problem can be solved with the MCDM-GIS integrated system by enabling the procedure of selecting a site and setting priorities to be done in a systematic manner taking into account spatial and nonspatial information. A study by Hickey and Jankowsi (1997) was notable in terms of the level of coupling. In this study, the contribution of GIS was considered not only as a method for data gathering but also as the tool for mapping the result. A composite overlay map was visualized in the GIS that reflect the weights for criteria obtained from the MCDM module.

The research trend of GIS-mathematical modeling integration indicates that multicriteria decision making techniques are preferred to deterministic optimization models especially in those areas that require considering of trade-offs of multiple decision criteria and of the decisionmaker's intervention for priority setting. Facilitating such purposes will require proper knowledge of MCDM techniques as well as GIS in order to select the right tools for specific needs and to determine how the data flow between the systems will take place.

6. Conclusions

This study has examined the previous approaches in the research issue of integration of GIS with other decision tools. The effort was primarily devoted not so much to reviewing the individual methodologies extensively, but to discussing current alternative viewpoints and deriving research trends relating to this integration agenda and, hence, eliciting the possible underlying principles from those experiences and the suggestions for improving the potential obtained from using integration methodologies.

Although during the examination of literature, various integration issues among the decision support tools that do not involve the GIS were discovered and viewed notable such as linkage of an expert system with other decision support techniques (e.g. van der Meulen 1992, Leimbach 1994), primary efforts were focused within the framework of three categories, that is, the integration of GIS with an expert system, with a spatial analysis tool and with a mathematical model.

Many researchers recognize the lack of analytical and modeling capabilities as a major deficiency of current GIS (Fischer and Nijkamp 1992, Goodchild *et al.* 1992). As Goodchild *et al.* (1992) stated, since developments in the GIS products largely reflect the demands of the GIS marketplace which has been dominated by applications in resource and facility management and land information, GIS uses in these areas have been confined to relatively simple purposes such as data query or visualization rather than complex analysis. However, as the users and applications of GIS become more mature and sophisticated, the efforts to improve decision making call for proper understanding and uses of diverse decision tools within current computerized environments. Interest in integration issues will also continue to increase.

On the premise that the perspective of the current GIS to include complex and specialized decision tools within their functionality is practically limited, one remedy on the manufacture's side will be to improve modules in their GIS packages to facilitate the program's interface with external programs. Although AML or Avenue is favored by many developers or researchers as a useful tool, especially for developing GUI (graphical user interface) code, it is not suited for extensive numerical calculations. Enhancement of programming features such as functional routines or libraries as in generic programming languages will make 'tighter' coupling of GIS with external programs possible and developing numerical models within it easier.

Some relevant facts identified through the review of the previous approaches are summarized as follows: (i) because, in a loosely coupled system, cumbersome data manipulations are generally required to make the data format to be acceptable in both applications, development of the user interface that aid close coupling of the systems where the user can interact with the applications flexibly are desirable. Although limited due to the limitations of currently available software, it is feasible to simultaneously operate a GIS and a decision support tool allowing dynamic data flow between the system components based on the user's control through the user interface; (ii) in those areas that involve multiple decision criteria, the use of multiple criteria decision tools are viewed to play a better role in handling trade-offs while respecting human's nature of uncertainty in assigning weights rather than the deterministic modeling techniques such as optimization techniques; (iii) expert systems have been proved powerful tools for handling such decision problems that require professionals' judgments for complex and routine decision steps. The benefits of using expert GIS become conspicuous, especially, when the type of problem requires such decision rules that depend on information of geographic location, or when complicated GIS data processing steps that is controlled by experts' decision rules needs to be simplified or automated; and (iv) current development trend of decision support systems favors such decision strategies that allow cognitively less demanding user interventions while the decision steps are transparently given to the user, which is viewed helpful to convincing the user of the consequences, ultimately leading to a desired solution.

The linkage of the GIS with a decision support tool expands the utility of both systems more than the simple sum of individual components. Integration between these systems expands the range of problems that either system can handle. The study efforts were for clarifying the system integration issues that have remained relatively obscure compared to the amount of literature devoted to this topic.

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