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LECTURE NOTE

SPATIAL DECISION SUPPORT SYSTEMS (SDSS)

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SPATIAL DECISION SUPPORT SYSTEMS

1. Introduction

Decision Support Systems (DSS) have been an important application area of Information Systems. While many decision support systems have been used in managerial decision making, a major limitation of these systems has been their inability to exploit spatial and temporal data. Because much useful hydrologic data is spatially referenced, ignoring this additional information has limited the decision support analyses. Therefore, a new type of DSS has emerged, known as the Spatial Decision Support System (SDSS). Currently, there is a growing interest in developing both spatial models and SDSS for decision making.

SDSS are designed to help decision makers solve complex problems such as river basin management, and flood management, that have a strong spatial component. An SDSS incorporates both geographic information systems (GIS) functionalities such as spatial data management, cartographic display, etc., as well as analytical modeling capabilities, a flexible user interface, and complex spatial data structures. Thus, SDSS provides a framework for integrating a) analytical and spatial modeling capabilities, b) spatial and non-spatial data management, c) domain knowledge, d) spatial display capabilities, and e) reporting capabilities.

SDSSs result from the melding together of GIS and DSS technologies. Effective use of SDSS in problem solving requires a tremendous amount of *a priori* knowledge about geo-spatial modeling and analysis. For example, users have to know which models are appropriate for what types of problems and the appropriate data to use. Fig. 1 is a representation of the combining of GISs and DSSs into SDSSs.

Note from Fig. 1 that the addition of GIS capability to DSSs will impact all of the major components of resulting SDSSs. GISs have user interfaces, a data base for features and attributes, and a limited model base. A basic design question for SDSS designers is how to integrate GIS components into SDSSs. Should the user-interface, data-base and model-base functions inherent in the GIS be isolated and added to the toolbox of each component or should the GIS functions be kept together? The philosophy of DSS suggests that the functions should be separated and added to the SDSS toolbox.

A significant capability of the SDSS is the ability to use spatial analysis and display tools with the full suite of water resource models and methods that would form the model base of water resources SDSSs. This spatial management capability would require some redesigning of the current crop of models. Likewise, SDSSs would offer more complex, compound modelling capability to be used to manipulate objects and attributes.

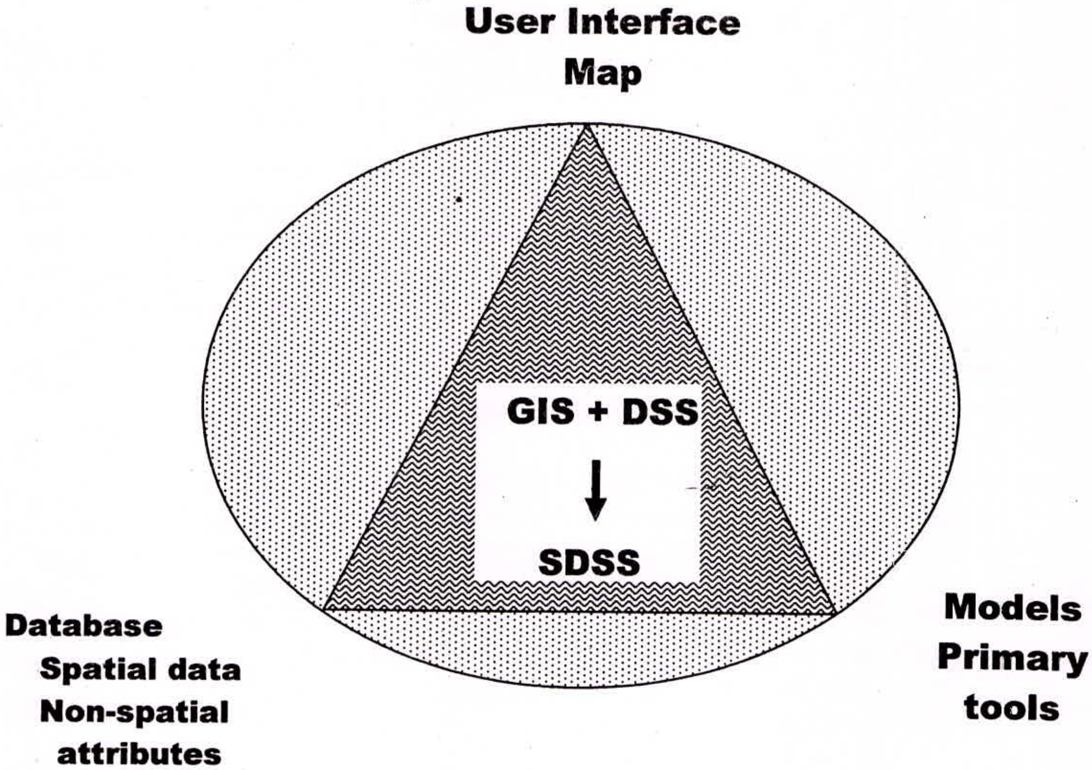

Fig. 1: SDSS as a combination of GIS and DSS

The modelling capability allows the user of the SDSS to simulate changes in objects and attributes. The data-base component of the SDSS can supply input data for the models. After the models are run, the resulting output can be written to the database for later display via the user interface, in tabular or map form. For planning purposes, this ability to dynamically change information, forecast, and perform sensitivity analyses is essential.

The most exciting applications of SDSSs involve an extension of the traditional approach of using a GIS. The manual methods of map analysis involved developing a grid over a map and subsequently examining the suitability of a site for development or other purpose by overlaying transparencies of different maps showing the value of one or more attributes. For example, one could find the best route for a highway by finding and blocking out unsuitable areas, such as parks or lands with poor structural soils, on transparent maps. The best sites are the areas still visible after all the transparencies showing the unsuitable areas were placed on the map. Much current work is a computerisation of this technique.

The SDSS concept is a way to improve on this traditional analysis. The models would depend on the traditional GIS for input data. The models would depend on the SDSS data-base component to provide data. The model base would take the needed data from the data base, perform some analysis or simulation, and write back the output from the modelling exercise to the data base. The results of the model would also be displayed by the map generation portion of SDSS.

Traditional water resources models can and should be a part of SDSSs. There are many models for water resource analysis that can be adapted to SDSSs. Any model that addresses problems with a spatial dimension is potential candidate for SDSSs. These models include many hydrologic models that deal with the spatial extent and variability of water over and beneath land surfaces. Another set of useful models might be economic and environmental models. Economic models, such as resource demand forecasting and input-output models, would be enhanced if the output of the models could be displayed visually via a map. Environmental models, such as those predicting the transport and fate of pollutants in a body of water, would also benefit from spatial analysis and display capability.

New approaches for model design and implementation will be needed. Most water resource models were designed before the availability of new spatial analysis and display capability. Traditional water resource models are often lumped-parameter models that do not take advantage of the ability to display the distributed aspects of spatial data. Models must be developed with the capabilities of the SDSS in mind during development. Data requirements will increase.

Object-oriented approaches provide a new way to encompass the functions of the user interface, data base, and model base of the SDSS. For example, suppose a control gate is depicted on a map of a river system. If the control gate were a true object, then it would know how to react to increasing water levels in the river, eventually opening at a flood level. Object-oriented approaches offer a new approach to representing features and attributes in a visual way. These new techniques offer many fascinating opportunities for increasing the usefulness of the SDSS.

To illustrate how an SDSS might work, consider that a decision maker has to decide whether to grant a permit for a proposed activity in a coastal wetland. The description of the wetland requires information about the land/water classification, vegetation, the value of different sections of the area, and types of structures. In a conventional GIS, the foregoing categories would correspond to separate layers of attribute information. For example, the land/water layer would contain attribute data to describe the characteristics of upland, wetland, and open water. An object-oriented approach might define an upland area object with appropriate attributes to describe it, and methods to determine how the upland area object would respond to events.

All the features of the wetland must be located spatially. Like a conventional GIS, the SDSS must be able to capture and manage the spatial and attribute data associated with a real-world situation. However the SDSS can offer improved modelling capability and integration of all components for better decision making.

Once the spatial and attribute data are stored in the SDSS, the user can make a query for example, the best location of a proposed canal. After gathering the relevant data, the query can then be passed on to an expert system in the model base that contains knowledge about regulations pertinent to wetlands. The expert system would examine its knowledge about regulations for canals to see what constraints exist about changes in the wetlands. The expert system would need information about the absolute location of the proposed projects and the relative location of other features in the wetland area. The relative location of the other features will impact the feasibility of adding the new projects. This information could be provided by the spatial analysis tools that are part of the SDSS. Additional analysis might be required by water quality or other models to examine the impact of the proposed developments.

After the analyses, the SDSS would display the results via the map representation of the physical wetland area and with other text or model result information. The user could initiate additional queries in an interactive dialogue with the SDSS until the impacts of the proposed additions have been examined in detail. This integration of spatial analysis and modelling via the SDSS is invaluable in the decision making process.

2. Evolution of Spatial DSS

Although GIS have been in existence for the past three decades, only recently GIS technologies are being incorporated into mainstream IT decision support solutions. While GIS has traditionally been used in areas such as utilities, environmental and urban planning, real estate, government, and natural resources management, there is a growing interest in the use of GIS technology for decision support within the business community because of analytical and visualization capabilities. Increasingly, organizations are adopting GIS-based solutions in a number of domains including customer relationship management, vehicle routing, and healthcare management. Spatial information supports specific business processes implemented in larger environments. This improves productivity and helps gain competitive advantage. For example, a company using geo-coded customer addresses can do some impressive direct marketing and potentially increase market share.

Research on SDSS originated from two different sources – decision support system and geographic information system. DSS has been an active area of research in Information Systems for many years. However, one of its major limitations is its inability to support spatial data. On the other hand, GIS is efficient in storing and managing spatial data, but has lagged behind in providing adequate tools to facilitate managerial decision making and cooperative problem solving. The integration of these two technologies has resulted in SDSS, which harnesses the decision analytic power of traditional DSS and the spatial capabilities of GIS. Thus, the two streams of research that lead to the development of spatial decision support systems can be characterized as geographical information based systems and decision support based systems. A schematic representation of the progression in SDSS development is shown in Figure 2.

The evolutionary path of the decision support technology from the information systems community contains four distinct stages (lower half of Figure 2): a) Traditional Model based DSS, b) Expert/Knowledge-based DSS, c) Web-based DSS, and d) Service based DSS.

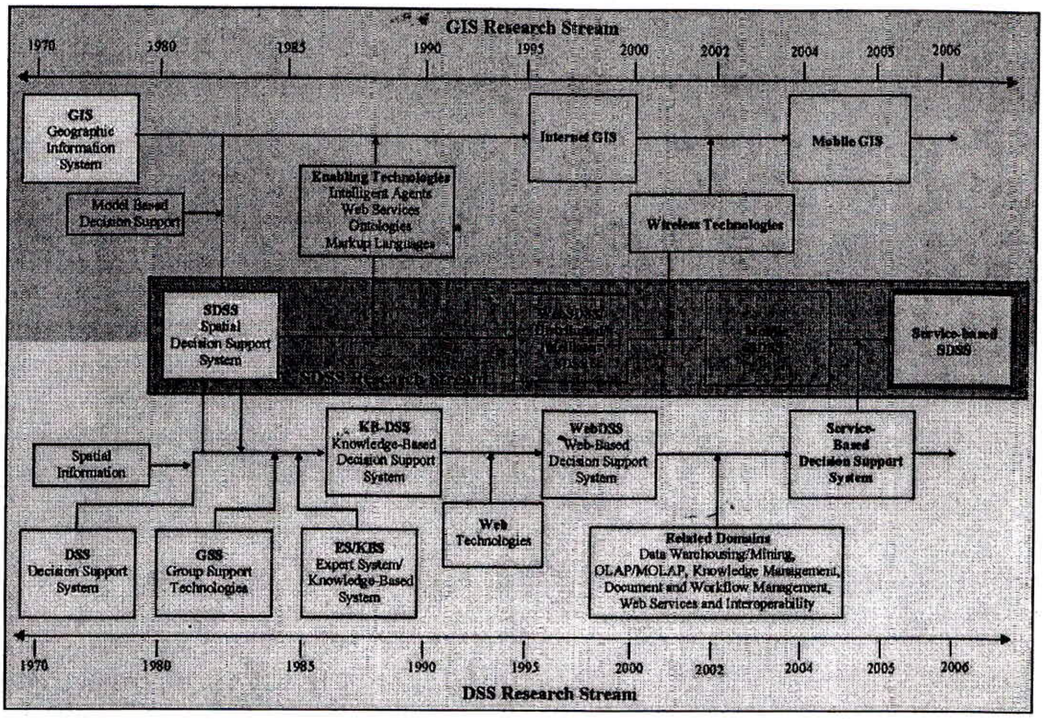

Figure 2: Progression of Spatial Decision Support Systems Development

Similarly, the GIS-driven evolutionary path of decision support systems from the earthsciences community contains (top half of Figure 2): a) Traditional GIS, b) Spatial Decision Support System, c) WebSDSS/Distributed SDSS, d) Mobile SDSS, and e) Service-based SDSS. The GIS-based development path is briefly described below.

2.1 GIS-based Development

Early GIS primarily focused on assembling, storing, manipulating, and displaying geographically referenced information. Geographical information consists of both textual data ("attribute" or "aspatial" data) as well as spatial data (data which includes cartographic coordinates). While the first generation of GIS provided some modeling capability, they were inadequate for supporting any type of business decision making. During this time, considerable strides were made in designing and developing DSS by the information systems community and the model-based and knowledge-based approaches for building decision support systems were adopted by the GIS community. This marked the next phase in GIS-driven evolution path and spatial decision support systems were created.

SDSS development entailed integrating analytical/decision models with GIS to produce systems capable of solving spatial problems. These systems assist users in the exploring, structuring, and generating solutions for complex spatial problems such as site selection, evacuation, routing, etc. They support problem solving and decision making activities by employing quantitative approaches with the use of geographic information that is stored in the GIS. This provides the capability to display the results of the analysis (including non-spatial aspects) on maps or satellite images or digital terrains. Such GIS applications for decision support have been used in a number of domains such as water resources, strategic planning, healthcare, etc.

Several researchers have demonstrated the use of Internet and GIS for application development to improve decision-making and environmental modeling. Although there has been some progress in the use of the Web as a medium for environmental data sharing and data visualization, not many studies focused on developing a Web-based planning tool using SDSS. There is now increased interest in pursuing the development of SDSS on the Web to support better decision-making and policy formulation.

The client-server model used in designing "Internet-based GIS" applications enables users to gain access to GIS databases through remote procedure calls and open database connectivity. However, the client can access only one source at a time with pre-specified connection frameworks. Some experts argue that this is very limiting and that the client should be able to access various sources dynamically and also have the capability to act as a server by itself. Since network computing is gaining momentum and the Web provides the infrastructure needed to materialize "peer-to-peer" computing, the next phase in the GIS-Driven development progression is the Mobile GIS environment. This architecture will permit many-to-many communications and facilitate distributed spatial problem solving.

SDSS functionalities can be modularized and implemented as components or services that one could subscribe to or embed them in other applications. These services can be executed at the provider's site to alleviate incompatibility problems. Thus, a Service-Based SDSS provides ubiquitous access to "spatial computational services" from anywhere any time using any device. Taking it one step further, these components can actually act as "Spatial Web Services" and users can compose a set of these services to achieve a particular functionality. Service-based SDSS can be effective in minimizing cognitive load on end users because of its ability to deal with heterogeneity in hardware as well as software components that may be written using different languages. It provides interoperability by seamlessly taking care of the translations that need to be performed for different components or services to work together.

GISs fall short of the goals of SDSS for a number of reasons:

- Analytical modeling capabilities often are not part of a GIS
- Many GIS databases have been designed solely for cartographic display of results - SDSS goals require flexibility in the way information is communicated to the user
- The set of variables or layers in the database may be insufficient for complex modeling
- Data may be at insufficient scale or resolution
- GIS designs are not flexible enough to accommodate variations in either the context or the process of spatial decision-making

SDSS provide a framework for integrating: 1. analytical modeling capabilities, 2. database management systems, 3. graphical display capabilities, 4. tabular reporting capabilities, and 5. decision-maker's expert knowledge. GISs normally provide capabilities numbers 2, 3 and 4. If 1 and 5 are added to it, a SDSS is created.

3. SDSS Architecture and Applications

Similar to DSS, a generic SDSS consists of the following components: a) spatial and non-spatial data management, b) model management (spatial and non-spatial), c) knowledge management, and d) dialog management including display and report generators. Typically, SDSS are flexibly integrated systems built on a GIS platform to deal with spatial data and manipulations, along with an analysis module, which could switch from exploration to explanation in an interactive, iterative and participatory way. Just like a DSS, SDSS support "what-if" analysis and also provide a range of tools to help the user in understanding the results. Much of the early work on SDSS development focused on developing stand-alone applications that incorporated sophisticated models for analyzing spatial data in various application domains. Some of the popular decision analytic models that are supported by SDSS are: multi-criteria evaluation models, network optimization models, ordered weighted averaging, artificial neural networks, spatial regression, and spatial clustering.

3.1 SDSS Applications

For the past two decades, there has been a tremendous growth in the development of PC based or stand-alone SDSS for planning and management of natural resources, environmental and business related applications. Recent developments and availability of powerful GIS and visualization tools in conjunction with the rapid growth of Internet technologies have played an important role in the emergence of Web-based decision-making and policy formulation.

There is increased interest in pursuing the development of SDSS on the Web to support better decision-making and policy formulation. Examples include: HYDRA – an SDSS for water quality management in urban rivers (Taylor, 2002), fish and wildlife assessment, agricultural farm analysis, environmental decision making, and urban prediction modeling and visualization.

3.2 Example: Site Selection for a Reservoir

Consider that the site for a reservoir is to be found such that the benefits are maximized. The feasibility of the project and the benefits are affected by:

- Suitability of the site and cost of construction,
- Geological conditions at the site, availability of construction material,
- Accessibility and connectivity of the site,
- Submergence of forests, villages, places of archeological importance,

Some of these factors are difficult to evaluate and the relative impacts of each of these factors on the benefits may be unknown (except the first – cost of construction). It is very difficult to structure the problem completely, i.e. define and precisely measure the objective for every possible solution. A decision system to support reservoir site selection must be flexible – it should allow new factors to be introduced, allow the relative importance of factors to be changed to evaluate sensitivity or to reflect differences of opinion and display results of analysis in a clear and simple way.

Problems of this type are best solved by generating a set of alternatives and selecting those that are feasible. Hence, the decision-making process is iterative, integrative and participative:

- It is iterative because a set of alternative solutions is generated which the decision-maker evaluates. The insights gained in this process are input to and used to determine what further iterations and analyses are needed.
- Participative because the decision-maker plays an active role in defining the problem, carrying out analyses and evaluating the outcomes and he works with the team.
- Integrative because value judgements that materially affect the final outcome are made by decision-makers who have expert knowledge that must be integrated with the quantitative data in the models.

4. SDSS CHALLENGES

There are major challenges confronting GIS developers, water resource modellers, DSS designers, and decision makers in developing SDSSs. These are enumerated next.

4.1 Interdisciplinary Collaboration

The first and foremost challenge is that SDSS will require a cross-discipline collaboration to solve the complexities of integrating these separate technologies. Decision support system designers can offer much toward the development of SDSSs. DSS designers are concerned with requirements analysis, proper design, and user needs as well as good software engineering practices. Finally, the water resource decision makers must be involved from the initial inception throughout the development process of the SDSS. Without this early and constant feedback from the ultimate user of the system there is little chance of success. SDSSs must have the benefit of input from all developers and users.

4.2 User Interface

The addition of GIS capability to the SDSS complicates the user interface. Visual displays of spatial data, such as maps, must be integrated with other visual graphics and tabular forms and reports. GUIs are often used in DSSs. Research is needed to find the best means to integrate GUI and spatial displays with other text-based displays of information. There is a wealth of information from the cognitive sciences about human-computer interaction which will be helpful to help design effective SDSS.

4.3 Model Base

The major change to the suite of models that make up the model base of the SDSS will be the structural changes to models that must be made to make the models spatially aware. Many models that have a spatial dimension do not reflect that spatial dimension very well in input, processing, or output from the models. The models will have to be redesigned to makes full and the best use of spatial data.

Another challenge to SDSS developers will be to broaden the suite of models to include artificial intelligence tools, such as expert systems, ANN, Fuzzy techniques, etc. The concept of the SDSS as presented in the wetland example offers many possible advantages. Other new techniques, such as neural networks and fuzzy-set modelling, may offer potential for water resource SDSSs. The SDSS framework allows the integration of these new techniques into the model base and access to the spatial analysis and display capabilities derived from the GIS.

4.4 Data Base

The research challenges involving the data-base component relate to the difficulty of representing spatial data using the relational data model and the potential for using object-oriented techniques. New mechanisms for handling features data must be developed. Object- oriented approaches may hold an answer for this problem.

4.5 Prototype Development

One way to refine and test the SDSS concept is to develop prototypes that encompass the capabilities of the GIS and water resource models and follow the principles of decision support system design. Of course, the SDSS concept will require some modification of concepts, design, and development principles borrowed from GIS, modellers and DSS, but the prototype approach is useful for finding what we know and what we don't know about SDSSs.

5. Future Applications and Architectures

There is consensus that using the SDSS concept has the potential to greatly aid decision making in water sector. Hence, DSS and SDSS will continue to be a major focal point for future development. Advances in computing, communication, and networking technologies will facilitate the development and deployment of SDSS.

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