

Web-based Spatial Decision Support Systems (WebSDSS): Evolution, Architecture, and Challenges

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Abstract

A new category of Decision Support System called Spatial Decision Support System (SDSS) has emerged which uses a spatial representation for displaying spatial data and supporting spatial modeling. SDSS originated from two distinct sources, namely, the GIS and the DSS research communities. The synergy between these two research groups has led to the adoption of state of the art technical solutions and the development of sophisticated SDSS that satisfy the needs of geographers and top-level decision makers. Recently, the Web has added a new dimension to SDSS and Web-based SDSS (WebSDSS) are being developed in a number of application domains. This paper provides an overview of the emergence of SDSS, its architecture and applications, and discusses some of the enabling technologies and research challenges for future SDSS development and deployment.

Keywords: Spatial Decision Support System (SDSS), Web-based SDSS, Geographic Information Systems (GIS), Internet GIS, Spatial Information Management, GIS Web Services.

1. Introduction

Decision Support Systems (DSS) have been an important area of Information Systems research. 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 business 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 managerial decision making (Sikder & Gangopadhyay, 2002).

Spatial Decision Support Systems are designed to help decision makers solve complex problems such as site selection, urban planning, and routing, 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 (Goodchild, 2000). Thus, SDSS provide 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 (cf., Armstrong and Densham, 1990).

Traditional GIS based SDSS are complex systems that require sophisticated hardware and infrastructure. They are capital intensive and most organizations cannot afford the resources needed to institutionalize such systems. Moreover, these systems are highly centralized and do not easily support group problem solving activities. Even in a client-server configuration, SDSS tends to use a thick client that requires high-end workstations and an intricate user-interface. These limitations of traditional GIS greatly hindered the wide spread adoption of SDSS technologies (Manson, 2000). However, WebSDSS are being developed to provide geographic information centered decision support facilities to a larger audience through the Web.

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. To minimize this cognitive burden new capabilities are being developed like intelligent agents that help the user in problem formulation and execution (Sugumaran and Sugumaran, 2003).

The objectives of this paper are to: a) review the evolution of spatial DSS, b) explore the architecture and enabling technologies for SDSS design, and c) identify challenges and future research directions. The contribution of this paper is to provide a broad review of the spatial decision support technology and its application in various domains.

2. Evolution of Spatial DSS

Although Geographic Information Systems (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, DSS researchers have always acknowledged one of its major limitations - 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 1.

The evolutionary path of the decision support technology from the information systems community contains four distinct stages (lower half of Figure 1): a) Traditional Model based DSS, b) Expert/Knowledge-based DSS, c) Web-based DSS, and d) Service based DSS.

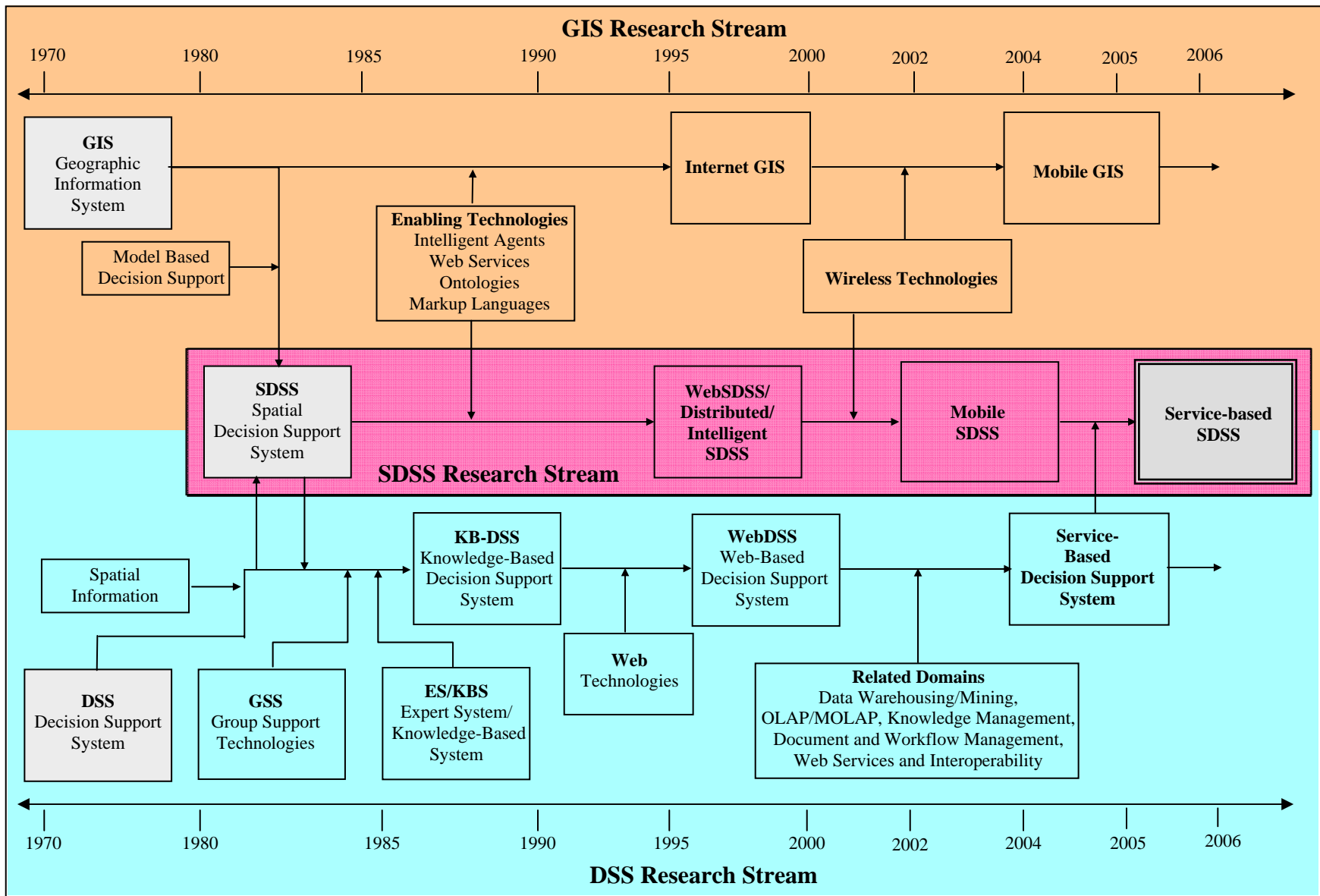


Figure 1. Progression of Spatial Decision Support Systems Development

Similarly, the GIS-driven evolutionary path of decision support systems from the geosciences community contains (top half of Figure 1): a) Traditional GIS, b) Spatial Decision Support System, c) WebSDSS/Distributed SDSS, d) Mobile SDSS, and e) Service-based SDSS. These two parallel development paths and the major categories of systems within each path are briefly described below.

2.1 DSS-based Development

Traditional decision support systems primarily consist of three major components: a) data management, b) model management, and c) dialog/interface management. As group support software matured, the traditional DSS was augmented with communication capabilities to create group decision support systems, which enabled geographically dispersed group members to work on complex unstructured problems and evaluate different scenarios. These systems also facilitated brainstorming, idea evaluation and team problem solving activities. The next phase in this progression of DSS development was influenced by advancements in artificial intelligence. Specifically, expert systems and knowledge-based systems added a new dimension to decision support systems. They enhanced DSS development and usage by incorporating knowledge components specific to an application domain or the organization. These knowledge-based DSS enable users to analyze relatively complex problems and perform what-if analysis with the aid of organizational and domain knowledge.

The Web has revolutionized application development. The ubiquitous nature of the Web and its simplistic user interface has facilitated the deployment of complex applications such as SDSS over the Web. The next stage in the DSS progression is the web-based DSS, which is a computerized system that delivers appropriate data and models to a manager or a decision maker using a thin-client web browser. Using Web-based DSS, organizations can provide DSS

capability to managers over a proprietary intranet, to customers and suppliers over an extranet, or to any stakeholder over the Internet. Bhargava and Power (2001) provide a status report on how web technologies are being used to provide decision support services over the Internet. Power (2002) provides examples of web-based DSS development software and includes a long list of vendors that market web-enabled decision support products.

Recently, several researchers (Power, 2003; Carlsson and Turban, 2002) have suggested that the domain of discourse of DSS has proliferated to such an extent that the traditional boundary of DSS has become quite fuzzy and is blending with related technologies such as business intelligence, OLAP, data warehousing, knowledge management, and Web Services. In fact, Power (2003) argues that there is a great need for re-classifying DSS because they have evolved to become more specialized and generic at the same time. The next generation of decision support systems are primarily service based and are classified based on the type of the core technology that drives them.

2.2 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 marketing, legal and government agencies, strategic planning, healthcare, etc. (Murphy, 1995; Jarupathirun and Zahedi, 2005; Heurta et al., 2005). In fact, Jarupathirun and Zahedi (2005) provide an excellent summary of the application of GIS based decision support systems in different areas. Similarly, Huerta et al. (2005) provide a review of the use of GIS for decision making within the business domain. The next phase in the GIS-Driven development has been shaped by the tremendous growth of the Web. Internet-based technologies have been assimilated into GIS leading to a variety of Web-enabled GIS applications.

Several researchers have demonstrated the use of Internet and GIS for application development to improve decision-making (Dragicevic et al., 2000; Rinner and Jankowski, 2002; Sugumaran et al. 2003) and environmental modeling (Zhang and Wang, 2001; Sugumaran et al., 2004; Compas and Sugumaran, 2004; Dung and Sugumaran, 2005; Shriram et al., 2006). Although there has been some progress in the use of the Web as a medium for environmental data sharing and data visualization (Dragicevic et al., 2000; Houle et al., 2000; Sugumaran et al., 2003), 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 researchers (Tsou and Buttenfield, 2002) 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. Mobile GIS integrates several technologies such as mobile devices, Global Positioning Systems (GPS), and Wireless communications for Internet GIS access. Mobile GIS are constructed by partitioning client and server sides of an application into self-contained units that can interoperate across networks, integrating languages, applications, tools, and operating systems (Tsou and Buttenfield, 2002). The distributed GIS components can be implemented using CORBA and DCOM and EJBs. Advances in wireless technology have given rise to the development of Mobile SDSS, which provide access to spatial data as well as decision support applications using hand held devices from remote locations. One such example is the development of integrated mobile geo-spatial information services to support and help optimize field-based management tasks for border security agents (NASA, 2005).

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. Web services technology is supported by several key protocols and standards such as XML, WSDL, SOAP and UDDI. 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.

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 (Murphy, 1995). 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 (Goodchild, 2000). 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 (Jarupathirun and Zahedi, 2005; Heurta et al., 2005). 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 WebSDSS Architecture

WebSDSS includes a web-based geographic information system as a problem solver and facilitates geographic data retrieval, display and analysis. It combines several different components including HTML user interfaces, Internet interface programs, computational models and geographic databases. There are two ways to set up a WebSDSS: a) server-side processing and b) client-side processing. The server-side approach uses a thin client and most of the processing, including spatial data access and manipulation is performed on the server side. The resulting information and image objects are then sent to the client to be rendered. The client-side processing approach uses a thick client in which GIS functionality is preloaded on the client machine and only the geographic data is accessed from one or more servers. The server-side WebSDSS requires only a browser installed on the client machine to carryout SDSS tasks. However, every user action requires communication between the client and the server. The typical components of a server-side WebSDSS are shown in Figure 2.

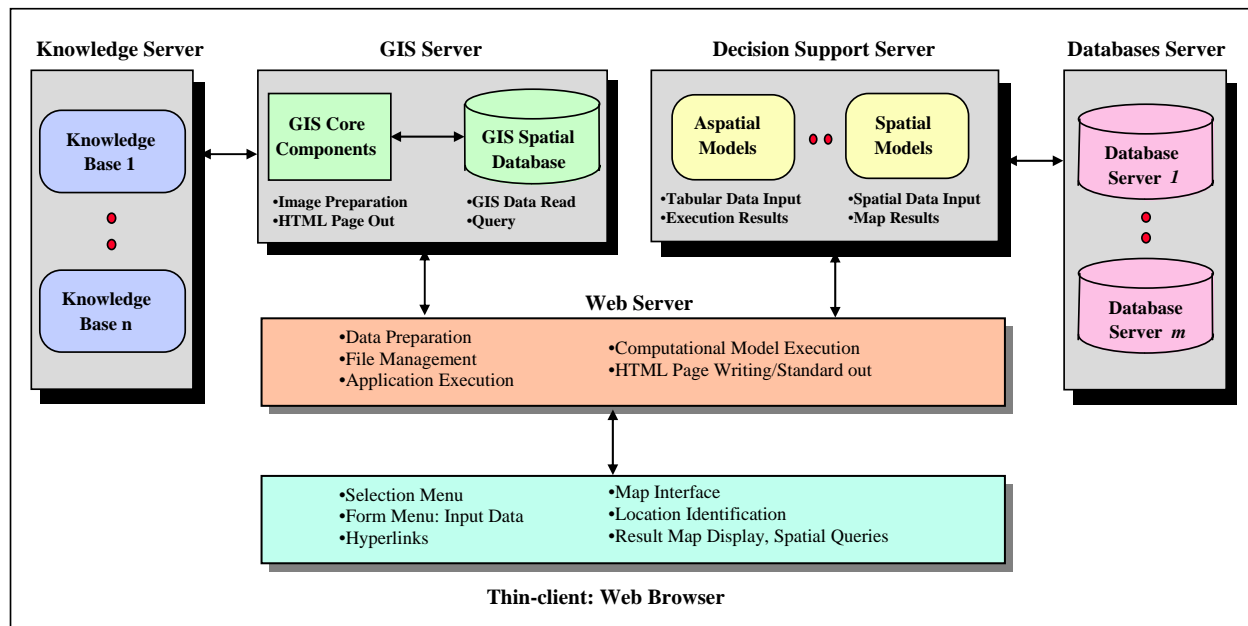


Figure 2. Schematic Representation of WebSDSS Components

The knowledge server shown in Figure 2 may contain rules that enable the user to select the appropriate type of model to use for a particular task and perform sensitivity analysis. It may also contain organizational policies, procedures, business rules and constraints that may be relevant for the problem at hand. The WebSDSS user interface includes menus, graphical maps, control buttons, and form input. These interface utilities execute selections, input data and map displays and queries, usually using HTML tags, Java Applet, Javascript and other Internet protocols. User inputs are submitted to the web server through the HTTP protocol, and jobs requested by the client are implemented through CGI or other Internet Interface applications.

3.2 Example 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 (CARES, 2003; Makropoulos et al., 2003; Shim et al., 2002; Sugumaran, 2002). 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 (Rinner and Jankowski, 2002; Sugumaran et al., 2003).

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 in the Columbia river (Parsley et al., 2000), business applications (Sikder and Gangopadhyay, 2002), agricultural farm analysis (Vernon 1999; Dung and Sugumaran, 2005;), emergency planning (Carver et al., 2001), environmental decision making (Kingston et al., 2000; Sugumaran et al., 2004), and urban prediction modeling and visualization (Compas and Sugumaran, 2004).

Although several authors (Casey and Austin, 2002; Sengupta and Bennett, 2003; Tsou and Battenfiled, 2002) have developed stand alone Knowledge-based SDSS, only few researchers have developed intelligent web-based SDSS (Shriram et al., 2006). Andrienko and Andrienko, (2001) developed a knowledge-based WebSDSS, which utilizes an intelligent user guidance in the analysis of geographical information. Recently, Sugumaran and Sugumaran (2003) have proposed an architecture for an agent based SDSS environment on the Web, which incorporates web services and a variety of intelligent agents.

4. Building Blocks for SDSS

4.1 Server-side Technologies

The server side environment typically includes a web server (Apache, IIS etc.) and a map server (ArcIMS ArcMap Server) that provides GIS services. The map server software establishes a common platform for the exchange of web-enabled GIS data and services. The web server transfers spatial and non-spatial data between the client side (Web browser) and the map server through sockets (Figure 3). The client side user interface is developed using JavaScript, HTML, and Applets. JavaScript is used to format URLs for communicating with map server (Figure 3) and allows users to directly interact with the spatial applications. Custom map display and report generator can be developed using java applets.

4.2 Intelligent Agents

Several research efforts have been reported that use agent technology in addressing spatial decision making problems (Manson, 2000; Sugumaran and Sugumaran 2003). Sengupta and Bennett (2003) provide an agent-oriented modeling framework to overcome some of the limitations of traditional SDSS. Their agent-based SDSS (DIGME) evaluates the ecological and economic impacts of agricultural policies. Rodrigues et al. (1997) describe a multi-agent system

for modeling geographic elements for environmental analysis in land use management. Ferrand (1996) reports on a system used to solve complex spatial optimization problems encountered in the search for the least environmental impact area.

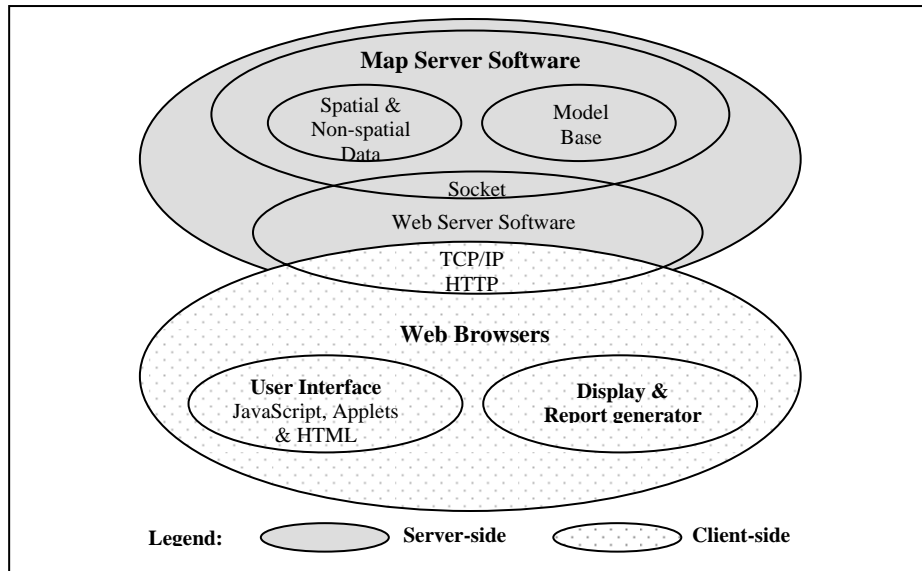


Figure 3. Client-server Technologies for WebSDSS Development

As demonstrated by these projects, there is great interest in applying agent technology to GIS environment. We are seeing only the beginning of this cross fertilization between Intelligent Agent technology and GIS technology, and lot more research is yet to be conducted. The agent technology seems to be a natural fit for making GIS user friendly and applicable in a variety of problem solving/decision making scenarios.

4.3 GIS Web Services

GIS Web Services provide commercially hosted spatial data and GIS functionality via the Internet to Web applications and users. In a nutshell, GIS Web Services provide GIS content and functionalities to applications without having to invest in costly GIS software and platforms. The clients don't have to host the GIS data or develop sophisticated tools to incorporate GIS capabilities within their applications. This facilitates even smaller organizations with limited resources to take advantage of GIS capabilities without having to incur development cost and

time. GIS Web Services will revolutionize how companies use and interact with geo-spatial information (Gonzales, 2003). Companies no longer have to address the technical side of GIS to exploit its value. User communities can gain extensive spatial analytic value from GIS Web Services without the problems of physically storing and maintaining spatial databases.

4.4 Ontologies and Semantic Web

Ontologies can play a major role in the design and development of GIS-based systems because it allows the establishment of correspondences and interrelations among different spatial entities. The use of ontologies also contribute to better GIS-based systems by avoiding inconsistencies between ontologies built in GIS and the user expectations of GIS application. Ontologies also help GIS move beyond the map metaphor and facilitate the development of a variety of spatial models including spatial uncertainty. Geo and eco-ontologies are being created by several researchers (Smith et al., 2001; Frank, 2001; Fonseca et al., 2002) to deal with the semantic heterogeneity, and enable different communities to exchange geographic information.

Semantic Web methodologies can enable SDSS to access and interpret spatial data and services using agent technology and extend their capabilities for the Internet age. For example, a semantic web-enabled navigational SDSS can use ontological references in providing specific directions to a user for navigating from one destination to another based on the constraints specified by the user and the physical and semantic constraints that have to be incorporated for reasoning and computational effectiveness.

5. Discussion

5.1 Future Applications and Architectures

There is consensus that using the Web has the potential to deliver GIS and decision support technologies to the masses. Hence, web-based DSS and SDSS will continue to be a

major focal point. Similarly, Web Services and Semantic Web are also showing signs of great potential and researchers are moving towards developing distributed applications using web services. We postulate that GIS Web Services will pave the way for developing heterogeneous distributed GIS applications that span organizational boundaries. Advances in communication and networking technologies (Internet, Intranet, Wireless, and Cellular) will facilitate the development and deployment of Inter Organizational SDSS that support spatial work-flows.

Advances in intelligent agent technology, ontology based information systems, knowledge-based systems, GIS web services, data warehousing and analytical processing, spatial and non-spatial modeling, and Web technologies will have a profound impact on the next generation of SDSS. We envision a distributed WebSDSS environment that integrates current and future enabling technologies to provide sophisticated spatial modeling and analysis capabilities needed to efficiently solve unstructured problems with spatial characteristics and provide seamless linkages to a variety of spatial and non-spatial resources. A schematic representation of such an SDSS is shown in Figure 4.

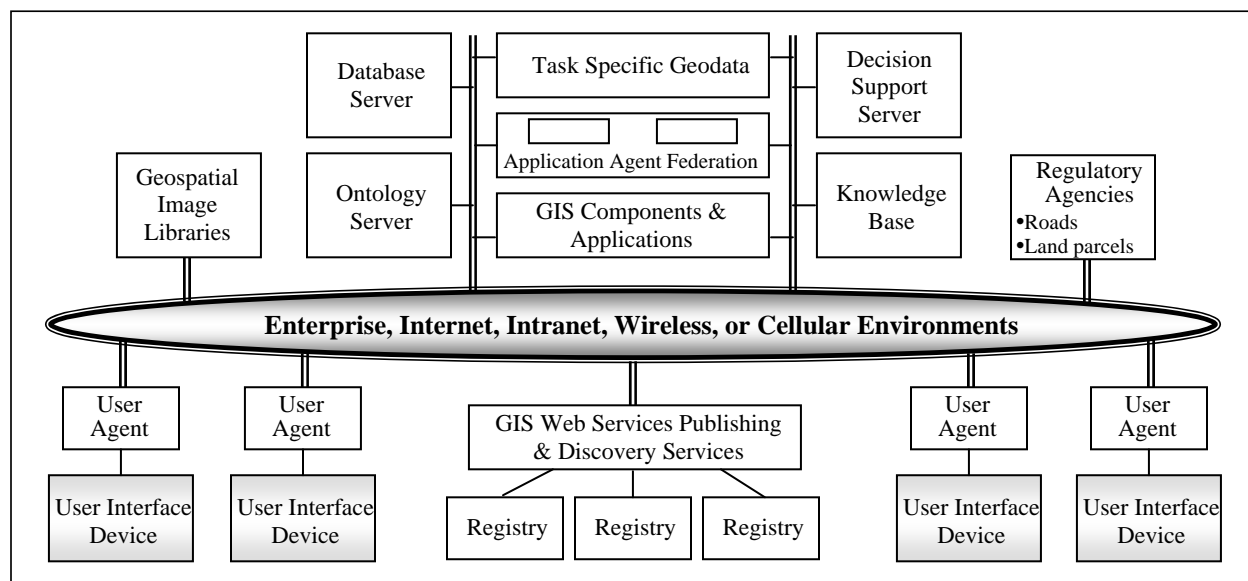


Figure 4. Distributed Web-based Spatial Decision Support System Architecture

5.2 Challenges in SDSS Development

Designing and implementing SDSS over the Web presents several issues and constraints. These include performance, technology integration, security, interoperability, etc. Even though some of these issues are quite common to all IT applications, the following section provides some specific examples related to WebSDSS.

5.2.1 Technical Challenges

Performance: Performance is one of the most important limitations in the development of WebSDSS. It is mainly because most spatial data including raster and vector data are large in volume (Peng and Tsou, 2003), and also involve moving large spatial objects over the network between server and client. Further, most of the SDSS models are complex and take substantial amount of time to run on the server. It is unreasonable to expect users to initiate the execution of a model and wait for hours or even days for the model results; Internet users expect results in a matter of seconds. Hence, it is crucial that users are informed of the incremental progress in model execution, which adds to the complexity of WebSDSS design. Besides the spatial data, SDSS models may use large non-spatial datasets (attribute data) that also have to be transported over the Web. Thus, the overall performance of a WebSDSS is impacted by the aforementioned issues in addition to the available bandwidth of the client and server as well as the number of simultaneous clients. If band-width problems are overcome in the near future, it is likely that mobile tools, mobile e-services, and wireless Internet protocols will mark the next major set of developments in WebSDSS.

Technology Integration: It is essential that SDSS are implemented using open architectures so that new components can be easily added resulting in “plug and play” geo-processing environments. In addition, these systems must be robust with efficient

communication mechanisms via the Internet/Intranet. Another challenge is integrating the distributed SDSS with legacy systems that may still have valuable GIS datasets and programs.

Interoperability: One of the main limitations of the present WebSDSS is the interoperability and non-compliance with widely accepted Web mapping standards. Creating interoperable commercial geo-processing software will still be a formidable challenge due to vendor and technology differences. Full integration of geospatial data and resources requires developing a common set of syntactic and semantic interoperability standards. GIS web services will need to tolerate heterogeneous frameworks because no distributed component technology will be optimal for all kinds of tasks. Most of the existing WebSDSS are not based on OpenGIS® Consortium (OGC) standards and do not easily interface with other products.

Security and Privacy: Security and privacy will remain a major consideration in implementing WebSDSS because many geospatial data sets and services are proprietary and private. A WebSDSS application will face additional security problems because of the sharing of spatial objects over the Internet, and is prone to viruses, hackers, and network jams. Moreover, the introduction of mobile spatial technologies into WebSDSS will add an additional layer of security concerns due to the inherent risks associated with wireless technology.

Quality of Service: In a distributed SDSS environment with commercial services, the level of service provided by the individual nodes may vary because of node failures, unreliable communication or disconnected network links. Hence, the architecture must include technical solutions to combat such disruptive events.

5.2.2 Managerial Challenges

Task-System Fit: While several WebSDSS have been implemented and used in various domains, there are no clear guidelines as to which types of WebSDSS are suitable for what types

of decision making tasks. Hence, it is critical that organizations systematically evaluate the task-WebSDSS fit and its effectiveness in decision making before investing in a particular WebSDSS. In order to promote widespread use of WebSDSS within an organization, clear evidence has to be presented to demonstrate their appropriateness as well as usefulness for the task at hand.

Policy Issues: Clear policies need to be developed for service level agreements, and how to handle sudden or gradual fluctuations in the quality of service. Similarly, organizations have to develop concise policies to ensure security and privacy of sensitive spatial and non-spatial data. Contingency plans for disaster recovery and security breaches must also be developed.

Organizational Commitment: A strong resource commitment from upper management is needed to promote the widespread use of WebSDSS throughout the organization. Use of WebSDSS may also require redesigning of some of the business processes. Hence, adequate training is needed.

6. Conclusion and Future Directions

GIS and SDSS have traditionally been difficult to use because of the complex nature of spatial data representation, presentation, and computation. However, with the advances in Web technologies, intelligent agents, ontologies and Web Services, complex SDSS systems can be made user friendly by providing intelligent interfaces. This paper has discussed the progression of SDSS development originating from both the GIS and DSS communities and presented an architecture for a generic WebSDSS environment. While some of the current WebSDSS have used some enabling technologies, we predict that future WebSDSS will incorporate web services and a variety of intelligent agents and ontologies to guide the user in executing core business processes. We have presented a framework for distributed WebSDSS and discussed some of the challenges.

Further research is needed to address the challenges highlighted in the previous section. In particular, future inquiries should concentrate on: a) novel ways of using intelligent agents and other knowledge-based techniques to minimize cognitive burden on the user in spatial modeling and analysis, b) GIS Web Services and distributed component technologies for designing distributed WebSDSS, c) wireless technologies, devices and communication protocols to facilitate true distributed WebSDSS environments, d) open architectures and GIS interoperability standards, and e) developing effective Inter/Intra Organizational WebSDSS.

Keen (1987) had proposed a DSS research agenda for the nineties and recently, Shim et al. (2002) have updated Keen's agenda and articulated a new DSS research agenda for the next decade. This new DSS research agenda is also pertinent to WebSDSS research and can be adapted to guide future developments in WebSDSS. Along similar lines, we propose the following tenets to shape future research in web-based spatial decision support technologies: 1) identifying potential uses for WebSDSS in solving business problems with spatial aspects as well as incomplete and uncertain data, b) building intelligent WebSDSS using enabling technologies, c) providing a distributed WebSDSS environment for cooperative spatial problem solving and linking GIS services, d) facilitating interoperability of spatial data and systems, and e) demonstrating and improving the effectiveness of WebSDSS in decision making through training and knowledge transfer. Considerable strides have been made in the development of Web-based SDSS and we envision future WebSDSS playing a major role in analyzing and solving complex business problems and strategic decision making.

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