SPATIAL DECISION SUPPORT SYSTEMS

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Decision makers increasingly are turning to geographical information systems to assist them with solving complex spatial problems. These systems do not adequately support decision making, however, because they are lacking in analytical modelling capabilities and do not easily accommodate variations in either the context or the process of spatial decision making. One response to these shortcomings is the development of spatial decision support systems which are explicitly designed to address complex spatial problems. The design of such systems, the types of problem to which they can be applied, the decision-making processes they support, and a framework for their implementation and subsequent evolution are examined.

INTRODUCTION

Decision makers faced with a complex spatial problem often have multiple, conflicting objectives for its solution. To be acceptable, a solution must reconcile these conflicting goals. A variety of analytical techniques have been developed to help decision makers solve problems with multiple criteria (for examples in location selection see Starr and Zeleny 1977; Cohon 1978; Nijkamp 1979). Consequently, decision makers have turned to analysts and analytical modelling techniques to enhance their decision making capabilities.

To be effective, these analytical techniques require that a decision maker defines the problem and articulates the objectives for its solution. If the decision maker can do so, the problem can be termed well structured. Many complex spatial problems are ill- or semi-structured (Gorry and Morton 1971; Alter 1980; Hopkins 1984), however, and decision makers cannot define their problem or fully articulate their objectives. The decision making process adopted to solve semi-structured spatial problems has often been perceived as unsatisfactory by decision makers (Densham and Rushton 1988). This perception arises because many mathematical models, including hybrid formulations, fail to capture the important dimensions of spatial problems (Dear 1978). Moreover, analysts, rather than decision makers, have selected the dimensions of the problem that are modelled. This often leads to the selection of variables with inappropriate levels of resolution and geographical extent and, ultimately, results in solutions that are deemed unsatisfactory when evaluated in terms of the quality of the decision-making process that generated them.

To assist decision makers with complex spatial problems, geoprocessing systems must support a decision research process, rather than a more narrowly defined decision-making process, by providing the decision maker with a flexible, problem-solving environment. Such an environment empowers the decision maker in two ways: first, the problem can be explored to increase the level of understanding and to refine the definition; and, second, the generation and evaluation of alternative solutions enables the decision maker to investigate the possible trade-offs between conflicting objectives and to identify unanticipated, and potentially undesirable, characteristics of solutions.

Spatial decision support systems (SDSS) are explicitly designed to support a decision research process for complex spatial problems. SDSS provide a framework for integrating database management systems with analytical models, graphical display and tabular reporting capabilities, and the expert knowledge of decision makers. Such systems can be viewed as spatial analogues of decision support systems (DSS) developed in operational research and management science to address business problems.

This chapter provides an overview of SDSS by differentiating them from geographical information systems (GIS) and examining the types of problem to which they can be applied, the decision-making processes they support, typical system designs, and a framework for their implementation and evolution during the decision research process. It begins with an example of a DSS that illustrates the nature of the problem which SDSS must address. The characteristics of geoprocessing systems in general are then reviewed. Following this, a framework and an architecture for SDSS are presented. Finally, some brief conclusions are offered.

A SEMI-STRUCTURED SPATIAL PROBLEM: BANK BRANCH LOCATION

In recent years the banking industry in the United States has undergone considerable change. Kimball and Gregor (1989) identify three emerging trends in the retail banking sector. First, because non-banks are offering what are traditionally considered to be banking services, banks are facing increasing levels of competition. Secondly, the merger and consolidation of banks, resulting in larger, less-dense branch networks, has been one response to these increased levels of competition.

> 'The best managers will see, however, that the real competitive advantage does not derive from size per se, but from integrating acquisitions quickly, cheaply, and with a minimum of disruption to service delivery.'
> (Kimball and Gregor 1989: 13)

The third trend, therefore, is a shift in management emphasis towards integrating acquisitions with existing branch networks, product lines and operations. Thus, in addition to determining which branches remain in the network and which are closed,

> 'Developing and implementing highly integrated product lines, marketing support functions, and service functions across branch networks and different geographical locations will be the major operations and organizational challenge of the 1990s.'
> (Kimball and Gregor 1989: 13)

Three questions must be addressed in the process of designing branch networks, whether the aim is expansion, reconfiguration, or contraction (Chelst, Schultz and Sanfhvi 1988):

1. How many branches should there be?
2. Where should these branches be located?
3. What services should each branch provide to its customers?

The answers to these questions are interrelated because the network must be considered as a whole rather than as a series of isolated, individual branches. To find answers, bankers must ask other questions, including:

1. How many potential customers are within the market area of each actual or potential branch location?
2. What types of products will customers want to purchase from the bank?
3. What is the accessibility of each site to customers and is it commensurate with the operational needs of the bank (e.g. is it on a main street, does it have a car park, and what other land uses are in the immediate area)?
4. What is the cost of a new site, is there an existing structure, and what are the planning regulations in force?

Some of these questions also are hard to answer because they involve factors which are difficult to evaluate or predict. The problem of designing a network of bank branches must be considered ill-structured because it is impossible to define and to measure precisely the objectives for every possible solution. Often, solutions to ill-structured problems are obtained by generating a set of alternatives and selecting from among those that appear to be viable.

To support bank branch location selection, a geoprocessing system must be flexible enough to enable bank managers to use their chosen decision-making approaches. The managers will want to use the system to identify and employ a variety of measures of performance to evaluate the current branch network; to estimate the current and future levels of market potential and market penetration; to characterize the success of different types of branch when faced with a variety of levels of competition; to generate and evaluate a series of alternative solutions; and, once a network is designed, to monitor performance so that short-term corrective actions are made and commensurate long term strategic plans can be developed.

Thus, to support a decision research process, a geoprocessing system must facilitate the introduction of new factors into analyses. The system also must enable its users to change the relative importance of factors in analyses, both to evaluate the sensitivity of solutions and to reflect different opinions and objectives for the solutions. Finally, the system should be able to display the results of analyses in a variety of ways that help users to understand them.

CHARACTERISTICS OF GEOPROCESSING SYSTEMS

Geographical information systems

The literature on GIS contains many definitions. Often, the functions of capturing, storing, manipulating, analysing and displaying spatial data form the core of these definitions and the idea that GIS are designed to support spatial decision making is implicit (see Maguire 1991 in this volume).

A geoprocessing system, which is to support a decision research process and enable decision makers to use their chosen decision-making processes, must provide geographical information analysis (GIA) capabilities. Current GIS fall short of providing GIA capabilities. First, their support of analytical modelling is lacking as has been argued on several occasions (see Openshaw 1991 in this volume).

A second problem is that many GIS databases, in addition to their query functions, have been designed to support only cartographic display. This design goal handicaps the support of analytical modelling and other functions. For example, many analytical modelling techniques are data intensive. The sets of variables or layers stored in a GIS database often are too sparse to support modelling. Furthermore, the scales and degrees of resolution chosen to support cartographic display may be inappropriate for modelling.

A third problem concerns the graphical and tabular reporting capabilities of GIS. The main metaphor for information exchange between GIS and their users is the map and the database report. A decision maker who is exploring a problem and generating and evaluating alternative solutions will require other forms of graphics and reports, many of them peculiar to the problem domain. Unfortunately, flexible mechanisms for communicating information to the user are not commonly found in GIS.

A final problem concerns the decision making processes supported by GIS. The literature shows that when different people are faced with the same problem, they will adopt a range of decision-making strategies (Davis and Elnicki 1984); they will place different values on variables and relationships; and they will select and use information in a variety of ways. The decision making process applied to ill-structured spatial problems must reflect these inherent difficulties and inter-personal differences. Current GIS designs are not flexible enough to accommodate variations in either the context or the process of spatial decision making. This is reflected in definitions of GIS which largely ignore the role of analytical modelling techniques and the decision-making processes supported.

Spatial decision support systems

Spatial decision support systems are explicitly designed to provide the user with a decision-making environment that enables the analysis of geographical information to be carried out in a flexible manner. These systems have evolved in parallel with decision support systems (DSS) developed for business applications. The development of SDSS has lagged that of DSS by about 10 to 15 years, however. Thus, the DSS literature can be used to guide the design, development, implementation and use of SDSS.

Gorry and Morton's (1971) seminal paper initiated a literature. It documented the development of decision support systems as a response to the perceived shortcomings of management information systems (MIS) in the late 1960s and early 1970s. Despite their advantages, MIS did not adequately support analytical modelling capabilities and did not facilitate the decision maker's interaction with the solution process. The resulting literature on DSS is rich in both theory and applications (see Keen and Morton 1978; Alter 1980; Bonczek, Holsapple and Whinston 1981; Ginzberg and Stohr 1981; Sprague and Carlson 1982; Bennett 1983; House 1983).

DSS, which have been developed for applications including strategic planning, scheduling of operations, and investment appraisal, provide a framework for integrating database management systems, analytical models, and graphics to improve decision-making processes. As with GIS, a variety of definitions of DSS have been developed (e.g. see Alter 1977), but recent definitions have concentrated on the characteristics of systems. Often, these definitions list a series of characteristics that must be present for a system to be considered a DSS. Geoffrion's (1983) definition suggests that a DSS has six distinguishing characteristics:

1. They are explicitly designed to solve ill-structured problems where the objectives of the decision maker and the problem itself cannot be fully or precisely defined.
2. They have a user interface that is both powerful and easy to use.
3. Such systems enable the user to combine analytical models and data in a flexible manner.
4. They help the user explore the solution space (the options available) by using the models in the system to generate a series of feasible alternatives.
5. They support a variety of decision-making styles and are easily adapted to provide new capabilities as the needs of the user evolve.
6. Such systems allow problem solving to be both interactive and recursive – a process in which decision making proceeds by multiple paths, perhaps involving different routes, rather than a single linear path.

Differentiating DSS, SDSS and GIS

The characteristics that Geoffrion uses to define a DSS can also be used to define a SDSS. Because of the nature of complex spatial problems, however, a SDSS will need to provide additional capabilities and functions that:

- provide mechanisms for the input of spatial data;
- allow representation of the complex spatial relations and structures that are common in spatial data;
- include analytical techniques that are unique to both spatial and geographical analysis (including statistics); and
- provide output in a variety of spatial forms including maps and other, more specialized, types.

The characteristics of a SDSS facilitate a decision research process that can be characterized as iterative, integrative and participative. It is iterative because a set of alternative solutions is generated which the decision maker evaluates. Insights gained from this evaluation are input to, and used to define, further analyses. Participation occurs because the decision maker plays an active role in defining the problem, carrying out the analyses and evaluating the outcomes. The benefit of participation is integration: 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 and qualitative information.

A SDSS normally is implemented for a limited problem domain. The database integrates a variety of spatial and non-spatial data and facilitates the use of analytical and statistical modelling techniques. A graphical interface conveys information, including the results of analyses, to decision makers in a variety of forms. Finally, the system both adapts to the decision maker's style of problem solving and is easily modified to include new capabilities (Keen 1980). In sum, the characteristics of a SDSS serve to distinguish it from a GIS.

A FRAMEWORK FOR THE DEVELOPMENT OF SDSS

The DSS literature can both inform and guide the development of SDSS. Of several frameworks used for the development of DSS, Sprague's (Sprague 1980; Sprague and Carlson 1982; Carlson 1983) is readily transferred to the spatial domain. The level of technological development of the system is differentiated from the functional roles of the people who work with the technology.

There are three levels of technology in Sprague's framework (Fig. 26.1). At the lowest level is the SDSS toolbox. This is a set of hardware and software components that can be assembled to build a variety of system modules. At the second level of technology is the DSS generator. A generator is a set of mutually compatible hardware and software modules that can be configured easily to produce a specific SDSS. A specific SDSS is used to address a problem, by combining some or all of the modules in the generator. As the needs of the decision makers change, other modules can be added to the specific SDSS from the generator or, if they do not exist, assembled from the components in the SDSS toolbox.

A SDSS generator represents an intermediate level of technology. By containing a series of mutually compatible modules, it can be rapidly configured to provide a particular set of capabilities. Generators are most likely to be built by system vendors and consultants. They will recoup the cost of developing a generator because the start-up costs of many broadly similar projects will be greatly reduced. Other SDSS users are likely to iterate directly between the top and bottom levels of technology. The SDSS toolbox will be used to develop a specific SDSS to address a problem. Components from the toolbox will be employed directly to supply new capabilities as they are required by decision makers.

Sprague's (1980) framework contains five functional roles, the first three of which correspond

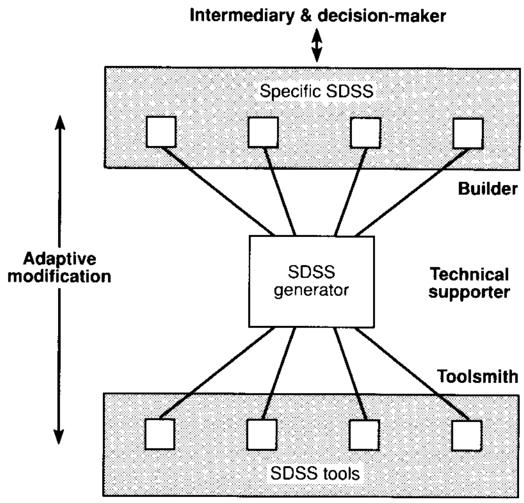

Fig. 26.1 Sprague's three-level framework for developing a SDSS.

to the three levels of technology (Fig. 26.1). Thus, the SDSS toolsmith develops new hardware and software tools for the SDSS toolbox; the technical supporter adds capabilities or components to the SDSS generator; and the SDSS builder configures the specific SDSS from the modules in the SDSS generator. The final pair of roles correspond to users of the specific SDSS. The intermediary sits at a console and interacts physically with the system whereas the decision maker is responsible for developing, implementing and managing the adopted solution. These five roles do not have to be filled by five people; individuals may have more than one function and one person may assume all five roles.

The decision maker specifies the analyses that are to be carried out and uses output from the system to evaluate interim solutions. The result of this evaluation may be a desire to investigate other aspects of the problem which may require new capabilities to be added to the SDSS. The system is updated as required by people filling the technical functional roles using the three levels of technology. Unlike the development path of more traditional geoprocessing systems, this process of system adaptation and evolution occurs rapidly during the decision-making process itself. This process of adaptive modification (Keen 1980) greatly enhances the flexibility and utility of the SDSS to the decision maker.

SDSS ARCHITECTURE

Adopting Sprague's (1980) development strategy for SDSS has implications for the architecture of the system. The addition of new capabilities, in a time frame which will not disrupt unduly the decision research process, is facilitated by a modular design. Working within Sprague's framework, Armstrong, Densham and Rushton (1986) design an architecture for SDSS generators. Their architecture consists of a set of five integrated software modules. Each module provides a group of functionally related capabilities; there are modules for database and model base management systems, display and report generators, and a user interface. To programmers (toolsmiths, technical supporters and builders), the modularity of the system facilitates software engineering; to SDSS users (intermediaries and decision makers), however, the system appears to be a seamless entity.

Figure 26.2 depicts one architecture for a SDSS (Armstrong *et al.* 1986). The five software modules are represented by boxes. The user interface encompasses the other four modules because all interaction with the user takes place via the interface. The flows of data and information between the modules are represented by the arrows joining them. The decision maker interacts with the system either directly or through the intermediary, employing an iterative solution process. System output – including the solutions to models and database queries in graphical and tabular form – is presented to decision makers who evaluate them. A solution may be accepted by the decision makers or, if unanticipated and unacceptable characteristics are evident, it may be used to help define further analyses.

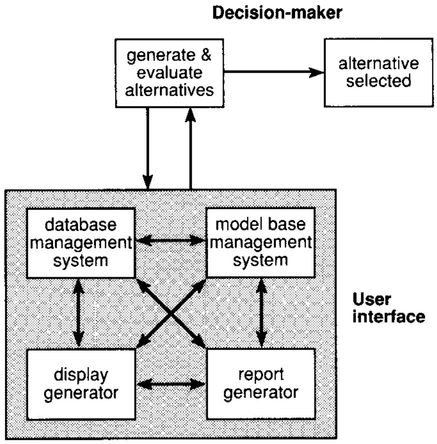

Fig. 26.2 A proposed architecture for a SDSS (after Armstrong, Densham and Rushton 1986).

Database management system

The core of the SDSS is the database management system (DBMS). The DBMS must be able to store and manipulate locational, topological and thematic data types to support cartographic display, spatial query and analytical modelling. Locational data consist of spatial primitives such as coordinates and chains. Topological data are attribute bearing objects including points, nodes and lines (examples include wells, road intersections and railway lines, respectively). Finally, thematic data are the attributes of topological objects (well depth, presence or absence of traffic lights, and the gauge of the track). The DBMS must permit the system user to construct and exploit complex spatial relations between all three types of data at a variety of scales, degrees of resolution and levels of aggregation.

The DBMS found in many GIS use the relational data model. Some fundamental problems occur when this data model is used in spatial applications, however (Calkins and Marble 1987). A study of the DSS literature reveals that alternative data models have proved effective in applications of DSS (Bonczek, Holsapple and Whiston 1984). Armstrong and Densham (1990) examine data models supported by commercially available DBMS. They demonstrate that the extended network model, an enhanced form of the network model, is effective for representing many forms of spatial relationships. A data structure is designed, using the Entity–Category–Relationship model (Chen 1983), to support location selection and is implemented using MDBS Associate's MDBS III.

Model base management system

Three approaches can be used to embed modelling techniques in SDSS. The first, and simplest, is to use the DBMS's macro or script programming language to implement modelling capabilities within the DBMS itself. This approach has several attractions. Capabilities are provided which make it easy to query and manipulate the database; and the only software required for developing models is the DBMS. The disadvantages of this approach are that DBMS macro programming languages tend to be slow because they are interpreted rather than compiled; the programming functions they offer are somewhat restrictive; and, finally, code generally is not portable across platforms and operating systems.

A second approach to incorporating analytical models is to develop libraries of analytical subroutines (Dixon, Openshaw and Wymer 1987). Such a library would be a spatial analogue of the general-purpose modelling and optimization subroutine libraries – including IMSL and NAG – which have been widely adopted. The appeal of this approach is that large numbers of models can be made accessible very easily. A user would invoke these subroutines from their own program via a standard interface. Furthermore, existing codes can be documented and object modules added to the library both easily and rapidly. There are several drawbacks to this approach: unless users are willing to write their own subroutines, they are restricted to using only the algorithms and techniques included in the library; and, second, a library is wasteful in terms of the amount of replicated code it contains. For this reason, a new area of interest in the DSS literature is the development of a model base management system (MBMS).

The development of a MBMS (Applegate, Konsynski and Nunamaker 1986; Konsynski and Sprague 1986) is a third approach to embedding models in SDSS. A MBMS performs a task which is analogous to the function of a DBMS. Instead of storing data, a MBMS stores elements of models. Its purpose, like that of a DBMS, is to use an organizing structure which supports the representation and exploitation of relationships between items and minimizes redundancy of storage. Thus, instead of individual pieces of data, a MBMS contains small pieces of code, each of which solves a step in an algorithm. Because many of these steps are common to several algorithms, this approach saves large amounts of code. The design and implementation of MBMS are attracting attention in the DSS literature. Several approaches are being investigated (Dolk 1986; Orman 1986), including the use of entity–relationship techniques (Blanning 1986).

Algorithmic solution methods are common for analytical models. The algorithms underlying these methods consist of a series of steps. When an algorithm is decomposed into its component parts, these steps are the 'atomic elements' – the smallest fragments of the algorithm. There is a degree of commonality in the steps used in algorithms for solving many types of spatial and non-spatial analytical models. Combining groups of steps in different sequences enables the MBMS to solve a wide range of algorithms. To function, the MBMS needs rules for combining steps. If steps are atomic elements, then combination rules can be thought of as formulae. Thus, when asked to employ a particular algorithm, the MBMS employs the appropriate formula and combines steps in the necessary sequence. This flexibility is achieved with minimal storage because each step cannot be disaggregated further, so redundancy is virtually eliminated.

One advantage of using a MBMS is that the implementation of new algorithms is simplified. In some cases this can occur simply by developing a new formula; in others, new atoms also may be added to the model base. A MBMS provides the researcher with the opportunity to develop and assess new algorithms rapidly. A second advantage is that the model base can be updated easily: individual steps can be replaced by improved versions without changing others. A final advantage concerns the support of modelling strategies. The flexibility of the MBMS permits the designers of the SDSS to support a variety of modelling strategies using new forms of user interfaces (see below).

Graphical and tabular report generators

The graphical and tabular report generators should provide a number of capabilities within the SDSS. The first capability is the generation of high resolution cartographic displays. These displays must be supplemented with other forms of graphics. For example, general-purpose statistical graphics, including two- and three-dimensional scatter plots and graphs, will be useful for exploratory data analysis. More specialized graphics will be necessary for depicting the results from analytical models and sophisticated statistical techniques. These graphics often will be domain specific: the use of strain ellipsoids in analysing geological faults, for example. Finally, tabular reports must augment and support each of these graphical capabilities.

User interface

To support decision making effectively, the user interface of SDSS must be easy to use. Unfortunately, the interfaces of many current geoprocessing systems are modelled on those of general-purpose business systems. These interfaces often are not suited to the graphical display of spatial information. Decision makers wish to receive information in both graphical and tabular forms – they are complementary, not mutually exclusive. Moreover, experience suggests that SDSS users want to interact with the modules of the system using either graphical or tabular representations. For example, the initial solution to a location-allocation model can be selected either by using a mouse to click on locations on a map or by typing in a list of node identifiers; the context in which this is done may determine which medium of interaction is the most appropriate.

The user interface of SDSS needs to represent two spaces: objective space and map space. Objective space depicts the parameters and solution space of an analytical model while map space is a cartographic representation of a study area and the output of the model. While a map space is likely to be displayed as a graphic, an objective space may be represented by either graphics or tables. In a location modelling context, for example, the allocations of fires to fire stations may be depicted by a series of lines between the fires and the fire stations in map space; in objective space, however, a table may simply list each fire and the station to which it is allocated. In contrast, the ranges of individual parameters in the location model may be represented graphically by bars or dials with the current value of the parameter indicated by a line or a needle. The user must be able to view these spaces simultaneously. Moreover, changes made in one space should be reflected automatically in the other space. Thus, changing the values of parameters in the objective space should be reflected by a change, where appropriate, in the allocations of fires to stations. Similarly, moving the location of a fire station in the map space should result in changes in the model in the objective space.

Providing users with this kind of interface will permit them to select data, model parameters, and output both easily and intuitively. Furthermore, such an interface permits the user to visualize the processes which underlie the model and to intervene and manipulate the model during the solution process. SDSS supporting these capabilities is truly providing the user with a problem-solving environment. The user can adopt a variety of decision-making approaches using visual interactive modelling (Hurion 1986) as a key element in the decision research process. Visual interactive modelling will be computationally intensive and the 'responsiveness' (Alter 1980) of the SDSS is important in determining its utility to a decision maker. Decision makers require timely support for their deliberations (Vazsonyi 1978, 1982), so an issue becomes how interactive is visual interactive modelling or how quickly can the results from an analysis be generated and presented to a decision maker? Keen (1983) refers to this as the 'turnaround test'. One approach that may prove fruitful in this area is the use of parallel programming techniques.

One area that is beginning to attract attention in geographical research is how to incorporate expert knowledge about modelling procedures into the SDSS itself. Because the models contained in SDSS often are complex and potentially can be misapplied, the system itself should help the user to select appropriate models, data sets and modelling strategies (Armstrong *et al.* 1990). To act like an expert analyst, the system must have access to three types of knowledge: a problem is described using environmental knowledge; procedural knowledge is used to help design a solution process and determine the values of parameters in models; and structural knowledge (the steps of algorithms and the data structures on which they operate) is used to solve problems. The elicitation (Waters 1989) and representation of this knowledge are fraught with difficulties.

CONCLUSIONS

SDSS are designed to provide decision makers with a problem solving environment within which they can explore, structure and solve complex spatial problems. The development of these systems requires that geographers increasingly to look to other disciplines for both current and future research findings. These findings must be used to inform and guide the design and implementation of the modules in an SDSS. Despite the increasing frequency with which the terms DSS and SDSS are appearing, the SDSS literature remains small and somewhat fugitive. Perhaps the earliest contributions to this literature stem from an IBM research project (see Carlson *et al.* 1974; Grace 1975; Holloway and Mantey 1976). More recent contributions have focused on either theoretical developments and implementation issues (Clarke 1989; Densham and Goodchild 1989; Fedra and Reitsma 1989; Jankowski 1989; Waters 1989; Armstrong and Densham 1990) or applications (White 1985; Dobson 1986; Bhatnagar and Jajoo 1987; Davis and Grant 1987; Densham and Armstrong 1987; Gould 1989; van der Vlugt 1989). The increasing interest in SDSS and the growing volume of publications can only be good news for decision makers.

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