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Past, present, and future of decision support technology☆

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Abstract

Since the early 1970s, decision support systems (DSS) technology and applications have evolved significantly. Many technological and organizational developments have exerted an impact on this evolution. DSS once utilized more limited database, modeling, and user interface functionality, but technological innovations have enabled far more powerful DSS functionality. DSS once supported individual decision-makers, but later DSS technologies were applied to workgroups or teams, especially virtual teams. The advent of the Web has enabled inter-organizational decision support systems, and has given rise to numerous new applications of existing technology as well as many new decision support technologies themselves. It seems likely that mobile tools, mobile e-services, and wireless Internet protocols will mark the next major set of developments in DSS. This paper discusses the evolution of DSS technologies and issues related to DSS definition, application, and impact. It then presents four powerful decision support tools, including data warehouses, OLAP, data mining, and Web-based DSS. Issues in the field of collaborative support systems and virtual teams are presented. This paper also describes the state of the art of optimization-based decision support and active decision support for the next millennium. Finally, some implications for the future of the field are discussed. © 2002 Published by Elsevier Science B.V.

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1. Introduction

Decision support systems (DSS) are computer technology solutions that can be used to support complex decision making and problem solving. DSS have evolved from two main areas of research—the theoretical studies of organizational decision making (Simon, Cyert, March, and others) conducted at the Carnegie Institute of Technology during the late 1950s and early 1960s and the technical work (Gerrity, Ness, and others) carried out at MIT in the 1960s [32]. Classic DSS tool design is comprised of components for (i) sophisticated database management capabilities with access to internal and external data, information, and knowledge, (ii) powerful modeling functions accessed by a model management system, and (iii) powerful, yet simple user interface designs that enable

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interactive queries, reporting, and graphing functions. Much research and practical design effort has been conducted in each of these domains.

DSS have evolved significantly since their early development in the 1970s. Over the past three decades, DSS have taken on both a narrower or broader definition, while other systems have emerged to assist specific types of decision-makers faced with specific kinds of problems. Research in this area has typically focused on how information technology can improve the *efficiency* with which a user makes a decision, and can improve the *effectiveness* of that decision [49].

The evolution of information technology infrastructures parallel the three eras of growth in the computer industry — the data processing (DP) era, the microcomputer era, and the network era [44]. Based on the infrastructures, DSS tools started in the DOS and UNIX environments around the late 1970s and then moved to Windows in the early 1990s. The advent of the Internet has given rise to many new applications of existing technology. The technology behind DSS is well suited to take advantage of the opportunities that the World Wide Web (Web) presents, especially the rapid dissemination of information to decision-makers. The Web's impact on decision making has been to make the process more efficient and more widely used. This is due largely to the fact that a typical browser serves as the user interface component of the decision-making systems, i.e., making the technology easy to understand and use.

The evolution of the human–computer interface is the evolution of computing. The graphical user interface (GUI) that was refined at Xerox, popularized by Macintosh, and later incorporated into Windows, and then the Palm, are typical examples of how significant the GUI is integrating technology into decision-maker's and/or user's daily tasks. In the future, decision-makers will access electronic services through their mobile phones or other wireless devices as much as through their desktop computers. In the future, mobile tools, mobile e-services, and wireless Internet protocols will mark the next major sets of development in DSS [15], thereby expanding the accessibility of the tools to decision-makers wherever they may be.

The primary purpose of this paper is to present the past, present, and future of decision support systems, including the latest advances in decision support tools. The paper discusses a number of important topics including development of the DSS concept, data warehousing, on-line analytical processing, data mining, Web-based DSS, collaborative support systems, virtual teams, knowledge management, optimization-based DSS, and active decision support for the next millennium. This paper has seven main sections. The next section discusses development of the DSS concept. Section 3 is a description of data warehousing, on-line analytical processing, and data mining. Section 4 discusses collaborative support systems, virtual teams, and knowledge management. Section 5 discusses optimization-based DSS, and Section 6 discusses active decision support for the next millennium. The final section provides some implications for the future of decision support technology.

2. Development of the DSS concept

The original DSS concept was most clearly defined by Gorry and Scott Morton [23], who integrated Anthony's [2] categories of management activity and Simon's [54] description of decision types. Anthony described management activities as consisting of strategic planning (executive decisions regarding overall mission and goals), management control (middle management guiding the organization to goals), and operational control (first line supervisors directing specific tasks). Simon described decision problems as existing on a continuum from programmed (routine, repetitive, well structured, easily solved) to nonprogrammed (new, novel, ill-structured, difficult to solve). Gorry and Scott Morton combined Anthony's management activities and Simon's description of decisions, using the terms structured, unstructured, and semi-structured, rather than programmed and nonprogrammed. They also used Simon's Intelligence, Design, and Choice description of the decision-making process. In this framework, *intelligence* is comprised of the search for problems, *design* involves the development of alternatives, and *choice* consists of analyzing the alternatives and choosing one for implementation. A DSS was defined as a computer system that dealt with a problem where at least some stage was semi-structured or unstructured. A computer system could be developed to deal with the structured portion of a DSS problem, but the judgment of the decision-maker was brought to bear on the unstructured part, hence constituting a human–machine, problem-solving system.

Gorry and Scott Morton also argued that characteristics of both information needs and models differ in a DSS environment. The ill-defined nature of information needs in DSS situations leads to the requirement for different kinds of database systems than those for operational environments. Relational databases and flexible query languages are needed. Similarly, the ill-structured nature of the decision process implied the need for flexible modeling environments, such as those in spreadsheet packages.

Fig. 1 describes what probably came to be a more customarily used model of the decision-making process in a DSS environment. Here, the emphasis came to be on model development and problem analysis. Once the problem is recognized, it is defined in terms that facilitate the creation of models. Alternative solutions are created, and models are then developed to analyze the various alternatives. The choice is then made and implemented consistent with Simon's description. Of course, no decision process is this clear-cut in an ill-structured situation. Typically, the phases overlap and blend together, with frequent looping back to earlier stages as more is learned about the problem, as solutions fail, and so forth.

Over the last two decades or so, DSS research has evolved to include several additional concepts and views. Beginning in about 1985, group decision support systems (GDSS), or just group support systems (GSS), evolved to provide brainstorming, idea evaluation, and communications facilities to support team problem solving. Executive information systems (EIS) have extended the scope of DSS from personal or small group use to the corporate level. Model management systems and knowledge-based decision support systems have used techniques from artificial intelligence and expert systems to provide smarter support for the decision-maker [5,12]. The latter began evolving into the concept of organizational knowledge management [47] about a decade ago, and is now beginning to mature.

In the 21st century, the Internet, the Web, and telecommunications technology can be expected to result in organizational environments that will be increasingly more global, complex, and connected. Supply chains will be integrated from raw materials to end consumers, and may be expected to span the planet. Organizations will interact with diverse cultural, political, social, economic and ecological environments. Mitroff and Linstone [43] argue that radically different thinking is required by managers of organizations facing such environments; thinking that must include consideration of much broader cultural, organizational, personal, ethical and aesthetic factors than has often been the case in the past. Courtney [11], following Mitroff and

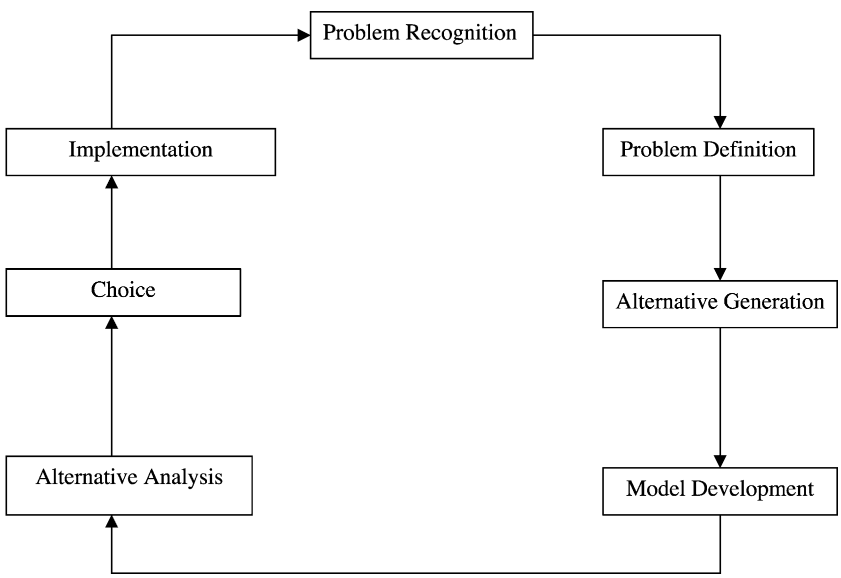

Fig. 1. The DSS decision-making process.

Linstone, suggests that DSS researchers should embrace a much more comprehensive view of organizational decision making (see Fig. 2) and develop decision support systems capable of handling much "softer" information and much broader concerns than the mathematical models and knowledge-based systems have been capable of handling in the case in the past. This is an enormous challenge, but is imperative that we face if DSS is to remain a vital force in the future.

The primary difference between Fig. 2 and typical decision models in a DSS context is the development of multiple and varied perspectives during the problem formulation phase. Mitroff and Linstone [43] suggest that perspectives be developed from organizational (O), personal (P) and technical (T) positions. In addition, ethical and aesthetic factors are considered as well. The mental models of stakeholders with various perspectives lie at the heart of the decision process, from defining what *is* a problem, to analysis of the results of trying to solve the problem.

The technical perspective has dominated DSS problem formulation in the past, and involves the development of databases and models. The organizational and personal perspectives are developed by discussing the problem with all affected stakeholders, at least as resources permit, so as to ensure that all relevant variables are either included in models, or taken into account during the analysis, if they cannot be quantified. As many of these factors may be more humanistic and nonquantifiable, especially ethical and aesthetic concerns. The need for broader forms of analysis, such as group sessions, may become even more appropriate in the future.

The remainder of the paper discusses recent and expected DSS developments in more detail. First, recent activity in data warehousing, online analytical processing (OLAP), data mining and Web-based DSS is considered, followed by treatment of collaborative support systems and optimization-based decision support.

3. Data warehouses, OLAP, data mining, and web-based DSS

Beginning in the early 1990s, four powerful tools emerged for building DSS. The first new tool for decision support was the data warehouse. The two new tools that emerged following the introduction of data warehouses were on-line analytical processing (OLAP) and data mining. The fourth new tool set is the technology associated with the World Wide Web. The Web has drawn enormous interest in the past few years and it can have an even greater impact in the years ahead. All of these tools remain "hot" topics in corporate and academic computing publications. This section attempts to briefly examine the past, present and future of these four decision support technologies.

The roots of building a data warehouse lie in improved database technologies. Initially, Codd [8] proposed the relational data model for databases in 1970. This conceptual data base model has had a large impact on both business transaction processing sys-

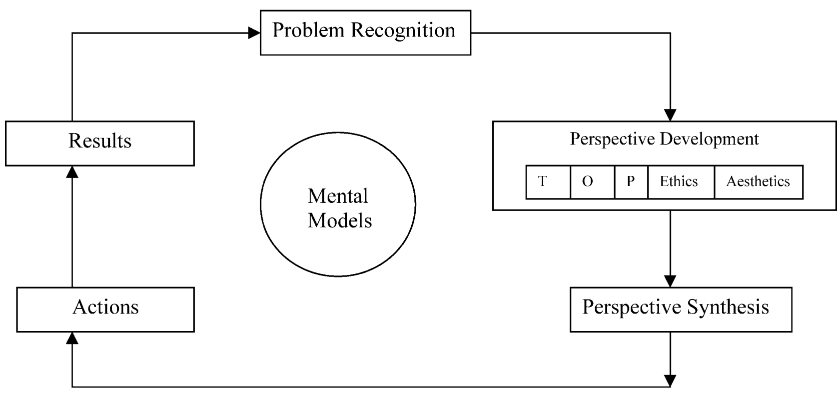

Fig. 2. A new decision paradigm for DSS. Source: Courtney [11].

tems and decision support systems. More recently, Codd's specification [9] of on-line analytical processing (OLAP) standards has had an equally large impact on the creation of sophisticated data-driven DSS [50]. In the early 1990s, only a few custom-built data warehouses existed. The work of Inmon [29], Devlin, and Kimball [33] promoted a data warehouse as a solution for integrating data from diverse operational databases to support management decision making. A data warehouse is a subject-oriented, integrated, time-variant, nonvolatile collection of data [29]. Many companies have built data warehouses, but there has been an ongoing debate about using relational or multidimensional database technologies for on-line analytical processing [55,59]. Both database technologies are currently used and relational structures like the star schema are preferred for very large data warehouses.

Building a large data warehouse often leads to an increased interest in analyzing and using the accumulated historical DSS data. One solution is to analyze the historical data in a data warehouse using on-line analytical processing tools. "On-line analytical processing (OLAP) is a category of software technology that enables analysts, managers, and executives to gain insight into data through fast, consistent, interactive access to a wide variety of possible views of information that has been transformed from raw data to reflect the real dimensionality of the enterprise as understood by the user." [45]

OLAP tools have become more powerful in recent years, but a set of artificial intelligence and statistical tools collectively called data mining tools [16] has been proposed for more sophisticated data analysis. Data mining is also often called database exploration, or information and knowledge discovery. Data mining tools find patterns in data and infer rules from them [50]. The rapidly expanding volume of real-time data, resulting from the explosion in activity from the Web and electronic commerce, has also contributed to the demand for and provision of data mining tools. A new category of firms, termed "infomediaries," will even conduct real-time data mining analysis of so-called "clickstream data" on behalf of their customers, who are typically highly interactive websites that generate a lot of data where managers wish to grasp the buying patterns of their visitors.

The Web environment is emerging as a very important DSS development and delivery platform. The primary Web tools are Web servers using Hypertext Transfer Protocol (HTTP) containing Web pages created with Hypertext Mark-up Language (HTML) and JavaScript accessed by client machines running client software known as browsers. This environment traces its roots to original research by Tim Berners-Lee, who in 1990 developed a point-and-click hypertext editor, which ran on the "NeXT" machine. Berners-Lee released this editor and the first Web server to a narrow technical audience in the summer of 1991 (cf., http://www.w3.org/People/Berners-Lee/ShortHistory.html). His innovation led to the exciting developments in e-business and e-commerce by the end of the 1990s.

At the beginning of the 21st century, the Web is the center of activity in developing DSS. When vendors propose a Web-based DSS, they are referring to a computerized system that delivers decision support information or decision support tools to a manager or business analyst using a Web browser such as Netscape Navigator or Internet Explorer [50]. The computer server that is hosting the DSS application is linked to the user's computer by a network with the TCP/IP protocol. Most Web data warehouses support a four-tier architecture in which a Web browser sends HTML requests using HTTP to a Web server. The Web server processes these requests using a Common Gateway Interface (CGI) script. The script handles Structured Query Language (SQL) generation, post-SQL processing, and HTML formatting. This application server then sends requests to a database server, which generates the query result set and sends it back for viewing using a Web browser. Many technology improvements are occurring that are speeding up query processing and improving the display of results and the interactive analysis of data sets.

Web-based DSS have reduced technological barriers and made it easier and less costly to make decision-relevant information and model-driven DSS [50] available to managers and staff users in geographically distributed locations. Because of the Internet infrastructure, enterprise-wide DSS can now be implemented in geographically dispersed companies and to geographically dispersed stakeholders including suppliers and customers at a relatively low cost. 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 global Internet. The Web has increased access to DSS and it should increase the use of a well-designed DSS in a company. Using a Web infrastructure for building DSS improves the rapid dissemination of "best practices" analysis and decision-making frameworks and it should promote more consistent decision making on repetitive tasks.

Web-based DSS vendors are rapidly innovating and mergers between vendors are common. Any analysis of the features of data warehouse, OLAP, data mining or other Web-based DSS products is obsolete before it is completed. A Web site like The Data Warehousing Information Center (http://www.dwinfocenter.org) has an extensive list of tools and tool vendors. The DSSResources.COM Vendors page at URL http://www.dssresources.com/vendorlist/ lists more than 75 companies that market DSS products. Many of these vendors have Web-based DSS products. A number of vendors have examples of products at their Web sites.

Building DSS with these new tools remains a complex analytical task. Some consultants use industry specific templates for data warehouses, others use structured design methodologies. Vendors promote Web-enabled business intelligence software and Web portal software as a means to speed the development of Web-based DSS. In some situations, an existing data warehouse can be Web-enabled or made available using a Web browser, but the data storage systems may have problems serving an increased number of online users. Web-based DSS with data warehouses and OLAP are available 7 days a week and 24 hours a day, so the needs of users have changed. Web database architectures must handle a large number of concurrent requests, while maintaining consistent query response times as the number of users and volume of data changes and will likely increase over time.

In most data mining applications, a data file of query results is created from a data warehouse and then analyzed by a specialist using artificial intelligence or statistical tools. This new data file could be made available through an Intranet to a broad group of business analysts by client-server technologies. In the 21st century, both e-commerce and customer relationship management (CRM) will increase the demand for more analysis of customer transaction data. Many software vendors and publications, such as Datamation (http://www.datamation.com/dataw/), are suggesting that all knowledge workers will become data miners in the future. This potential use of the technologies would likely lead to poorly conceived end-user analyses and dubious results. In many academic disciplines, data mining is viewed disparagingly as "data dredging." Knowledgeable, well-trained business users need to work with the data mining classification and clustering tools. Making tools like neural networks, decision trees, rule induction, and data visualization widely available to naïve users using Web technologies will be a mistake.

So where does the Web lead the technologies of data warehousing, OLAP, data mining and model-driven DSS? The universal TCP/IP protocol or Web platform leads to widespread use and adoption of decision support systems in organizations. Managers who have not used DSS will find the new tools powerful and convenient. New managers, sales staff and others who were not exposed to client-server tools or other DSS tools of the 1980s and 1990s will expect DSS to be easy to use and available from their office, home, and client/customer locations.

4. Collaborative support systems[1]

One of the more significant trends over the past 20 years has been the evolution from individual standalone computers to the highly interconnected telecommunications network environment of today. Initially, computers within firms were connected via local area networks (LANs), allowing teams and workgroups to share decision-making information more easily. Then, firms began to connect their networks in wide area networks to facilitate sharing of information across organizational boundaries. Finally, the Internet and Web created an environment with almost ubiquitous access to a world of information. At the same time, many organizational decisions migrated from individual decisions to ones made by small teams to complex decisions made by large diverse groups of individuals within a firm or even from multiple firms. In this environment, several key technological developments have occurred in the area of decision support. Various tools to support collaboration and group processes have been developed, implemented, evaluated, and refined.

[1] Note: Certain elements from this section are adapted from Ref. [58].

4.1. Group processes supporting decision making

Individuals often make decisions in small groups or in large organizational networks. Alavi and Keen [1] define a business team as a "small, self-regulating, self-contained task-oriented work group" that "typically focus on organizationally assigned tasks." *Collaboration* occurs within the context of cooperative work and is defined as "multiple individuals working together in a planned way in the same production process or in different but connected production processes" [60]. Because individuals who cooperate or perform tasks together share only partially overlapping goals, individual group members' activities must be *coordinated* to ensure that the disparate individuals come to share the same goals. Coordination involves actors working together harmoniously [37,38] to accomplish a collective set of tasks [56]. A group decision results from interpersonal communication among group members [14].

4.2. Group support systems

Group support systems (GSS) or collaboration support systems enhance the communication-related activities of team members engaged in computer-supported cooperative work. The communication and coordination activities of team members are facilitated by technologies that can be characterized along the three continua of time, space, and level of group support [1,14,30]. Teams can communicate synchronously or asynchronously; they may be located together or remotely; and the technology can provide task support primarily for the individual team member or for the group's activities. These technologies are utilized to overcome space and time constraints that burden face-to-face meetings, to increase the range and depth of information access, and to improve group task performance effectiveness, especially by overcoming "process losses" [41,42]. In short, GSS facilitates more effective group interaction, leading to greater decision-making effectiveness in modern distributed organizations. [58]

GSS and computer-mediated communication systems (CMCS) provide support for either synchronous or asynchronous meetings. Synchronous meetings are spontaneous where ideas are exchanged with little structure. Participants communicate with each other in such a way that it is sometimes difficult to attribute an idea to one participant or establish the reason behind a particular decision. It is estimated that managers spend 60% of their communication time in synchronous meetings [46], which include face-to-face meetings, telephone calls, desktop conferencing, certain group decision support systems (GDSS), and Web-based "chat rooms."

On the other hand, asynchronous meetings are more structured than synchronous meetings. These meetings rely more on documents exchanged among participants. Compared to synchronous meetings, asynchronous meeting participants have longer to compose their messages and, therefore, it is easy to attribute an idea to its originator and establish the reason behind a particular decision. However, asynchronous meetings require more time than synchronous meetings because information exchange takes longer. Asynchronous meetings are frequently used by groups where at least one participant is in a remote location [34]. Technologies that facilitate asynchronous meetings include e-mail, bulletin board systems, and Internet newsgroups. Computer conferencing, which is a "structured form of electronic mail in which messages are organized by topic and dialogues are often mediated" [3,27], can be asynchronous (such as bulletin board systems and Internet newsgroups) or synchronous (such as "chat rooms").

4.3. Virtual teams and the impact of technology

As decision making moves from an individual activity toward a group one, many organizations are forming "virtual teams" of geographically distributed knowledge workers to collaborate on a variety of workplace tasks. The effects of the reduced "communication modalities" on virtual team members and the circumstances in which these effects occur has been the focus of much of the CMCS research [28,42]. Although not definitive in terms of specific effects, the research in this area suggests that virtual teams communicate differently than face-to-face groups [6,25, 42,58]. While there is a plethora of research describing various technologies for computer-mediated communications, there is a lack of studies examining "sustained, project-oriented teamwork of the sort that is important in most real-world organizations" [20]. An analysis of CMCS communication characteristics is warranted.

Collaboration support systems play a central role in facilitating communication among members of virtual teams. The technology imposes constraints on communication that are likely to affect a group's performance. People rely on multiple modes of communication in face-to-face conversation, such as paraverbal (tone of voice, inflection, voice volume) and nonverbal (eye movement, facial expression, hand gestures, and other body language) cues. These cues help regulate the flow of conversation, facilitate turn taking, provide feedback, and convey subtle meanings. As a result, face-to-face conversation is a remarkably orderly process. In normal face-to-face conversation, there are few interruptions or long pauses and the distribution of participation is consistent, though skewed toward higher status members [36,40]. Collaboration support systems preclude these secondary communication modes, thus altering the orderliness and effectiveness of information exchange. Such communication modalities are constrained to a varying extent depending on the characteristics of the technological system. For example, electronic mail prevents both paraverbal and nonverbal cues, telephone conference calls allow the use of most paraverbal cues (but not nonverbal ones), while videoconferencing enables extensive use of both paraverbal and nonverbal cues. The lack of these cues reduces the richness of the information transmitted by virtual team members. Daft and Lengel [13] define media richness as "the ability of information to change understanding within a time interval." Rich media allow multiple information cues (the words spoken, tone of voice, body language, etc.) and feedback. It takes more time and effort by group members to achieve the same level of mutual understanding in a lean medium, such as CMCS, than in a rich one such as face-to-face communication. This communication constraint affects the group's ability to reach a consensus decision.

Because virtual teams communicate less efficiently than face-to-face groups [25,26,42], they tend to be more task-oriented and exchange less social–emotional information, slowing the development of relational links [6]. Development of relational links is important because researchers have associated strong relational links with many positive outcomes including enhanced creativity and motivation, increased morale, fewer process losses, and better decisions [57,58].

4.4. Creating effective virtual teams

Face-to-face teams generally report greater satisfaction with the group interaction process than virtual teams [57,58]. Therefore, since virtual teams are becoming a necessary tool, organizations must strive to bolster the satisfaction level of CMCS. If this were accomplished, there would be no significant drawback to the use of virtual teams, which can be made more acceptable and satisfying in several ways. Zack [61] showed that the highly interactive nature of face-to-face meetings makes this mode "appropriate for building a shared interpretive context among group members, while [CMCS], being less interactive, is more appropriate for communicating within an established context." Ongoing groups have an established culture and set of routines, and may have a greater commitment to achieving effective communications. Further, Zack suggested that while "social presence" (a sense of belonging) is diminished in virtual teams, it is the lack of interactivity that primarily constrains computer mediated communication.

Users of CMCS must exercise leadership and influence with little means of social control, and some members may become "lost in cyberspace" and may "drop out" of virtual teams in the absence of familiar communications patterns. Care must be exercised to develop and foster familiarity and proficiency with these new tools and techniques of social interaction. The most important goal of CMCS is to foster interaction, inclusion and participation [39], which are all related to the feeling of "being there" or social presence [61]. Social presence defines the extent to which a communications medium allows participants to experience each other as being psychologically close or present [19]. Face-to-face communication, for example, is characterized by social cues such as nonverbal and paraverbal communications channels and continuous feedback [52]. The success of group support systems lies in part on their ability to provide the participants with socioemotional content sharing. Clearly, videoconferencing offers a greater opportunity for sharing these social cues than text-based communications modes, yet the latter do not entirely lack such cues [51,57]. Designers of GSS should explicitly work to incorporate innovative methods and channels for sharing various cues between participants, such as "emoticons" (also known as "smileys") to increase the media richness of their communications. Whereas many first-time users of CMCS such as e-mail might write formal messages that read like business letters, the messages of high-volume users usually evolve into a far more familiar tone with personal comments and common terms and abbreviations that can create a greater sense of actually speaking with someone.

Kraut et al. [35] suggest that whereas formal communication is characterized by preset agendas between arranged participants scheduled in advance with "impoverished content," informal communication often occurs spontaneously with no arranged agenda between random participants with richer content. Further, they show that informal encounters create a common context and perspective that support planning and coordination of group work. Without informal exchanges, "collaboration is less likely to start and less productive if it does occur" [35]. Participants in purely computer-mediated systems who have never met and exchanged informal conversation have exhibited a strong desire to do so when given the opportunity — GSS developers should facilitate informal face-to-face contact wherever possible.

In the future, organizations introducing these decision support technologies into the workplace must leverage the beneficial differences inherent in computer-mediated communications and mitigate the negative differences. Managers must become familiar with the strengths and limitations of the relevant technologies. The use of collaborative support systems will increase as the Web enables more strategic alliances and as intranets become a widespread platform for group decision making.

5. Optimization-based decision support models

This section describes the state of the art of optimization-oriented decision support, and speculates on the future of such systems. Model-based decision support can be divided into three stages: formulation, solution, and analysis. *Formulation* refers to the generation of a model in the form acceptable to a model solver. The *solution* stage refers to the algorithmic solution of the model. The *analysis* stage refers to the 'what-if' analyses and interpretation of a model solution or a set of solutions. The development of DSS tools to support these three stages has occurred at different rates. Research in optimization traditionally focused on generating a better solution algorithm; as the technologies have evolved, more progress has been made in the formulation and analysis functions of DSS support.

5.1. Formulation

Converting a decision-maker's specification of a decision problem into an algebraic form and then into a form understandable by an algorithm is a key step in the use of a model. We have come a long way from the days of requiring an optimization problem to be input in the commonly used Mathematical Programming System (MPS) format. Several algebraic modeling language processor systems (AMLPS) have been developed that make it convenient to input the modeler's form of an optimization problem directly into a solver. These AMLPS also can read and write data files from/to many diverse databases, enabling a truly integrated model generation. Some of theses AMLPS support ODBC calls and thus now can be used for development of a model that depends upon many data sources located across an enterprise. Indeed, the growth in these systems is now leading to the development of a Modeling Environment (ME) where the solver takes a support role. The ME serves as the model translator and manager of all input/output and interaction with the user. These systems are extensible through a link to any other solver.

The next generation of formulation support is displayed in further integration of the model specification in host computing platforms. Modeling Environments are becoming available as APIs so that these can be called directly into an end-user application. The formulation support is also extended through the growth of enterprise resource planning (ERP) movement. Optimization-based DSS will play a key role in the next wave of ERP software, and the modeling languages will make it happen.

5.2. Solution

Historically, most of the research effort in operations research (OR) has been concentrated on development of new algorithms to solve problems faster. The good news is that decision support software developers appear to incorporate advances in the solution algorithms quite quickly to let the user benefit from these enhancements. Some major trends are highlighted below.

The traditional linear programming software continues to be refined in both simplex method and interior point algorithms. The emphasis is on taking advantage of problem characteristics to reduce the problem size or to speed up a specific algorithmic step. The result is the ability to solve really large problems. It has also enabled the modelers to consider uncertainty in the decision situation through stochastic programming with recourse type approaches.

Perhaps the biggest gains in the solution algorithms are evident in the mixed-integer programming (MIP) arena. With the incorporation of various tricks, solutions of much larger MIP problems are now possible. A major development is the solution of integer programming problems is the use of constraint logic programming [17,18]. This approach employs the tree search philosophy of branch and bound, but does not require solution of LP problems.

The next major trend in the solution software is the growth of metaheuristics to solve combinatorial problems [21,22]. The techniques employed include tabu search, genetic algorithms, simulated annealing, neural networks, and several others. For example, Evolver is a commercially available tool (from Palisades Software) that solves MIP problems using genetic algorithms. The combination of techniques from artificial intelligence and operation research to attack much larger problems is going to benefit the DSS movement in the next few decades.

Traditionally sold optimization software is becoming a foundation in the DSS platform. A casual look at a recent issue of *ORMS Today* would show advertisements from companies such as Maximal Software offering their solver in Application Programming Interface (API) form to XA offering their product for full integration in ABAP/4, SAP's programming language.

5.3. Analysis

Only recently have vendors of optimization software begun to focus on the final stage of the modeling process — analysis. This stage includes delivery of model solution in a usable form to enhance the ability to analyze and understand the problem and the solution. Report generating functionality is now a common feature used to present the results to the user in a usable form that can be integrated into databases. Solutions can also be stored in popular spreadsheet formats for simple graphical analyses or report generation. Some modeling environments offer their own graphical display tools to display results in easy to use format. It is likely that the growth of new visualization tools will benefit the process of solution delivery in OR models as well. It would be possible to incorporate multimedia in highlighting solutions or especially exceptions to the norm or signal infeasibilities.

The analysis stage has also benefited from incorporation of deductive techniques such as IIS [7] to diagnose the cause of infeasibilities or ANALYZE [24] to perform post solution analysis beyond the classic sensitivity analysis. A new trend is the ability to store and analyze multiple solution scenarios. The Scenario Manager tool within Microsoft Excel popularized the concept of saving multiple solutions and understands any underlying patterns. Some researchers [53] have proposed the use of inductive analysis techniques to further generate insight into the problem by studying multiple solutions. The concept of generating multiple 'what-if' scenarios and solutions is now available in commercial software such as Risk Optimizer from Palisade Software.

We have seen many developments in analytical models, optimization and model-based DSS, but the possibilities for greater exploitation of models in decision making are enormous. In the next section, we examine some broader issues in actively supported management decision making.

6. Active decision support for the next millennium

The need for active decision support was asserted by Keen [31] when he outlined "the next decade of DSS" in 1987. His first point is that the DSS technology itself is not important — it is the *support* we intend to provide which is the key element. Keen gave DSS research the following broad agenda: (i) it should look for areas where the proven skills of DSS builders can be applied in new, emergent or overlooked areas; (ii) it should make an explicit effort to apply analytic models and methods; it should embody a far more prescriptive view of how decisions can be made more effectively; (iii) it should exploit the emerging software tools and experience base of AI to build semi-expert systems, and (iv) it should re-emphasise the special value of DSS practitioners as being their combination of expertise in understanding decision making and knowing how to take advantage of developments in computer-related fields.

We will use Keen's agenda for "the next decade of DSS", but we will update it from 1987 to 1997, and look ahead to the year 2007. Managers and knowledge workers in the late 1980s and 1990s are different from earlier DSS users, and will be quite different from those of 2007. Technological proficiency levels of all users continue to increase. The compromises we made with system designs in order to facilitate the use of DSS by inexperienced users in the late 1980s will not be necessary for the users of the 2007. On the other hand, this new generation of technologically advanced users will also expect more functionality in DSS technology. The DSS technology of the future will be enhanced by mobile tools, mobile e-services, and wireless protocols such as Wireless Applications Protocol (WAP), Wireless Markup Language (WML), and iMode, thereby leading to ubiquitous access to information and decision support tools. Greater collaboration functions will be enabled, facilitating more interactive decision processes.

In the last few years, we have seen a steady inflow of models and tools for multiple-criteria decision making in DSS applications (Keen's second point), and it appears that this will continue as developers incorporate more advanced mathematical programming software integrated with (for instance) MS Excel. The use of artificial intelligence (AI), as advocated in Keen's third point, is being replaced with intelligent systems and soft computing, which are emerging new technological platforms. In fact, rather than stand-alone AI modules, intelligent logic is now usually inherent in the processing of all decision support tools.

Because more senior executives are comfortable with information technology (IT), the roadblocks of the 1980s and 1990s for using IT in executive decision making are being removed. In fact, IT is now viewed as a strategic tool that is central to the pursuit of competitive advantage. Therefore, various DSS technologies will be more accepted throughout the enterprise, from operational support to executive boardrooms. Further, modern corporations and their strategic business units will continue to lose their hierarchical organizational structures. Companies seek to create business entities that are leaner, more flexible and more responsive to a rapidly changing business environment. With reductions in staff and middle management personnel, senior managers and executives get more directly involved with problem solving, decision making and planning than they were in the 1980s. Agile and flexible organizations also ask their managers and staff to frequently change their focus. Therefore, decision support tools will play a more central role in this rapidly changing environment.

The first target for intelligent systems technology should be the overwhelming flow of data, information and knowledge produced for executives by an increasing number of sources. Expert systems technology, which was a focal area for venture capital in 1985–1990, is now being replaced by intelligent systems, which are built to fulfill two key functions: (i) the screening, sifting and filtering of a growing overflow of data, information and knowledge (described above), and (ii) the support of an effective and productive use of the Executive Information Systems (EIS), which quite often is tailored to the needs and the personality of the user. Intelligent systems, which can be implemented for these purposes, range from self-organizing maps to smart add-on modules to make the use of standard software more effective and productive for the users. Intelligent data mining will also play a significant role in helping organizations transform huge volumes of data into valuable corporate knowledge and intelligence.

Software agents (also called intelligent agents) have also been designed and implemented to address this process of data screening and filtering. These Java-based components can be designed and implemented to search for data sources with user-defined search profiles, to identify and access relevant data, to copy the data, and to organize and store it in a data warehouse. Other agents of the same "family" can then be used to retrieve the data, insert it in reports and to distribute it over e-mail according to topic-specific distribution profiles.

7. Conclusions

The developments in the last decade will guide us in understanding the coming evolution of decision support technologies. Changes will occur in technologies and in the implementation environment — users are becoming more sophisticated and more demanding, organizations are becoming more complex yet more agile and flexible, and global regulatory and competitive factors rapidly change, affecting the design and use of these tools. The future will offer surprises, to be sure, but certain trends can be observed.

One such trend is the meteoric rise of the Web as a common platform from which to extend the capabilities of DSS to a very large number of users. The fact that a standard Web browser can be used as the user interface/dialog means that companies can introduce new DSS technologies at their sites at relatively low cost when compared to client-based DSS. A Web browser user interface allows the implementation of DSS technology with very little user training. The potential exists for web-based DSS to increase productivity and profitability, and speed the decision making process without regard to geographic limitations [48]. Through increased decision making ability, reduced costs, and reduced support needs, Web-based DSS can significantly improve companies' use of their existing infrastructures. More executives and managers can have access to technology that increases overall organizational efficiency and effectiveness.

The Web also dramatically increases the usability factors for DSS. Standard interface design factors mean that users can more quickly adopt new DSS with less training and with more confidence. However, while standards are advantageous from that perspective, we also recommend that *personalization* of the DSS user interface is a future area that should be addressed by developers and researchers. The processing power of today's platforms enables the design of highly configurable interfaces that identify the usage patterns of individual users and modify themselves (by reducing menu choices, for example) in order to provide higher usability for each DSS user.

Another trend is the increasing sophistication of model-based DSS software. For example, model-based DSS software is standardizing on Web technologies as the fundamental technology for interface design. Most major DSS software developers now have websites and offer downloading trial software for further exploration. Even more exciting is the trend toward using the Application Service Provider (ASP) model for delivery of DSS functionality. DSS software customers no longer need to purchase and install the software on their own servers; they may just rent it on a per-use basis from an ASP who hosts the decision support application and provides secure access over the Internet. This is especially useful for solver software so that a modeler can employ the best solver software appropriate for a specific situation without having to buy every single program. Examples of this approach include IBM's OSL site (http://www.research.ibm.com/osl/bench.html) and the NEOS Server (http://www.mcs.anl.gov/otc/Server/). Bhargava et al. [4] have been developing Decision Net (http://www.ini.cmu.edu/emarket/) as a portal to enable the modeler to rent a specific program on a per use basis.

A major trend is how the Web is supporting more interactivity and collaboration in DSS. Organizations are building not only virtual team structures, but also entire virtual organizations, based on this technological platform. With the application of intranets and enterprise resource planning (ERP) systems, entire organizations routinely interact via technology with little or no face-to-face interaction. Such virtual organizations have seemingly overcome all barriers of time and space, and have created entire firms with remote business partners. A final trend in this domain is the development of *ubiquitous computing* based on secure wireless bandwidth and new "thin client" devices such as Web-enabled digital phones and digital assistants. In this environment, virtual teammates can truly collaborate anywhere and anytime. Without the need to physically be at a computer tied to a wired network, individuals are free to collaborate more naturally and nearly all the time. This ensures even greater connectivity to members of workgroups and virtual teams, with greater access and more robust decision support. Another benefit of this wireless interactivity is the enhancement of the ability of knowledge workers to collect multiple perspectives on decision problems as suggested in Fig. 2. Using the multiple perspectives approach to problem formulation should help lead us towards Keen's goal of finding areas where tools can be developed for turning qualitative insights and uncertain and incomplete data into useful knowledge. Ultimately, this new environment allows individuals and organizations to make more informed, more collaborative decisions that will achieve the organization's goals more effectively.

Though information technology is advancing the form, style, and content of decision support, we believe the development of model-based DSS is still at an early stage, and finally poised to emerge as a powerful tool for managerial support. One of the challenges in employing models for decision support has been the availability of data from across various data warehouses within an organization. The client server model of the web allows more transparent access to this data, making it possible to run models based on actual data. In a recent paper, Cohen et al. [10] describe several implementations of optimization-based DSS that integrate data from several sources. Many optimization software providers and professional service organizations are building specific interfaces to bring all the data together to make these applications possible. The extraordinary growth of i2 Technologies and many other companies that employ optimization models to enhance the supply chain is a good example. Growth of the Internet enables smaller organizations to also employ some of the same tools. This opportunity will grow substantially and result in the next generation of cheaper, faster, and better DSS tools for a much larger client base than we have seen before.

By extending Keen's agenda for DSS research to the year 2007, we can reformulate it with the potential support of the new technologies. DSS researchers and developers should (i) identify areas where tools are needed to transform uncertain and incomplete data, along with qualitative insights, into useful knowledge; (ii) be more prescriptive about effective decision making by using intelligent systems and methods; (iii) exploit advancing software tools to improve the productivity of working and decision making time, and (iv) assist and guide DSS practitioners in improving their core knowledge of effective decision support. This process will be enhanced by continued developments in Web-enabled tools, wireless protocols, and group support systems, which will expand the interactivity and pervasiveness of decision support technologies.

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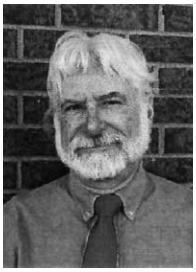

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