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Human-Computer Partnership in Decision-Support Systems: Some Design Guidelines

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Abstract

The design of useful human-computer collaborative decision-support systems requires some understanding of the behavioral and organizational characteristics of human problem solving practices. This paper identifies the principal areas in which computer-based decision making assistance is particularly attractive and critically examines several human problem solving traits that may not be appropriate for direct emulation in the computer-assisted environment. In particular, the author examines the manner in which emotions and hierarchical leadership structures could unnecessarily inhibit the realization of the full potential of a human-computer partnership. Finally, a number of guiding principles are proposed for the design of computer-based decision-support systems.

The Nature of Complex Problems

Decision making is a problem solving activity that human beings undertake on a daily basis in all of their endeavors. Although there are many definitions of decision making, depending on the goals, beliefs, and current knowledge of the researcher (Frensch and Funke 1995), it is generally agreed that decision making is a goal-directed activity that involves a wide range of cognitive operations and that the specific process and strategies employed by individual decision makers can vary widely.

The work of the CAD Research Center in this area has been specifically focused on 'complex problems' and computer-based decision systems that are designed to assist, not replace, human decision makers in the solution of these problems (Pohl et al. 1997). We consider the relative level of complexity of a problem to be a primary function of the number and strengths of the inter and intra relationships that exist among internal and external components of the problem, and the degree of uncertainty that surrounds the definition of these components. Typically, complex problems involve many strong relationships among internal components as well as important dependencies on external factors. The external factors are often determined by events, the cause of which may be unrelated to the problem situation. For example, in planning a new production line an industrial engineer may have to consider not only the many variables and their interrelationships that impact the actual manufacturing process (e.g., product design, material supplies, labor, space, availability of plant and equipment, etc.) but also higher level considerations such as internal and external company relationships, governmental interference, and global economic fluctuations that are largely unrelated to the manufacturing problem and yet may have serious impact on its successful solution.

A more specific example of the dependency on external factors is a fairly common occurrence in the transportation field. Cargo specialists may spend up to two man-days to design a cargo load plan for a ship, a complex undertaking that involves many interrelationships among issues ranging from the trim and stability constraints of the vessel, hazardous material segregation requirements, lift capabilities, to loading sequences and stow area accessibility restrictions. External dependencies include the availability of port facilities (e.g., mobile port cranes, electrical lighting for nighttime loading operations, etc.), port traffic conditions that may impact the movement of cargo from staging areas to the pier, labor relations that will influence loading operations, and the arrival condition of the vessel to be loaded. The latter can vary significantly from the expected. Such variations may range from the inoperability of specific ship equipment (e.g., onboard cranes) to the amount and actual location of pre-loaded cargo. It is even possible that the vessel that arrives at the port is not the vessel that was considered during the planning stage. The factors that may have forced a change in vessels are likely to be quite independent of the internal problem conditions. For example, the original ship may have broken down in transit, or it may have been required for other purposes that took precedence for reasons unrelated to either the destination of the cargo or the purpose of the planned loading operation.

As shown in this example, uncertainty in complex problems extends beyond the lack of definition of the individual problem elements, such as hazardous material considerations and stow area accessibility, to the relationships of these elements to each other and external factors (e.g., replacement of the expected vessel with another vessel). In other words, the dynamic information changes that are characteristic of complex problems tend to modify, delete and create new relationships among both the internal elements and the external dependencies of the problem situation. Even a relatively small change in one element can trigger a series of major relationship changes that may essentially restructure the entire problem. This interconnectedness of complex problem situations poses particular difficulties to the human cognitive system, because it forces the decision maker from the normal sequential paradigm into a parallel reasoning process.

Heightened expectations of quality, accuracy, execution speed, and responsiveness to dynamically changing conditions, are increasingly challenging the capabilities of human decision makers in the many complex problem situations that they face in their varied endeavors. It is therefore not surprising that mankind should be looking more and more to technology in the form of computer-based decision-support systems, for assistance. Such assistance would appear to be appropriate and welcome in at least the following functional areas:

1. To provide access to factual data that describe past and present conditions of dynamically changing aspects of the problem situation.

2. To provide access to relatively static reference information (e.g., cost rates, equipment characteristics, etc.).

3. To provide access to existing knowledge and specialized expertise in domains that are relevant to the problem situation. This knowledge may range from standard practices and procedures (i.e., prototype knowledge-bases (Gero et al.1988, Rosenman and Gero 1993, Pohl et al. 1994 and 1988)) to rule-based sequences and strategies that are commonly applied by human experts to similar problem conditions.

4. To assist in the analysis and fusion of information derived from multiple sources for purposes of establishing and maintaining an accurate view of the current state of the problem (e.g., 'situation awareness' in the military environment).

5. To alert the human decision maker to possible conflicts and transgression of boundaries (i.e., violations), based on parameters that may be modified from time to time.

6. To propose alternative solution strategies and identify opportunities for pursuing specific directions.

7. To provide explanations of how and why particular recommendations and conclusions were generated by the components of the decision-support system.

8. To learn from the interactions between the human decision maker and the decision-support system the methods and strategies that the former employs in particular problem situations, and to be able to apply these methods and strategies in the absence or on the instructions of the human decision maker.

The human decision maker brings a complex interplay of many cognitive, motivational, personal, and social factors into the human-computer partnership. Most of these factors are poorly understood, being based on neuro-physiological, biological and behavioral processes that are still largely undeciphered. This requires a great deal of flexibility to be built into the user-interface so that the human-computer partnership can evolve in directions and capabilities that cannot be predetermined at the outset.

The Influence of Intuition and Emotions

The ability to analyze problem situations, reason about solution strategies, and develop one or several alternative courses of action is a fundamental human cognitive skill. This skill has and will continue to evolve as human beings interact with their environment and challenge themselves to understand, predict and control phenomena and events of increasing complexity.

In this environment complexity is a function of the many interrelationships that influence the nature and behavior of the factors that we identify as being pertinent to a given situation. In fact, the process of making decisions is mostly concerned with unraveling these interrelationships, a task that is pervaded by difficulties. First, there is a need for establishing some solution objectives to provide a direction for determining priorities and an orderly sequence of actions. However, the ability to establish objectives presupposes at least some level of understanding of the problem situation. In other words, at least the vestige of a conceptual solution, even if only in terms of an intuitive feeling about the kind of solution that is likely to eventuate, will be formed by the decision maker during the earliest stages of the solution process. The existence of this conceptual solution is both advantageous and disadvantageous. An early conceptual solution is helpful and arguably an essential prerequisite for defining the framework within which exploration of the problem situation and the decision making process at large, will proceed. Without such a framework, in the realm of spontaneous, unsystematic exploration of aspects of the problem, the human cognitive system tends to perform unevenly and unpredictably at best.

While there is much historical evidence that the early formulation of a conceptual solution can be the decisive factor in the realization of a timely final solution, there are also outstanding examples to the contrary. Early commitment to a solution path can introduce biases and misconceptions that will lead to contrived solutions that become weaker and weaker as more and more information about the problem situation becomes available. The decision makers are faced with a dilemma: discard the original concept; or, modify an increasingly flawed concept to bring it into closer alignment with the perceived situation. Political and emotional factors from both outside and within the problem solving team will inevitably emerge to fuel the dilemma. A well known example of such a problem situation was the insistence of astronomers from the 2nd to the 15th Century, despite mounting evidence to the contrary, that the heavenly bodies revolve in perfect circular paths around the earth (Taylor 1949). This forced the astronomers to progressively modify an increasingly complex geometric mathematical model of concentric circles revolving at different speeds and on different axes to reproduce the apparently erratic movement of the planets when viewed from earth. Neither the current scientific paradigm nor the religious dogma of the church interwoven within the social environment allowed the increasingly flawed conceptual solution of Ptolemaic epicycles to be discarded. Despite the obviously extreme nature of this historical example, it is worthy of mention because it clearly demonstrates how vulnerable the rational side of the human cognitive system is to emotional influences.

This does not mean that it would be best to strive to remove the human element altogether from decision making systems. On the contrary, particularly in complex problem situations where there tends to be a significant element of uncertainty, human intuition and emotions are not only desirable but often necessary ingredients of a successful outcome. In any case, for valid reasons, human beings are unlikely to trust themselves completely to the decisions made by machines for many years to come, if ever.

A second difficulty that faces problem solvers as they attempt to identify interrelationships, is their inability to fully define the problem. The problem situation is likely to include factors that are unknown at the time when a solution is desired. This means that parts of the problem are not understood and in particular, that the relationships among these parts and the known parts of the system cannot be explained. Still worse, these unknown factors will influence other apparently 'known' relationships with misleading results. In other words, the decision makers may believe that they understand certain relationships but are in fact misled by the influence on these relationships of other unknown factors. One can argue that it is an intrinsic characteristic of complex problems that they are never fully defined, nor are they ever fully solved, because they constantly mutate as the issues and forces that feed them change.

The Role of Leadership

Historically, in the field of management, decision making has been exercised within a framework of hierarchical authority. It was held, and this continues to be a somewhat fundamental notion in corporate, government and military organizations, that important decisions can be made only by persons that have the authority to make such decisions. This authority is typically vested in position, rank, and ownership, on the a priori assumption that knowledge and problem solving abilities are demonstrated prerequisites of persons attaining such stature.

On closer examination this would appear to be a rather simplistic and limiting view of the real world. This notion of decision making places an emphasis on process with the objective of exercising control over both the contribution of the participants and the tempo of the problem solving activities. It implies a deep-seated fear that errors in judgment introduced at the lower levels of the hierarchy can easily and decisively mislead the general direction of the solution path. It further suggests that the decision making process itself should be hierarchical in nature. Neither of these contentions would appear to be valid. First, due to the continuous information changes that are characteristic of complex problems, there is a need to maintain a high level of responsiveness and openness. While the information changes may enter the system from any direction, they are more likely to be detected first at the operational levels and then percolate through to the management levels. However, management has a tendency to suppress these changes when they negate or interfere with the current view of the situation or run counter to a predetermined course of action.

Second, the hierarchical structure itself seriously constrains the initiative and contribution potential of the lower levels. Yet these operational levels are normally closest to the source of the information changes that drive the decision making process and are therefore in a good position to interpret and judge the relevancy of their observations. Third, a hierarchical decision making process is by its very nature designed to control the vertical flow of information. The information channels are typically laid out in pipeline fashion on the assumption that the information flow will be progressively filtered and reduced in volume toward the upper echelons of the pyramid. This is necessary to avoid communication bottlenecks at the highest level where the decisions will be made. Unfortunately, in practice, the opposite usually occurs. For example, during military operations commanders tend to be overwhelmed by the shear volume of information that competes for their attention. The lower levels, being mainly authorized to collect and pass on information rather than analyze and interpret what they collect, will be reluctant to exercise initiative in case their actions will contravene the chain of command.

In this environment information is viewed as a commodity that is 'owned', to be made available on a limited basis typically only when the owner is directed to do so. Under these circumstances information tends to flow: upward, mostly on request and when the owners feels that their objectives will be served without jeopardizing their status and position in the hierarchy; downward, based almost exclusively on directions and authorizations received from above, mostly in support of execution orders; and laterally, within a network of domain specific activities that is often governed predominantly by informal relationships. Clearly in this model the information flow is severely restricted by the organizational structure. The hierarchical model places paramount importance on organizational leadership, on the assumption that the problem exists mainly for the organization and that the problem solving objectives are therefore subservient to the objectives of the organization. In fact, this assumption is difficult to defend. Usually organizations, whether commercial, government or military, exist for the purpose of serving and/or protecting the welfare and interests of others. It therefore follows that the objectives of the organization should be subservient and adaptable to the needs of the problem situation. The structural notions of organizational leadership and information ownership are relevant to the problem situation only to the extent that they facilitate the solution of the problem.

More relevant to decision making in complex problem situations is the notion of *situational leadership*. The need for this kind of leadership arises whenever any of the participants in a problem solving task see an opportunity for action that will accelerate the completion of their own tasks and/or contribute to the tasks of others. In this respect situational leadership assumes a non-hierarchical cooperative operational structure in which the participants collaborate freely within the existing organizational levels. Under these circumstances the purpose of organizational leadership is to support and not to dictate the problem solving process; to remove obstacles and empower the individual problem solvers, rather than control their participation and the tempo of their contributions. In particular, the role of the organizational leadership is to prevent anarchy by guiding the situational leaders toward consensus. Naturally each situational leader cannot be the sole judge as to his or her contributions to the tasks of others. However, situational leadership is akin to initiative and should be encouraged to occur at any node of the problem system regardless of the organizational position or level of the person exercising the initiative. It is a spontaneous response to the current state of the problem, as viewed from a particular node, that maximizes concurrent problem solving activities.

Problem solving is a cooperative activity which dynamically develops its own supportive structure in direct response to the current needs, restrictions and opportunities of the problem system. To constrain this decision making activity within the rigid framework of an hierarchical organizational structure inhibits those human capabilities, such as exploration, experimentation, initiative and intuition, that have been found to be among the most effective problem solving skills. Typically, the evolving structure assumes a flattened network configuration with both nodes and inter-node communication channels appearing and disappearing spontaneously, driven almost entirely by the changing context of the problem situation. In this network the relative strengths of relationships and the relative importance of nodes changes readily in response to factors that are largely independent of any predetermined organizational leadership structure. Schmitt (1997), in discussing maneuver warfare, presents strong arguments in favor of asynchronous military operations in which the various components of an operation are not synchronized to occur in a predetermined order (i.e., in unison). He presents the example of a soccer team, "... 11 players, each with assigned responsibilities but acting independently..." as the situation on the field offers and demands. While there are preset plays and team strategies "...the players react individually to the ball, and yet somehow the result is that they manage to work together as a team".

Guiding Principles for the Design of Decision-Support Systems

Based on these comments and our experience with the design and implementation of decision-support systems over the past decade, we have identified the following general guiding principles. These evolving principles have and will continue to serve as a framework for most of the work of the CAD Research Center and are therefore reflected to some degree in all of the systems that we have built to date (i.e., ICADS (Pohl et al. 1989); ICODES, FEAT and CIAT (Pohl et al. 1997); KOALA (Pohl 1996)).

Principle 1: Emphasis on Partnership

A successful decision-support system is one that assists rather than replaces the human decision maker. Human beings and computers are complementary in many respects. The strengths of human decision makers in the areas of conceptualization, intuition and creativity are the weaknesses of the computer. Conversely, the strengths of the computer in computation speed, parallelism, accuracy and the persistent storage of almost unlimited detailed information are human weaknesses. It therefore makes a great deal of sense to view a decision-support system as a partnership between human and computer-based resources and capabilities. Automation should be restricted to the monitoring of problem solving activities, the detection of conflicts, and the execution of evaluation, search and planning sequences.

In this partnership a high level of interaction between the user and the computer is a necessary feature of the decision-support environment. It provides opportunities for the user to guide the computer in those areas of the decision making process, such as conceptualization and intuition, where the skills of the user are likely to be far superior to those of the computer. Particularly prominent among these areas are conflict resolution and risk assessment.

Principle 2: Cooperative and Distributed

Complex problem environments normally involve many parties that collaborate from widely distributed geographical locations and utilize information resources that are equally dispersed. The decision-support system can take advantage of the distributed participation by itself assuming a distributed architecture. Such an architecture typically consists of several components that can execute on more than one computer. Both the information flow between these components and the computing power required to support the system as a whole can be decentralized. This greatly reduces the potential for communication bottlenecks and increases the computation speed through parallelism.

Another advantage of the distributed approach is the ability to modify some components of the system while the system as a whole continues to operate with the remaining components. Similarly, the malfunction or complete failure of one component does not necessarily jeopardize the entire system. This is not so much a matter of redundancy, although the distributed architecture lends itself to the provision of a high degree of redundancy, but rather a direct result of the physical independence of the components. While the components may be closely integrated from a logical point of view they can operate in their own autonomous physical environment.

Principle 3: **Open Architecture**

The high degree of uncertainty that pervades complex problem environments extends beyond the decision making activity of the collaborating problem solvers to the configuration of the decision-support system itself. The components of the system are likely to change over time, through modification, replacement, deletion and extension. It should be possible to implement these changes in a seamless fashion through common application programming interfaces and shared databases.

Principle 4: **Tools, not Solutions**

The decision-support systems should be designed as a set of tools rather than as solutions to a predetermined set of problems. The indeterminate nature of complex problems does not allow us to predict, with any degree of certainty, either the specific circumstances of a future problem situation or the precise terms of the solution. Under these circumstances it is far more constructive to provide tools that will extend the capabilities of the human decision maker in a highly interactive problem solving environment. In this sense a tool is defined more broadly than a sequence of algorithms, heuristics or procedures that are applied largely on the direction of a user. Tools can be self-activating, be capable of at least semi-autonomous behavior, and cooperate with each other and users in requesting and providing services.

Principle 5: **High Level Internal Representation**

The ability of a decision-support system to have some level of understanding of the meaning of the information it processes is the single most important prerequisite for a cooperative and collaborative problem solving environment. A high level representation of the real world objects that define the problem system forms the basis of the interactions between the users and the system and, also, the degree of intelligence that can be embedded in its components. For example, it is virtually impossible to build a useful computer-based tool that can provide meaningful assistance to a military commander in the analysis of the physical battlefield if the battlefield terrain is represented in the computer in terms of ‘x,y’ coordinates and pixels. To the commander the battlefield consists of real world objects, such as mountains, roads, rivers, trees, observation posts, buildings, and so on. Each of these objects has attributes that determine its behavior under certain conditions. These semantic descriptors form the basis of collaboration among human problem solvers, and are likewise the fundamental unit of communication in a computer-based decision-support environment.

Principle 6: Embedded Knowledge

The decision-support system should be a knowledge-based system. In this context knowledge can be described as experience derived from observation and interpretation of past events or phenomena, and the application of methods to past situations. Knowledge bases capture this experience in the form of rules, case studies, standard practices, and typical descriptions of objects and object systems that can serve as prototypes. Problem solvers typically manipulate these prototypes through adaptation, refinement, mutation, analogy, and combination, as they apply them to the solution of current problems.

Principle 7: Decentralized Decision Making

The decision-support system need not, and should not, exercise centralized control over the decision making environment. Much of the decision making activity can be localized. For example, components of the system (e.g., mentor-agents) that are responsible for pursuing the interests of real world objects, such as soldiers in military applications and technical and management personnel in commercial and industrial applications, can achieve many of their objectives through service requests and negotiations that involve only a few nodes of the problem system. This greatly reduces the propensity for the formation of communication bottlenecks and at the same time increases the amount of parallel activity in the system.

The ability to combine in a computer-based decision-support system many types of semi-autonomous and autonomous components (i.e., agents), representing a wide range of interests and incorporating different kinds of knowledge and capabilities, provides the system with a great deal of versatility and potential for problem solving to occur simultaneously at several levels of granularity. This is similar to human problem solving teams in which individual team members work concurrently on different aspects of the problem and communicate in pairs and small groups as they gather information and explore sub-problems.

Principle 8: Emphasis on Conflict Identification

The decision-support system should focus on the identification rather than the automatic resolution of conflicts. This notion gains in importance as the level of complexity of the problem system increases. The resolution of even mundane conflicts can provide subtle opportunities for advancing toward solution objectives. These opportunities are more likely to be recognized by a human decision maker than a computer-based agent. The identification of conflicts is by no means a trivial undertaking. It includes not only the ability to recognize that a conflict actually exists, but also the determination of the kind of conflict and the relationships that appear to have precipitated the conflict. Tracing these relationships may produce more progress toward a solution than the resolution of the conflict itself.

Principle 9: **The Computer-User Interface**

The importance of a high degree of interaction between the user(s) and the various components of the decision-support system is integral to most of the principles described here. This interaction is facilitated by two system characteristics: a high level object representation; and, an intuitive user interface. The user interface should be graphical in nature. The human cognitive system excels in pattern matching. Words and numbers require the performance of a translation task that is relatively time consuming, subject to information loss, and carries with it the potential for confusion and misinterpretation.

An on-line help system should be available to both assist the user in the execution of operational sequences and provide explanations of system activities. The latter should include exploration of the recommendations, evaluation results and proposals contributed by the various components (e.g., agents) of the system.

Principle 10: **Functional Integration**

In the past it has been considered helpful, as a means of simplifying complex problems, to treat planning and execution as distinct activities. Under this school of thought the purpose of planning is to clearly define and analyze the problem, and then develop a solution as a course of action that can be implemented during the execution stage. However, as the complexity and tempo of problem solving situations increases, these apparently distinct functional areas can no longer be categorized as discrete operational spheres of activity. They tend to merge into a single integrated functional pool of capabilities from which the human decision maker draws assistance as necessary. In such problem solving situations continuous information changes require constant replanning, even during those phases when the need for action and execution overshadows all other activities.

This is particularly apparent in the military field, but equally relevant in management, marketing and manufacturing situations where changing conditions require the most thorough and carefully laid out plans to be spontaneously reformulated. For example, in military missions the impacts of enemy actions dictate the need for continuous replanning and training during execution. Under these conditions functional integration is essential. Not only must the planning functions be accessible from the same computer system, but they must be able to operate on the same information that applies to the execution functions. Similarly, in the manufacturing fields changing production conditions such as equipment failures and material supply delays may require significant modification of the original design that may border on a complete redesign. These design modifications have to be accomplished while production operations are in progress.

In a distributed, cooperative decision-support system architecture the necessary level of integration has the potential to be achieved, since functional modules and information resources are treated as sharable components. In such a shared environment distributed databases may be accessed by any of the functional components whenever the need arises and the necessary authorizations are available. The ability to switch from one functional mode to another then becomes largely a function of the user interface and does not require the user to move out of the current application environment. In other words, the physical separation of individual computer-based components need not exist at the logical level of the user interface.

Conclusion

In its evolutionary process human society has developed methodological and organizational frameworks for facilitating the decision making process in complex problem situations. The methods have tended to oversimplify the problems so that solutions could be found through the application of largely sequential, decomposition dependent problem solving techniques. The organizational structures that have served as a framework for decision making operations have tended to be strictly hierarchical with an emphasis on maintaining control. These existing paradigms place unnecessary limitations on the effective utilization of new information technologies and, therefore, need to be critically reexamined. Since major changes in human behavior are evolutionary in nature it can be postulated that for the near future the opportunities offered by advances in computer-based information systems will be only partially exploited by human society.

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