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The Role of Information Technology in Emergency Management: Expert System or Cognitive Instrument?

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THE ROLE OF INFORMATION TECHNOLOGY IN EMERGENCY MANAGEMENT: EXPERT SYSTEM OR COGNITIVE INSTRUMENT?

Kim J. Vicente

Abstract. The purpose of the NKA/INF project is to improve the functionality and efficiency of accident and emergency planning by verifying, demonstrating, and validating the possible implementation of advanced information technology. This paper is concerned with the role that such an information system should take. It is argued that the role that has been adopted, that of a classical expert system, may not be the most appropriate, given the characteristics of the problem. An alternative role for the system is proposed, that of a cognitive instrument. This perspective should be able to effectively address the problems of the domain in a manner that will maximize the performance and reliability of the joint human-computer system.

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TABLE OF CONTENTS

1. INTRODUCTION

The purpose of the NKA/INF project is to improve the functionality and efficiency of accident and emergency planning by verifying, demonstrating, and validating the possible implementation of advanced information technology. This paper is concerned with the role that such an information system should take.

2. FORMS OF COMPUTERIZED DECISION SUPPORT

There are many different roles that a computer system for emergency management could take. Table 1 provides a list of some of the general categories of computer support that could be provided. The list is not meant to be exhaustive nor definitive, but merely illustrates the range of alternatives that can be considered for information support. The categories are ordered in increasing order of computational sophistication, or alternatively, in decreasing order of degree of user involvement in the decision making process. The first category represents the case where the computer system serves as a means for communicating data between decision makers. Each user has unlimited access to the available data and no processing of the data is performed. Thus, the locus of decision making control resides entirely with the users, and they must base their decisions on the raw data presented to them via the computer system. This is the most primitive role that information technology could be used for. At the other extreme, category six, we have the case where the entire decision making process is completely automated. In this case, the locus of control resides entirely with the computer; no user involvement is required.

The other four categories represent incremental additions to the baseline case of category one. For instance, in the second category, each user only has access to the information that she needs. Thus, the system filters away the raw data that is extraneous to each user. In the third category, the representation of information is tailored to the user's requirements. Unlike the previous categories which only communicate raw data, in this category, the data that each user needs are processed by the system to provide higher level information about the state of affairs. Thus, the form of the information provided by the system is more appropriate for decision making purposes. In the fourth category, the information system also provides context sensitivity. Thus, the system uses its knowledge about the present state of the emergency, and adapts its data presentation accordingly. As with the other categories, there are many forms that this type of support could take. Typical examples are: withholding the presentation of information if it can be inferred that it is not needed at the present time; bringing the user's attention to a certain problem if it is deemed urgent; using knowledge about logical constraints within the organization to provide a reduced list of action alternatives; providing a different representation of the problem according to current system state. In the fifth category, computer support is provided in the form of an expert system. In this case, the user provides input data into the system, and the system provides recommendations for action or hypotheses about the state of the emergency by accessing its knowledge base of heuristic rules. The final decision concerning what action to take resides with the user. In addition, the system can also provide some form of explanation facility so that the user can know how the system arrived at its conclusion.

Table 1. Categories of Computerized Decision Support for Emergency Management.

Category	Form of Decision Support Provided
1	A means for data communication.
2	A means for filtered data communication.
3	Tailored representation of each user's information needs.
4	Tailored representation with context sensitivity.
5	Expert advice with explanation facility.
6	Fully automated decision system.

2.1 Selecting an Appropriate Role for Computerized Decision Support

Clearly, the choice of the type of computer support that will be provided should be based on many considerations including the reliability of the resulting decision, financial resources, availability of software and hardware, and above all, the characteristics of the problem. We would like to be able to make the most of the possibilities that advanced information systems have to offer. Taking this view to an extreme, the ideal solution would be to automate the entire decision making process. Clearly, this is not possible for obvious technical reasons. However, even if it were possible, there are those who are strongly opposed to any system in which the locus of control resides with the computer (Fitter and Sime, 1980). This points out the importance of considering, not just how good a solution the computer can provide, but also how the role of the computer will affect the human-computer interaction process. Therefore, when deciding which category of computer support is best suited for emergency management, the most important consideration is the interaction between the characteristics of the problem and the selected role that the information system will play. This interaction will determine the quality of the joint human-computer system as a whole, and thus will greatly affect the efficacy of the system. While conceptual in nature, the role that the computer support will take constrains the possible implementations that are to be considered, and thus it will have an important impact on system design. The issue is fundamental yet important.

2.2 The Role That Has Been Chosen for the NKA/INF Project

The goal of the NKA/INF project is to develop a set of guidelines for directions to take in designing an information system for emergency management, and not to actually develop such a system. Consequently, an incremental implementation strategy has been chosen. Thus, as the prototype system evolves, more advanced features will be added on. The approach is described by Berg et al. (1987, p. 24):

> "The implementation strategy chosen is thus a multistage process. The first stage is to establish a basic datastructure to work with and a basic message handling/passing system between centres in the emergency organisation. The next stage will be to build up databases concerning knowledge for each centre and common process data. The third step will take care of the intelligence in the system. That means to implement the inference/reasoning mechanisms the people in the organization use."

After reviewing the relevance of expert system techniques to computerised support systems in emergency management, Berg and Yokobayashi (1986, p. 39) concluded that "In order to implement this system it seems quite obvious that expert system techniques can be applied." Thus, the decision has been made to adopt expert system technology for implementation of the third phase described by Berg et al. (1987).

It is the contention of this paper that, given the characteristics of the problem, expert systems may not be the most appropriate role for an information system for emergency management to take on. In order to avoid any misunderstanding, it is important to note two qualifications to this statement. First, we are referring to what the global role of the information system should be. This does not rule out the possibility of implementing an expert system for a specific function within the overall system, e.g., for diagnosis. Secondly, when we refer to 'expert system' we are referring to the classic expert system approach of which MYCIN is the prototype. The definition of what we mean by 'expert system' will be defined more clearly below.

The remainder of the paper will attempt to provide a convincing argument to back up this statement. The line of reasoning will follow two paths. First, reference will be made to a review paper by Bobrow, Mittal, and Stefik (1986) of XEROX PARC who, based on their extensive experience with such systems, outline the types of problems that expert systems are useful for, and those where expert systems may not be the best alternative. A comparison of the limitations of expert systems with the characteristics of the emergency management problem will support the contention made above. Secondly, a psychological explanation of the limitations of the expert system paradigm for decision support developed by Woods, Roth, and Bennett (1987) will be described. This account will suggest an alternative role for implementing the intelligence in the information system that is more in line with the characteristics of the emergency management problem.

3. LIMITATIONS OF THE EXPERT SYSTEM APPROACH

As mentioned above, Bobrow et al. (1986) provide an excellent review of both the capabilities and the limitations of state of the art expert systems. They begin by stating: "Expert systems are no panacea for achieving the impossible or even the very difficult....Instead, there are a number of fundamental issues and requirements that must be considered" (Bobrow et al., 1986, pp. 881-2). Based on their extensive experience in the area, they then go on to provide a set of guidelines for choosing appropriate problems and developing successful systems. The emphasis is on the fact that the characteristics of the application are the prime factor in determining the success of the expert system. In this section, we will take up some of their guidelines and see how the problem of emergency management measures up to the types of problems they consider appropriate for expert system use.

In general terms, expert system technology is best suited for tasks that are "fairly routine and mundane, not exotic and rare" (Bobrow et al., 1986, p. 886). Compare this with a description of the emergency management problem: "The problem domain of industrial emergency management has a very unstructured nature. The task domain does not exist until an accident has happened" (Rasmussen, 1986, p. 39); "The situation may often be rather complex and unpredictable" (Rasmussen, 1986, p. 48). While this does not preclude the use of expert systems for a specific subset of the information system, the mismatch between the capabilities of the tool and the characteristics of the problem gives reason to seriously reconsider the applicability of the approach.

Another prerequisite for a successful expert system is the availability of a domain expert. "The expert must...understand what the problem is and have actually solved it quite often. It is not enough to have somebody with a theory about how cases like this should be handled or some good ideas about a new way to do things" (Bobrow et al., 1986, p. 887). Again, this description does not compare favorably with the characteristics of emergency management. It is true that there are a group of people who have some general knowledge about how to handle emergencies. But, the fact that the existing knowledge is distributed implies that there are multiple decision makers. This also presents a problem because very little is known about how to create knowledge bases that encompass the knowledge of various experts (Bobrow et al., 1986).

Also, Bobrow et al. (1986, p. 887) warn that "problems that are known to require English-language understanding, complicated geometrical or spatial models, complex causal or temporal relations, or understanding of human intentions are not good candidates for the current state of the art in expert systems." We can compare these characteristics to those of the emergency management domain, as listed in Berg et al. (1987, p. 11). There they describe the problem as being characterized by: uncertain data, dynamic situations, many different types of information sources, and many organizational units. Clearly, emergency management posesses many of the problematic qualities listed by Bobrow et al. (1986). In particular, the requirement for understanding human intentions is critical, since "the individual decision maker will face a larger system including - in addition to the physical problem space - the intentional system formed by the rest of the task force. In the resulting inter-person communication, there will be a need for extensive communication of intentions and goals, unless the roles are very well specified in advance as it is the case in military organizations" (Rasmussen, 1986, p. 48).

The evidence presented so far gives strong reasons to believe that expert systems may not be the most appropriate technology for the emergency management problem. It is interesting to note that the two other existing applications of information technology to this problem domain discussed by Berg and Yokobayashi (1986) are not centred around the expert system approach. In the approach adopted by Kobayashi et al. (1985), the role of computer support is one of information management with access to a common database. An expert system is used, but only for plant status and diagnosis. In the approach taken by Jaske (1985), decision making is supported by simulation models, a geographic database, and map displays. Expert system technology is not part of the effort. Is it a coincidence that expert systems are not the central focus in either of these projects, or is this a reflection of the utility of expert systems for emergency management? Given the evidence reviewed so far, we tend to opt for the latter view. Interestingly enough, after reviewing the state of the art in expert systems, Rasmussen (1986, p. 11) reached a similar conclusion: "From this review, use of expert systems for support of the decision making process on-line seems to be premature. However, AI tools for organization of the distributed data base available to emergency management may be feasible." This last point suggests that it may be possible to design a so-called 'intelligent' decision support system without inheriting the problems associated with the expert system approach.

A potential obstacle to adopting an alternative approach to computerized information support is that the functional requirements of the system may, of necessity, be achievable only through expert systems. To examine whether this is the case, the functional specifications for the system must be examined. Berg et al. (1987) provide a description of both the on-site and the off-site system requirements. For the on-site case,

> "The role of the system is to advise, guide and call the user's attention to the following subjects:
>
> - to reshape and present information needed in different decision-making situations
>
> - when requested: to supply advice and guidance in the emergency operations, call attention to important tasks and dependencies between the organizational units, functions and subprocesses involved

- to estimate the reliability of measurement data

- to assist in the preparation of situation assessments and prognosis reports" (Berg et al., 1987, p. 9).

For the off-site case, the system should:

"- supply each user with only the relevant data

- inform the centres in the off-site emergency organisation of the extent of the accident

- display activities at other centres

- have a common database with a record of events, counteractions, predictions, etc.

- keep a record of messages sent and received by the user via computer links

- contain registers of available resources

- assist each centre in establishing an appropriate organization" (Berg et al., 1987, p. 23).

These specifications result in the information structure shown in Figure 1. If we compare these functional requirements to the different types of information support shown in Table 1, then we see that these specifications can be accomplished by support at level four. In fact, Figure 1 is very similar to the examples of information support that were described for category four. Thus, there are no characteristics inherent in the emergency management problem that make it imperative that an expert system be used.

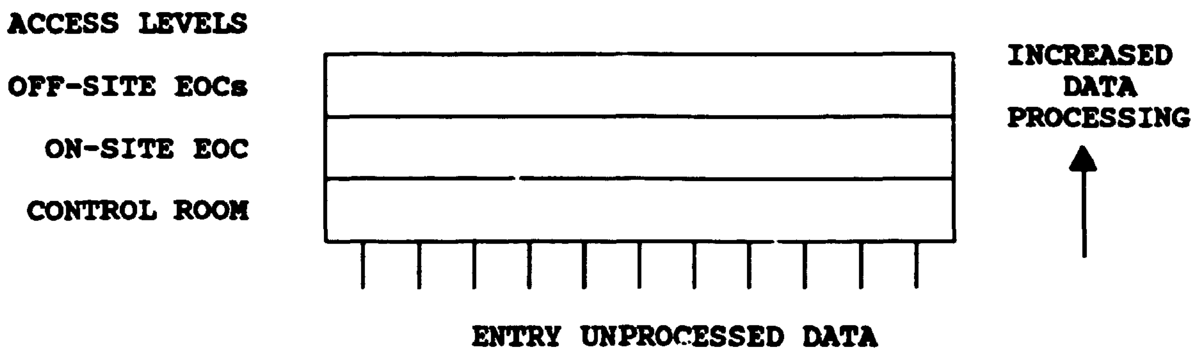

Figure 1. Database hierarchy with a number of access levels. The data are processed and stored in a convergent way. Adapted from Berg and Yokobayashi (1986).

4. AN ALTERNATIVE FORM OF DECISION SUPPORT: COGNITIVE INSTRUMENTS

In the incremental implementation strategy described above for the NKA/INF project, the third stage involved implementing "intelligence" into the information system. While the use of the term intelligence is questionable (see Dreyfus, 1979), the intent is to provide powerful computer support for the decision making process. In the previous section, we have argued that, due to the characteristics of the emergency management problem, expert systems are not the most appropriate means for providing this type of decision support. However, it was also shown that this does not rule out the possibility of implementing other powerful AI tools in order to provide the desired system functionality. This is an important point, for with the enthusiasm with expert systems, it is often overlooked. The choice to adopt AI techniques does not necessarily entail the use of expert systems. There are many other symbolic processing techniques that can be adopted to implement the "intelligence" in the system. In this section, we will first describe a psychological explanation of the perils of expert systems described in the previous section.

Secondly, we describe an alternative means for providing decision support via powerful AI techniques.

4.1 Decision Support Systems as Cognitive Tools

Woods et al. (1987) apply the metaphor of cognitive tools to describe decision support systems (DSS). Given this view, they describe two general approaches that can be followed in designing a DSS. The first of these attempts to design a cognitive tool as a prosthesis, - as a replacement or remedy for a deficiency. The second approach consists of designing cognitive tools as instruments, - as a means for action in the hands of a competent practitioner. Each of these paradigms will be described in turn. The discussion that follows borrows heavily from Woods et al. (1987), but the reader is urged to consult the original reference. In addition to providing a more detailed description of the ideas presented here, it also provides very convincing empirical evidence to support the argument of the present paper.

4.2 Cognitive Tools as Prostheses

The primary design goal with the cognitive prosthesis paradigm is to apply computer technology to produce a stand-alone machine expert that provides the user with a solution to a problem (Woods et al., 1987). The majority of existing expert systems fit into this form of decision support (see category five in Table 1). The interaction process in such systems follows a typical pattern. The user is prompted by the computer to enter data that is relevant to the problem. Thus, one of the user's responsibilities is that of data gatherer. Also, because of the computer's inherent limitations as a problem solver, the user must view the computer's output as advice rather than as a guaranteed solution. Thus, she must decide whether to accept, reject, or modify the machine's output. Consequently, the user will also act as a solution filterer. Usually, a limited form of explanation facility is also available to support this role.

Figure 2 shows the resulting role of the human in the prosthesis paradigm to computerized decision support. It is obvious that the user has a very limited role to play in the system.

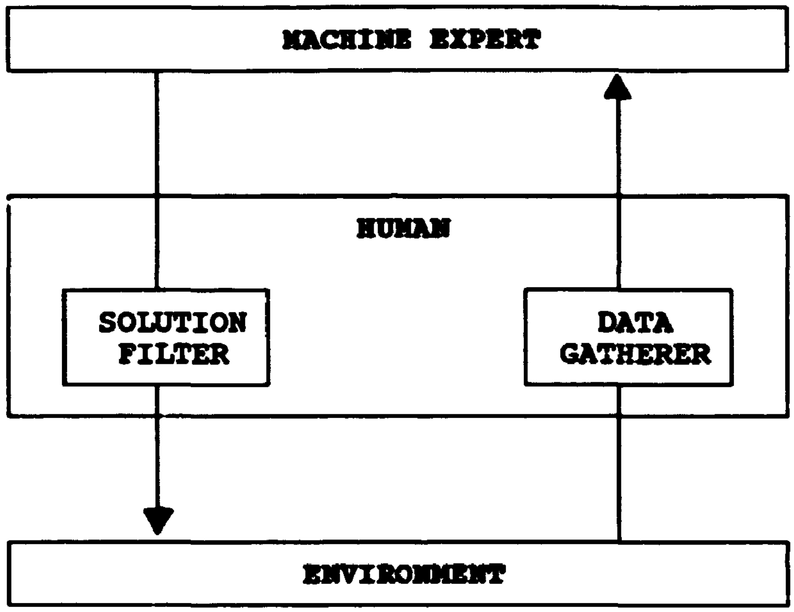

Figure 2. The role of the human in the prosthesis paradigm to decision support. Adapted from Woods et al. (1987).

Of course, it is possible to provide expert assistance without adopting the cognitive prosthesis approach. Indeed, it might be argued that the approach advocated in this paper is not that different from the approach that has been adopted for the NKA/INF project prototype, and that the differences in opinion can be attributed to a different definition of what an expert system is. Unfortunately, this is not the case. If we compare Figure 2 to Figure 3, which shows the control structure that has been proposed by Berg et al. (1987) for the information system for emergency management, it becomes clear that the approach that has been adopted is typical of the cognitive prosthesis approach being described above.

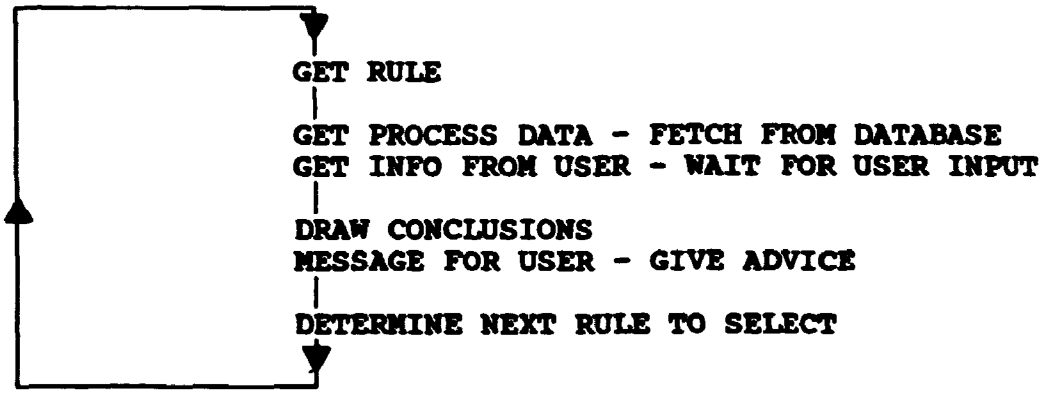

Figure 3. Sequence of the inference engine. Adapted from Berg et al. (1987).

4.3 Cognitive Tools as Instruments

As an alternative to the approach described above, Woods et al. (1987) describe the cognitive tools as instruments paradigm to computerized decision support. The view of humans as adaptive, goal-oriented beings is at the heart of this approach. Thus, expertise is viewed as the adaptive ability to utilize tools to accomplish a given purpose. The resulting implication for DSS is that the user should be allowed to have an active role in the problem solving activity. This is in contrast to the passive role inherent in the cognitive tool as prosthesis view. Thus, the emphasis is on providing the user with powerful tools that allow him to attain his goals, rather than recommending a solution that is usually appropriate.

4.4 Limitations of Cognitive Prostheses

A suitable criteria by which to judge the efficacy of a DSS is its ability to enhance the range of problems that the user can effectively deal with (Woods et al., 1987). To be able to do this, the system must be able to deal with the unanticipated variability that will always be present in real-world applications. This is where the cognitive tools as prostheses paradigm runs into trouble. Because there will always be unanticipated situations which the computer cannot cope with, the user must take on an active role in order to 'rescue' the machine, and thereby ensuring adequate performance. Thus, successful system performance depends on the human's ability to adaptively apply his domain knowledge in order to deal with unforeseen situations. The DSS should be designed in such a way as to provide the user with as much help as possible in carrying out this essential role. The problem with the prosthesis view is that, not only does it not provide support for an active user, but it actually makes it more difficult for the user to take on such a role! The case study described in Woods et al. (1987), in which a typical expert system was evaluated, shows specific instances of the problems associated with the cognitive tools as prostheses approach. Users ran into difficulties when: the problem was outside the computer's competence; adaptation to special conditions were required; and recovery from computer or user errors was necessary. The obvious question is: How can we design DSS that avoid these problems?

4.5 The Cognitive Instrument Alternative

The beauty of having a psychological explanation of the problems asociated with the cognitive prosthesis approach is that it suggests an alternative approach to decision support. The alternative is, of course, the cognitive tools as instruments paradigm. But what exactly does this mean? How does one go about designing cognitive instruments?

A cognitive instrument is viewed as a provider of the information the user needs in order to carry out his problem solving activities effectively. This fundamental reorientation in perspective (tools vs. prostheses) is an important step towards the design of effective DSS. Based on a review of the existing literature, Woods et al. (1987) suggest some strategies for designing DSS as cognitive instruments. For instance, the system could process raw data into forms that are more directly applicable to the questions that the user must answer during decision making (see category three in Table 1). Perhaps the most powerful, but as yet unexplored, form of decision support is to provide users with the ability to conceptualize the problem in various ways (see category four in Table 1). For instance, the computer could enhance the user's ability to: experiment with alternative views of the problem space; predict the effects of different decisions before deciding on which one to take; understand the implications of a concept or an action by making the abstract properties of the problem visible; cope with errors by providing better feedback. Above all, the key to designing DSS as cognitive instruments is to allow the user to retain the capability to use and direct the computer's resources so that full advantage is taken of her domain knowledge and her ability to adapt. This is essential if effective decision support is to be provided.

While the metaphor of DSS as cognitive tools leads to some important implications, the prosthesis/instrument distinction should not be taken too stringently. Obviously, this is a simplification of the problem, but what is important is that it does serve to point out some pitfalls that should be avoided.

A more rigorous account of the differences between the prosthesis and the tool paradigms described above, can be described by comparing a top-down integrated approach to system design (Rasmussen, 1986) with the automation of a single system function via an expert system. The latter is likely to result in a mismatch between the demands of the task and the cognitive capabilities of the user (i.e., the same problems identified with cognitive prostheses). In contrast, the top-down approach aims at designing a resource envelope within which the user can act in normal, as well as unforeseen situations, without violating her resource limitations (i.e., the characteristics associated with cognitive instruments). Within this approach, it is irrelevant whether the DSS is a prosthesis or an instrument. What is important is that the allocation of functions between human and computer results in an adequate resource/demand match for both computer and human. Nevertheless, this view of the situation leads to the same conclusions as those that Woods et al. (1987) arrived at with their cognitive tool metaphor. The latter framework was preferred in order to provide a clearer and more convincing exposition of the ideas.

5. IMPLICATIONS FOR THE NKA/INF PROJECT

The discussion above has shown that the role that the human plays in the decision making process has a major impact on the quality of the decisions that are made. This empirical fact reinforces the importance of the subject of the present paper. The role of information technology in emergency management is, without doubt, a critical issue. This paper has concentrated on pointing out the limitations with the role of computerized support that has been selected for the NKA/INF project (i.e., the expert systems, or cognitive tools as prostheses approach). But rather than limiting ourselves to a critique, we have suggested an alternative solution that is believed to be more in line with the characteristics of the emergency management problem - the metaphor of decision support as a cognitive instrument.

It should also be noted that the suggested approach has the benefit that it capitalizes on the excellent work that has been done on the project to date. Thus, the great effort that has gone into specifying the system's functional requirements (Berg et al., 1987) and detailing the information needs for the preparedness organizations (Holmstrom, 1987) can still be incorporated with the approach being proposed in this paper. In addition, the view of decision support as a cognitive instrument complements the conceptual description of emergency management as a control system provided by Brehmer (1987). Brehmer's work provides a fruitful framework for discussing the goals of emergency management, and the conditions that will affect the possibilities of achieving these goals, while the cognitive instruments metaphor provides recommendations for how the implementation of the DSS should be undertaken. Thus, while Brehmer is concerned with the problem of how to design a system that will cope with the characteristics of the domain (functionality), we are concerned with how to design a system will cope with the characteristics of the human decision makers that will use the system (cognitive coupling). Together, these two conceptual frameworks provide a sound basis for the development of effective decision support, one that will effectively address the problems of the domain in a manner that will maximize the performance of the joint human-computer system.

At the same time, it is also realized that the approach being suggested here is somewhat idealistic, given the advanced state of the project. It is highly unlikely that the expert system approach that has been adopted so far will be abondoned in favor of a top-down design following the cognitive instrument paradigm (the ideal design solution). However, given that an expert system approach will be implemented, there are several things that could be done to support the user in dealing with unanticipated variability. These are listed below.

1. If at all possible, base the rules on first principles, i.e., support knowledge (Clancey, 1983), rather than uncertain inferences (i.e., heuristics).

2. Explicitly represent the entire inference structure, i.e., structural knowledge usually programmed as meta-rules (see Clancey, 1983), and make that knowledge available to the users so that they are aware of the justifications for the lower level rules.

3. Ensure that the strategic knowledge, i.e., the meta-rules that determine which goals to pursue and in what order (see Clancey, 1983), is also explicitly represented and available to the user.

An in depth discussion of the rationale behind these recommendations can be found in Vicente and Rasmussen (1987). These measures will allow the operator to recognize the situations where the system's heuristics are inappropriate, and allow him to cope with the novel events. If the expert system approach is to be adopted, it is imperative that these recommendations be followed in order to ensure effective system performance. At any rate, the pitfalls that may be encountered with the expert system approach, as described in this paper, will be useful points to check for in the evaluation of the prototype. Also, the alternative form of decision support being suggested might provide useful input for the final phase of the project in which recommendations for future consideration will be made.

As a final note, it is important not to misinterpret the motivation for writing this paper. The purpose was not to pointlessly criticize the existing work, but rather to suggest that if the expert system approach is retained for the emergency management information system, problems are likely to result. In developing the argument to back up this claim, it was necessary to carefully review the previous work done on the project. This process was greatly facilitated by the fact that the project participants have provided detailed descriptions of the decisions that have been taken, and the rationale behind these decisions. In fact, it should be stressed that we were struck by the impressive quality of the work that has been done.

The goal of all involved in this project is to provide a set of guidelines that will be instrumental in designing an effective and reliable DSS for emergency management. We hope that this paper will be viewed as a valid contribution to such an effort, rather than as a critique of what has been accomplished until now.

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