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Advanced Decision-Oriented Software for the Management of Hazardous Substances: Part III - Decision Support and Expert Systems: Uses and Users

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ADVANCED DECISION-ORIENTED SOFTWARE FOR THE MANAGEMENT OF HAZARDOUS SUBSTANCES

Part III
Decision Support and Expert Systems: Uses and Users

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This paper was originally prepared as a background paper for a Task Force meeting which was convened to discuss the implications of computer-based expert systems for decision support in this application area and to explore their potential uses in decision making at various levels.

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1. PROJECT SUMMARY DESCRIPTION

1.1 Background

Many industrial processes, products, and residuals such as hazardous and toxic substances, pose risks to man and are harmful to the basic life-support system of the environment. In order to reduce risks to individuals and society as a whole, and to ensure a sustainable use of the biosphere for present and future generations, it is imperative that these substances are managed in a *safe and systematic* manner.

The aim of this project is to provide software tools which can be used by those engaged in the management of the environment, industrial production, products, and waste streams, and hazardous substances and wastes in particular. This set of tools is designed for a broad group of users, including non-technical users. Its primary purpose is to improve the factual basis for decision making, and to structure the decision-making process in order to make it more consistent, by providing easy access and allowing efficient use of methods of analysis and information management which are normally restricted to a small group of technical experts.

In order to design and develop an ***integrated set of software tools***, we build on existing models and computer-assisted procedures. For the casual user, and for more experimental and explorative use, it also appears necessary to build much of the accumulated knowledge of the subject areas into the user interface for the models. Thus, the interface has to incorporate **elements of knowledge-based or expert systems** that are capable of **assisting any non-expert user** to select, set up, run, and interpret specialized software. By providing a coherent user interface, the interactions between different models, their data bases, and auxiliary software for display and analysis become transparent for the user, and a more experimental, educational style of computer use can be supported. This greatly facilitates the design and analysis of alternative policies for the management of industrial risk.

An important element in the overall concept is the direct coupling of large data bases of scientific and technical information with human expertise, of formal algorithmic methods and models with heuristics and human judgement. The expert-systems approach not only allows direct and interactive use of the computer, it is designed as a tightly coupled man-machine system where the vastly different data handling, analysis and judgement capabilities of man and computer are integrated into one coherent framework. For a fuller treatment of structure and design, and the implementation of a demonstration prototype, see Fedra (1985, 1986).

1.2 An Integrated Software System

The model-based decision support system discussed here combines several methods of applied systems analysis and operations research, planning and policy sciences, and artificial intelligence (AI) into one fully integrated software system (Figure 1.1). A demonstration prototype system called IRIMS (Ispra Risk Management Support System) has been developed in the framework of a collaboration between the Joint Research Centre of the Commission of the European Communities (Ispra, Italy) and IIASA's Advanced Computer Applications project.

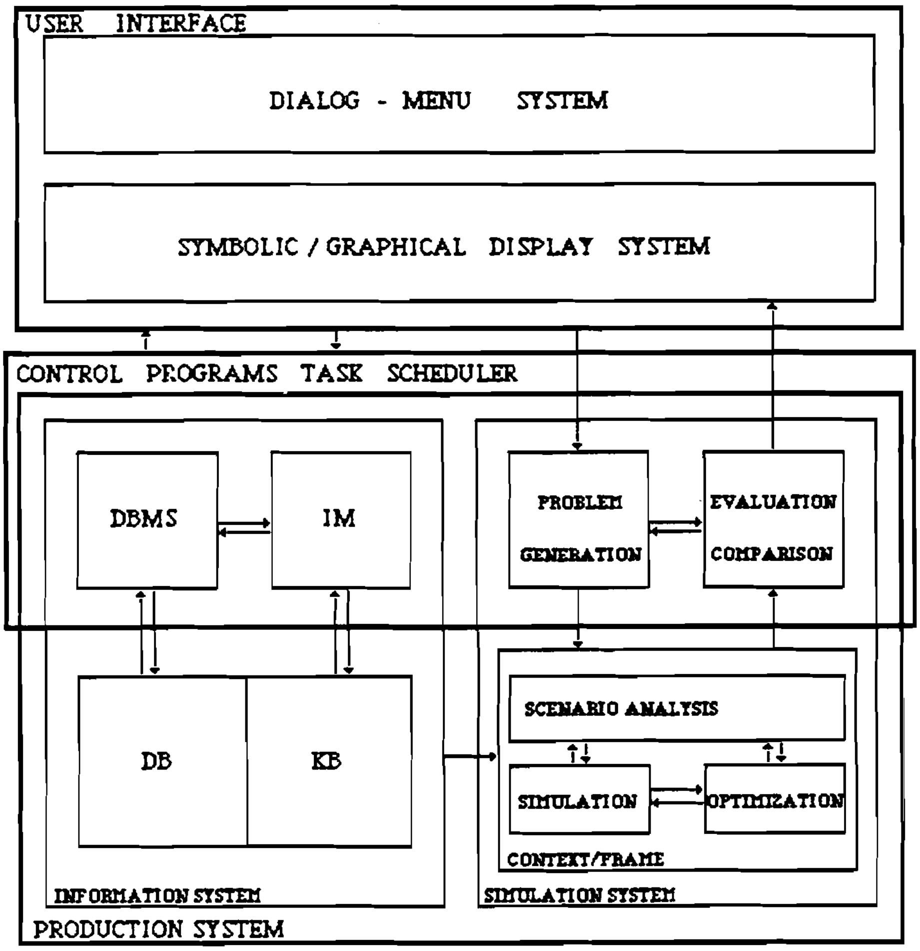

Figure 1.1: Elements of the integrated software system

Conceptually, the main elements of such a model-based decision support system are:

- **an Intelligent User Interface,** which provides easy access to the system. This interface must be attractive, easy to understand and use, error-correcting and self-teaching, and provide the translation between natural language and human style of thinking to the machine level and back. This interface must also provide a largely menu-driven conversational guide to the system's usage (dialog - menu system), and a number of display and report generation styles, including color graphics and linguistic interpretation of numerical data (symbolic/graphical display system);

- **an Information System**, which includes Knowledge and Data Bases (KB, DB), Inference Machine and Data Base Management Systems (IM, DBMS). It summarizes information on application and implementation and contains the most useful domain-specific knowledge.
- **the Simulation System**, which consists of a set of related models (simulation, optimization) which describe individual processes, perform risk and sensitivity analyses on the relationship between control and management options and criteria for evaluation, or optimize plans and policies, given information about the user's goals and preferences, and rules for evaluation.
- **the Decision Support System**, which assists in the interpretation and multi-objective evaluation of modeling results, and provides tools for the selection of optimal alternatives with interactively defined preferences and aspirations.

At this point, it seems appropriate to caution against excessive technological optimism. Computers alone are not going to solve anything, and in fact, much can be said against their all too intimate involvement in human affairs (Weizenbaum, 1976). However, the expanding technology of expert systems could provide a common language and a framework for multidisciplinary cooperation, and stimulate new approaches to the solution of both old and new problems.

2. INTRODUCTION: FRAMEWORK AND APPROACH

Whether they appear as raw materials, as finished products, as by-products, or as wastes, hazardous substances pose risks to man and the environment which must be responsibly managed. Recent accidents have dramatically demonstrated the need for not only better risk management, but also for better, and more comprehensive, management of information (e.g., Hay, 1982; Saxena, 1983; Otway and Peltu, 1985).

The regulatory framework for hazardous substances within the European Community is largely defined by a number of Directives of the Council of the European Communities and the corresponding national legislation which these Directives require (see, e.g., Haigh, 1984; Majone, 1985; Baram, 1985). For example, the so-called Seveso Directive (Council Directive on the major accident hazards of certain industrial activities, 82/501/EEC) specifies that manufacturers must provide the competent authorities with information on the details of substances and processes involved in high-risk facilities. Further, people outside the establishment who might be affected by a major accident must be informed of the safety measures to be taken in the event of an emergency.

The Council Directive on toxic and dangerous wastes (78/319/EEC) calls for a comprehensive system of monitoring and supervision of facilities and operations involving hazardous wastes, specifically mentioning risks to water, air, soil, plants and animals, while also including nuisance due to noise and odors and possible degradation of countryside and places of special interest. More recently, the Directive on the assessment of the effects of certain public and private projects on the environment (85/337/EEC, June 1985) requires comprehensive environmental assessments of projects and installations involving hazardous materials. These assessments are to include consideration of the production and storage of materials such as pesticides, pharmaceuticals, paints, etc. A broad analysis of the direct and indirect effects on people, environment, property and cultural heritage is also foreseen and the evaluation of alternatives is required.

As systems containing hazardous substances have become more technically complex, it has increased the importance of systems interactions and the need to evaluate policy alternatives, and this is reflected in recent legislation. Paradoxically, however, the decreasing cost of computing power seen in the past few years has been exploited more for the creation of sophisticated models of technical subsystems (Vesely et al., 1981; ICE, 1985) rather than for the development of overall systems models that treat the aspects most relevant to risk management: the interactions and tradeoffs amongst production, environmental dispersion, use, transportation, and ultimate disposal.

2.1. The User: A Tentative Profile

The software system discussed here is designed for a broad and diverse group of users, with various backgrounds, and different degrees of involvement with the decision problem at hand. This group also includes non-technical users, who may be experts in one domain or the other of the problem situation, or may be directly concerned, but not have formal training in engineering, toxicology, environmental sciences, systems, risk or decision analysis, or computer sciences. Given the broad scope of the problems addressed by the system, and the large number of scientific, technical, economic, and administrative elements involved, we can safely assume that no likely user or groups of users can possibly have sufficient expertise in all the areas of concern.

So far, we have referred to the 'user' of our system in an abstract sense. However, it is important to add some substance to the term, to make the 'user' someone we can more readily conceptualize and cater to as the project progresses. The following three speculative questions relating to use are proposed to stimulate discussion and to generate further questions:

Who are the likely users? The nature of our system, focusing on interactions and trade-offs rather than detailed subsystem behavior, means that it would be more suitable for strategic planning than for technical design. Consideration of organizational goals (Otway and Ravetz, 1984), suggests use by a regulatory agency or regional planning authority, especially in view of their typical resource constraints and the problem of maintaining technical competence vis-a-vis industry. Industry seems less likely to be interested at the outset, although a system used by regulatory authorities would be likely to attract the attention of industry as well. Could it be used to help develop and evaluate emergency plans? If so, by whom? Could it play a role in post-accident emergency management? Is there a potential application for meeting laws that require industry to inform the public of the risks to which they are exposed and what actions to take in an emergency?

What features will users want? It is generally agreed that user acceptance of management information systems depends upon full user participation in planning and design processes (Keen, 1985). This sort of system being relatively new, and potential user organizations relatively conservative, a user can probably not be found until there is a completed prototype system to demonstrate. This "chicken-and-egg" situation makes it necessary to seek participation of surrogate users to anticipate, as far as possible, the needs of "real users".

A regulatory agency using the system would want enough transparency to defend decisions to public groups, industrial interests, and politicians. They would also want at least qualitative treatment of socio-political issues, such as employment implications of alternatives. Information on the economic implications of regulatory policies for industry would also be necessary for regulatory use, especially since industry often advances economic arguments to oppose regulations. In the case of industrial strategic planning, a thorough analysis of trade-off costs would also be required. What other features would users require?

What are the implications of system use? There are at least four paradigms of decision making and counsel whose implications for interface design should be explored: the artificial intelligence paradigm, the decision analysis paradigm, the operations research paradigm, and the 'cognitive styles' paradigm. For example, expert systems are based on the assumption that formal knowledge can be supplemented by knowledge elicited from experts as an inferential basis for decision making. This implies that experts are able to impart their expertise and, further, that they can make rational use of it – an assumption that the existing world, to some extent shaped by expert knowledge, is basically all right. Decision models, in contrast, usually assume that human beings, including experts, are rather more limited in their abilities to make rational decisions or, at least, that decisions would be better if they were more formally structured.

There is also a dichotomy between the traditional operations research belief that the adviser must be as close as possible to the "problem holder" if his expertise is to be of use and that of the expert systems paradigm. The expert system tacitly assumes that the expert adviser does not need to be in direct contact with the policy maker, but that his expertise can be summarized, condensed and drawn upon when required (Figure 2.1). These, and other, decision and expert advice paradigms should be examined, if the full

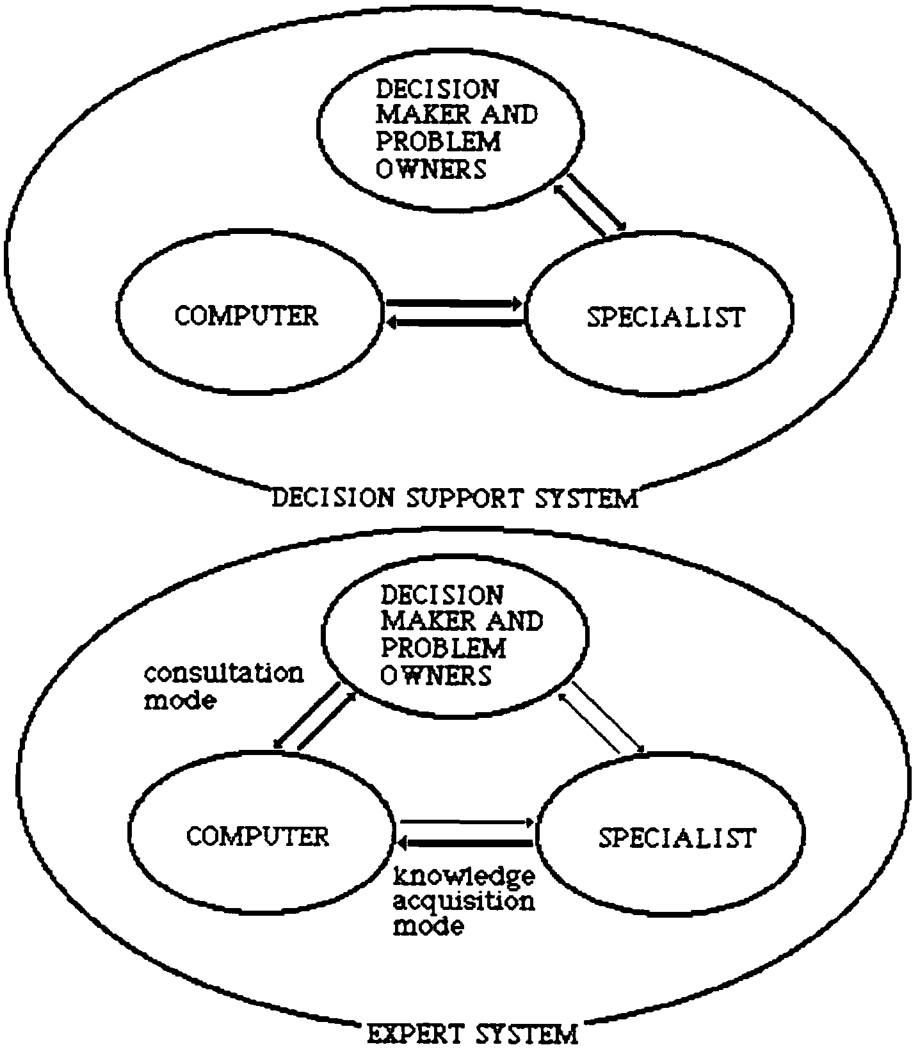

Figure 2.1: The roles of decision makers, specialists and the computer: DSS versus expert systems paradigm.

consequences of system use are to be understood.

2.2 Expert Systems and Model-based Decision Support

Underlying the concept of decision support systems in general, and expert systems in particular, is the recognition that there is a class of (decision) problem situations, that are not well understood by the people involved. Such problems cannot be properly solved by a single systems analysis effort or a highly structured computerized decision aid (Fick and Sprague, 1980). They are neither unique – so that a one-shot effort would be justified given the problem is big enough – nor do they recur frequently enough in sufficient similarity to subject them to rigid mathematical treatment. They are somewhere in between. Due to the mixture of uncertainty in the scientific aspects of the problem, and the subjective and judgmental elements in its socio-political aspects, there is no wholly objective way to find a best solution.

One approach to this class of under-specified problem situations is an iterative sequence of systems analysis and learning generated by (expert or decision support) system use. This should help shape the problem as well as aid in finding solutions. Key ingredients, following Phillips (1984), are the *Problem Owners*, *Preference Technology* (which helps to express value judgements, and formalize time and risk preferences, and tradeoffs amongst them), and *Information Technology*, (which provides and organizes data, information, and models (Figure 2.2)).

There is no universally accepted definition of ***decision support systems***. Almost any computer-based system, from data base management or information systems via simulation models to mathematical programming or optimization, could possibly support decisions. The literature on information systems and decision support systems is overwhelming (e.g., Radford, 1978; Bonczek et al., 1981; Ginzberg et al., 1982; Sol, 1983; Grauer et al. 1984; Wierzbicki, 1983; Humphreys, 1983; Phillips, 1984). Approaches range from rigidly mathematical treatment, to applied computer sciences, management sciences, or psychology.

Decision support paradigms include ***predictive models***, which give unique answers but with limited accuracy or validity. ***Scenario analysis*** relaxes the initial assumptions by making them more conditional, but at the same time more dubious. ***Normative models*** prescribe how things should happen, based on some theory, and generally involve optimization or game theory. Alternatively, ***descriptive or behavioral models*** supposedly describe things as they are, often with the exploitation of statistical techniques.

Most recent assessments of the field, and in particular those concentrating on more complex, ill-defined, policy-oriented and strategic problem areas, tend to agree on the importance of interactiveness and the direct

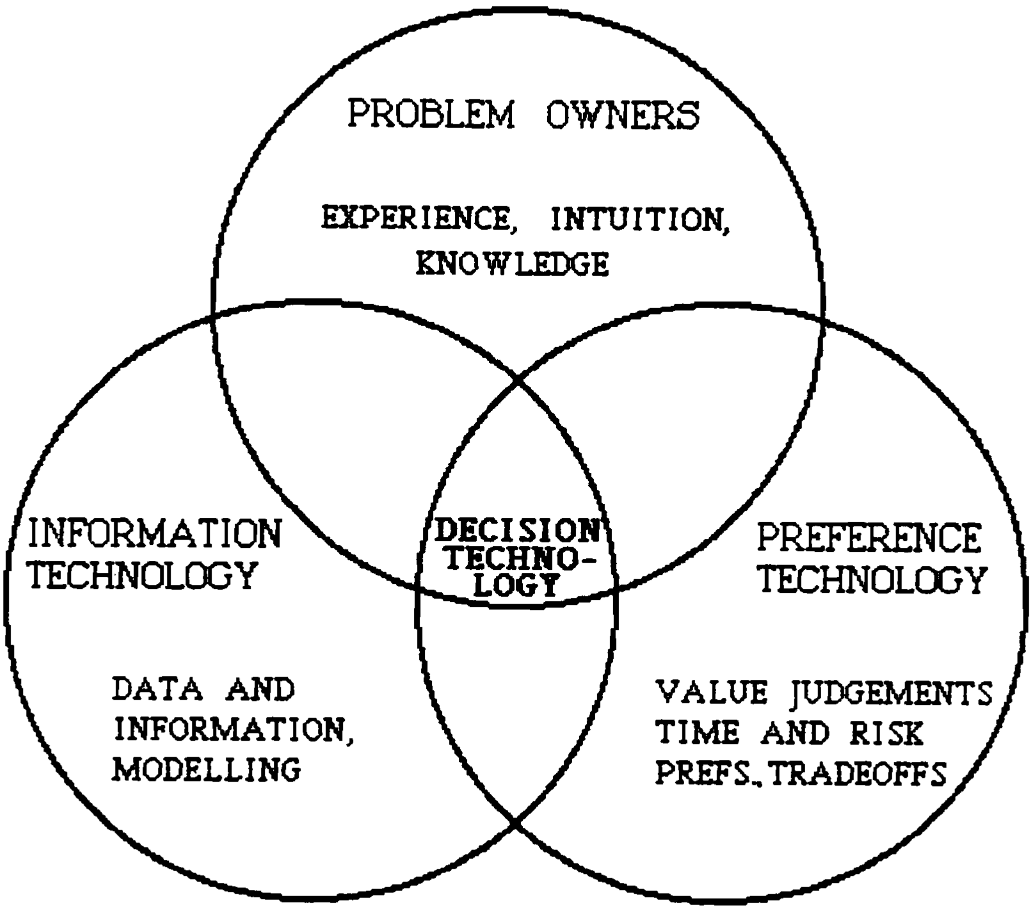

Figure 2.2: The components of decision technology (after Phillips, 1984).

involvement of the end user. Direct involvement of the user results in new layers of feedback structures (Figure 2.3). The ***information system model*** is based on a sequential structure of analysis and decision support (i.e., the relationships shown in the upper part of Figure 2.3, from Radford, 1978). In comparison, the ***decision support model*** implies feedbacks from the applications, e.g., communication, negotiation, and bargaining onto the information system, scenario generation, and strategic analysis.

The realism of formal models is increased, for example, by the introduction of ***Multiattribute Utility*** theory (Keeney and Raiffa, 1976; Bell et al., 1977), extensions including uncertainty and stochastic dominance concepts (e.g., Sage and White, 1984), by multi-objective, multi-criteria optimization methods, and finally by replacing strict optimization, requiring a complete formulation of the problem at the outset, by the concept of satisficing (Wierzbicki, 1983).

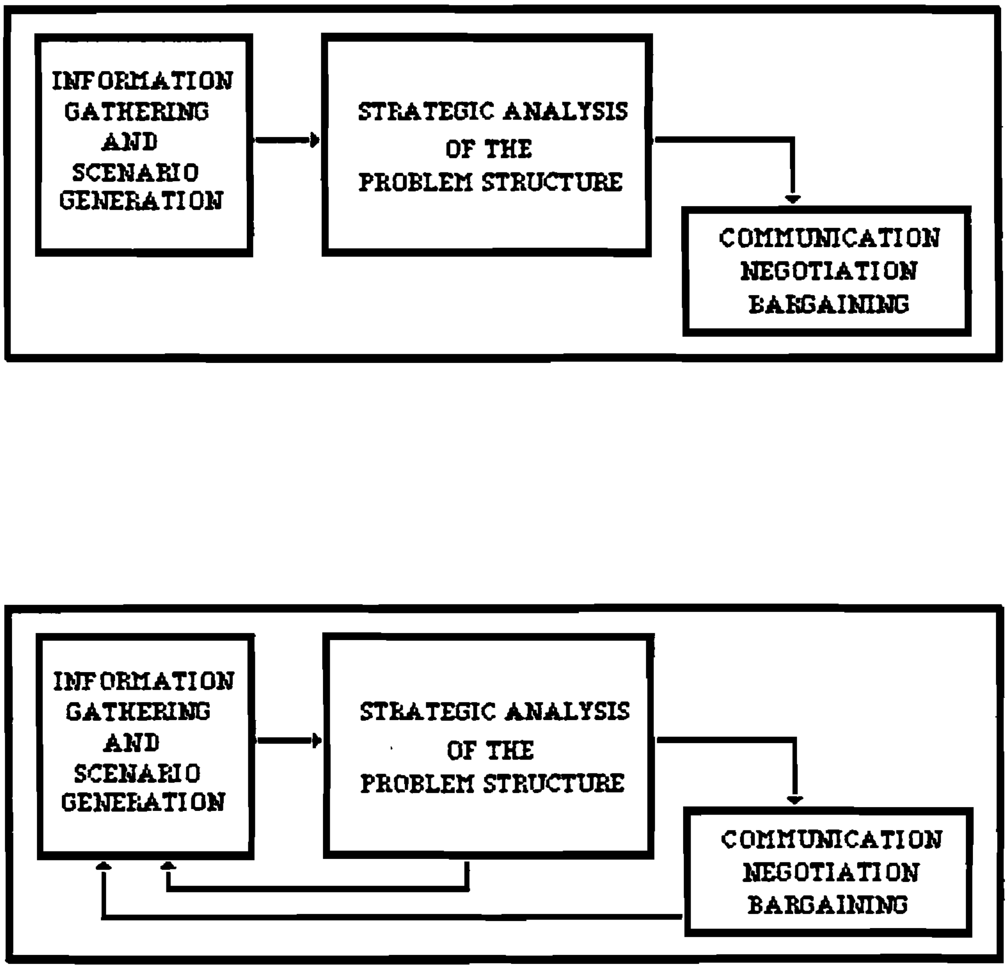

Figure 2.3: Strategic decision problems: information systems versus DSS approach (partly after Radford, 1978).

Another basic development is getting closer to the users. Interactive models and computer graphics are obvious developments here (e.g., Fedra and Loucks, 1985). Decision conferences (Phillips, 1984) are another approach, useful mainly in the early stages for the clarification of an issue. While certainly interactive in nature, most methods involve a decision analyst as well as a number of specialists (generally supposed to be the problem holders). Concentrating on the formulation of the *decision* problem, *design and evaluation* of alternatives, i.e., the *substantive models*, are only of marginal importance.

Often enough, however, the problem holder (e.g., a regulatory agency) is not specialized in all the component domains of the problem (e.g., industrial engineering, environmental sciences, toxicology, etc.). Expertise in the numerous domains touched upon by the problem situation is therefore as much a bottleneck as the structure of the decision problem. Building human expertise and some degree of intelligent judgement into decision supporting software is one of the major objectives of AI.

Only recently has the area of *expert systems* or *knowledge engineering* emerged as a medium for successful and useful applications of AI techniques (see for example, Pearl et al., 1982; Sage and White, 1984; or O'Brien, 1985 on expert systems for decision support). An expert system is a computer program that is supposed to help solve complex real-world problems, in particular, specialized domains (e.g., Barr and Feigenbaum, 1982). These systems use large bodies of *domain knowledge*, i.e., facts, procedures, rules and models, that human experts have collected or developed and found useful to solve problems in their domains.

Typically, the user interacts with an expert system in a consulting dialog, just as he would with a human expert. Current experimental applications include tasks like chemical and geological data analysis, computer systems configuration, structural engineering, and medical diagnosis (e.g., Duda and Gaschnig, 1981; Barr and Feigenbaum, 1981; for a recent overview, see Weigkricht and Winkelbauer, 1986). Expert systems are machine-based intermediaries between human experts (who supply the knowledge in a *knowledge acquisition mode*), and the human user, who seeks consultation and expert advice from the system (*consultation modes*). An important element in the user interface and the dialog with such systems is their ability to guide the user in formulating his problem, and to *explain* the reasoning used by the system.

The system under design combines several methods of applied systems analysis, operations research, planning, policy sciences, and artificial intelligence into one fully integrated software system (Fedra, 1985, 1986). The basic idea is to provide direct and easy access to these largely formal methods and a substantial factual information basis.

2.3 Information Requirements for Decision Support

Given the theoretical framework discussed above, the kind of user we anticipate, and the regulatory background briefly described in the introduction, we can now try to compile or define a set of information requirements for decision support. What are the major characteristics of decision-making processes within the above framework, and what is, or rather should be, the factual and procedural basis (in a decision analysis sense) for these decision processes?

The kind of regulatory decision making described above is characterized by at least three major problems:

- the necessity for making or accepting **trade-offs**;
- the **incommensurability** of the effects weighed in the trade-offs;
- the **uncertainty** or lack of information about the consequences of alternative courses of action.

Based on a report by the Committee on Principles of *Decision Making for Regulating Chemicals in the Environment* (NAS, 1975), the Study Group Report on *Risk Assessment* by the Royal Society (1983), a Brookings Institution Report on *Quantitative Risk Assessment in Regulation* (Lave 1982), and finally the industry's point of view, summarized in the Institution of Chemical Engineers International Study Group Report on *Risk Analysis in the Process Industries* (ICE, 1985), we have compiled, extracted and condensed these wishlists and recommendations into the following specifications for a Decision Support (DS) framework:

- The DS framework should be based on a simplified model (preferably in graphical representation, e.g., a picture, or flow diagram) of the total system of production, distribution, use, and disposal of the chemical. The model should help identify points of economic impact, nature and source of benefits and damages, and possible means of control. This information will provide the basis for specifying alternative control strategies, and the quantification of costs, hazards, and benefits.
- The decision framework should make it possible to identify and present information on a full range of alternatives the decision maker has. Alternative control strategies as well as alternative implementation procedures and schedules should be included.
- The framework should display the data so that all relevant alternatives can be considered together. Other major factors that might influence the decision maker's choice, e.g., legal constraints, previous action, or ease of implementation, should also be identified.
- The framework should make it possible to meet the increased public interest in risk estimates, which are inherently imprecise, and risk management procedures, by supporting open discussions with the aim of achieving a more balanced approach.
- The framework should include all identifiable effects and consequences of alternative actions. This would include social and economic benefits of the chemical's use; its health effects, ecological effects, cost of control, economic impacts (plant closure, unemployment, economic indicators such as regional or national product), enforcement and monitoring costs, and distributional effects (who pays, who benefits).
- The DS framework must ensure that no relevant categories of effects are overlooked. Use of a chemical always involves benefits as well as risks. For example, it may entail health benefits as well as risks; and the benefits and risks might impinge upon different population groups. For example, an insecticide might control infectious disease vectors while having long-term carcinogenic effects after bioaccumulation. The decision maker may also wish to distinguish between risks borne voluntarily with full knowledge, and those borne involuntarily or without knowledge.

- The level of detail to be included in the description of effects should be easily adapted to the decision problem. It is partly determined by the decision maker to the extent that he chooses the time and resources available for study and analysis, and partly by the quality, amount, and availability of data. The level of detail will also vary with the stage of the decision-making procedure in that a brief and quick analysis may be made to screen potential options and then a more elaborate analysis conducted on those options selected for more careful study. The framework should be flexible enough to meet these various needs.
- The framework should facilitate the comparison of major effects resulting from alternative actions and should serve as a convenient basis for the discussion and review of trade-offs. To this end, the results of the analysis may need to be presented in a variety of formats (e.g., verbal, graphical, tabular) and at different levels of detail. The final "briefing version" may only present major effects and major alternatives. However, the most detailed analysis available should be provided as background material so that the decision maker can examine these details if he wishes to.
- The framework and procedures should be flexible enough to meet the demands of different kinds of decisions, at different levels, by different groups of decision makers.
- All effects should be quantified and measured in commensurate terms to the greatest extent possible. Further, the number of incommensurable measures should be as small as possible to simplify the trade-off considerations of the decision maker.
- While quantitative methods are to be used wherever practical and feasible within reason, the apparent certainty of numerical outputs should be carefully interpreted and presented with responsible qualifications.
- The framework should indicate the range of uncertainty and level of ignorance about key pieces of information. If detailed analyses are aggregated or summarized for presentation to the decision maker, information about the degree of uncertainty must be presented.

- All assumptions made by the analyst or implied in the methods used in reducing detailed data to summary or aggregate measures should be made explicit and clearly indicated as such.
- Where uncertainty exists in some key pieces of information, or where assumptions must be made about the relative importance of certain effects, the decision maker should be able to examine the sensitivity of the results to variations in both input data and different assumptions about relationships.
- The framework should make it convenient to determine the value of obtaining further information and specifically what information should be obtained. In other words, it should make it clear that resolving uncertainty (collecting more information) is a relevant choice for the decision maker although it may involve some time and cost. In this way the framework will facilitate the process of continuous review or sequential decision making.
- Key value judgements about weights or values to be assigned to incommensurables should be the responsibility of the decision maker. The presentation of information should make it clear what the key tradeoffs are and facilitate the examination of alternative value judgements by the decision maker.

To be useful and relevant, an information and decision support system should be responsive to the above list of requirements – and quite a few more. However, it is obvious that any computer-based information, decision support or expert system is only one tool in a large arsenal of methods and procedures used for the management of hazardous substances. We do believe, however, that well-designed and sufficiently "intelligent", i.e., flexible, responsive, and knowledge-based systems could be very effective and useful tools indeed.

3. THE PROBLEM AREA: MANAGEMENT OF HAZARDOUS SUBSTANCES

Depending on how one counts and classifies, there are more than 100,000 registered chemical substances, with up to 1000 added to this list every year. A substantial number of these substances are hazardous, or potentially hazardous to man and/or the environment.

Hazardous substances appear as feedstocks, interim or by-products, final products, or wastes of industrial processes; a few hazardous substances are even produced by natural processes.

The major sources of these hazardous substances, that may cause human exposure or environmental contamination, include:

- the use of hazardous substances, i.e., dispersive use of agrochemicals, solvents, paints and lacquers;
- accidental release during the production process, i.e., accidents such as Seveso or Bhopal;
- transportation accidents;
- routine release of wastes, from the production process or from waste treatment and disposal operations.

The dimensions of the problem are also staggering in volumetric terms: About 2 gigatons of waste are produced annually in the countries of the EC, somewhat less than 10% of which is from industrial sources. Roughly 10% of these industrial wastes are classified as hazardous.*) More graphically, this amounts to 20 million metric tons, or a train of roughly 10,000 km length.

The effective management of these wastes calls for:

- a minimization of waste production by process modification and recycling;
- the conversion to non-hazardous forms;
- finally, a safe disposal of whatever is left.

---

*) J. Schneider, JRC, Ispra, 1984. Personal communication. For comparison, the US Chemical Manufacturers Association reports 314 million tons of hazardous wastes (311 million tons wastewater, 3 million tons non-wastewater) treated and disposed in 1983; CMA (1983).

In addition to hazardous wastes, there is a large number of commercial products that are also hazardous. Their production, transportation, and use – before they enter any waste stream – is also of concern. Industrial production processes that involve hazardous raw materials, feedstocks, or interim products, which may reach the environment after an accident, causing direct health risks to man, have to be considered.

As a special category, although implied in the above, transportation of hazardous substances (including, of course, hazardous wastes), must be included in any comprehensive system.

The entire life-cycle of hazardous substances (Figure 3.1), from their production and use to their processing and disposal, involves numerous aspects and levels of planning, policy and management decisions. Technological, economic, socio-political and environmental considerations are involved at every stage of the management of these life cycles, and they involve various levels, ranging from site or enterprise to local, regional, national and even international scales, and over different time scales, from immediate operational decisions to long-term planning and policy problems.

3.1 The Systems View: Comprehensive Assessment

The problems of managing hazardous substances are neither well defined nor reducible to a small set of relatively simple subproblems. They always involve complex trade-offs under uncertainty, feedback structures and synergistic effects, non-linear and potentially catastrophic systems behavior – in short, the full repertoire of a real-world mess. The complexity and ill-defined structure of most problems makes any single method or approach fall short of the expectations of potential users. The classical, mathematically-oriented, but rigid, methods of operations research and control engineering, that require a complete and quantitative definition of the problem from the outset, are certainly insufficient.

While only the combination of a larger set of methods and approaches holds promise of effectively tackling such problems, the subjective and discretionary human element must also be given due weight. This calls for the direct and interactive involvement of users, allowing them to exert

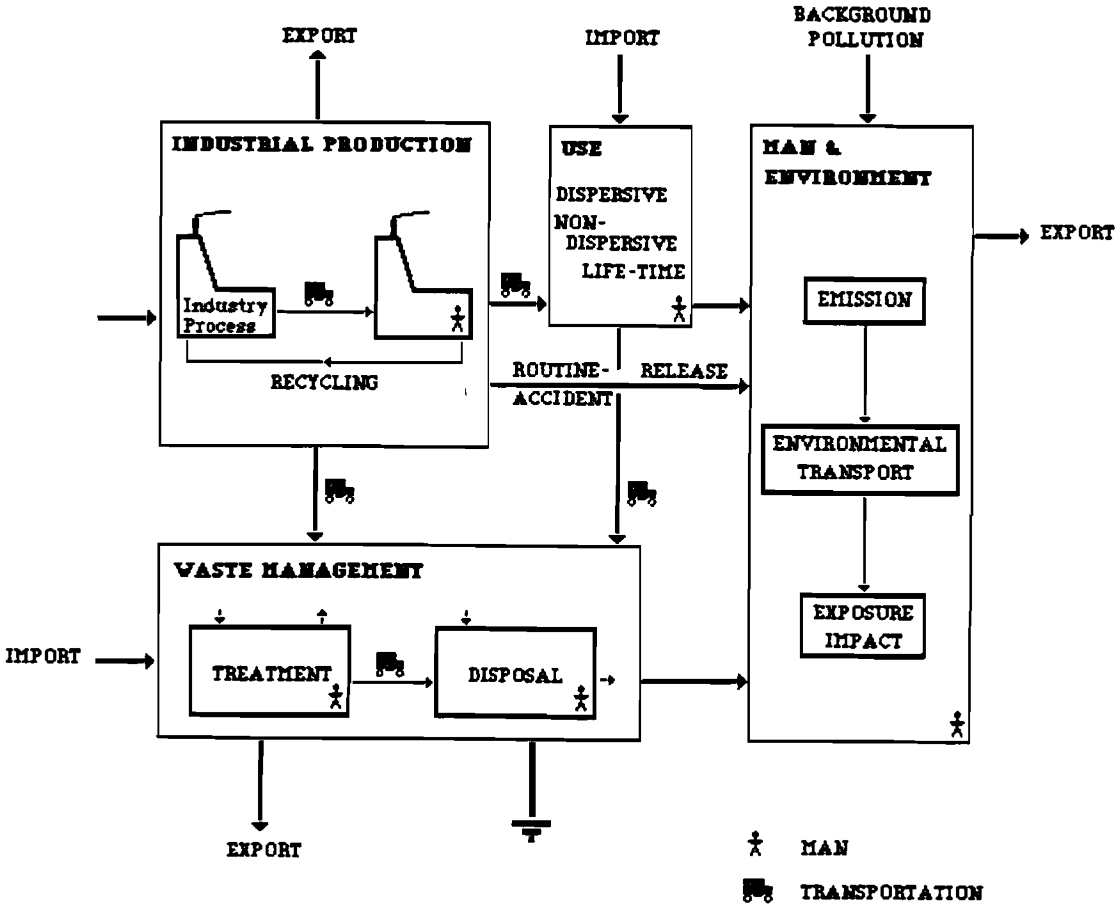

Figure 3.1: Life cycle of hazardous substances: components of the simulation system (from Fedra, 1985)

discretion and judgement wherever formal methods are insufficient.

We are developing an integrated and interactive computer-based decision support and information system within the framework of a Study Contract between IIASA and the CEC's Joint Research Centre (JRC), Ispra. Recognizing the potentially enormous development effort required (e.g., Pollitzer and Jenkins, 1985) and the open-ended nature of such a project, we propose a well-structured cooperative effort that takes advantage of the large volume of scientific software already available. A modular design philosophy allows us to develop individual building blocks, which are valuable products in their own right, and to interface and integrate them in a flexible framework easily modifiable with increasing experience of use.

With the functional and problem-oriented, rather than structural and methodological design of this framework, working prototypes that allow us to explore the potential of such systems can be constructed at relatively low cost and with only incremental effort.

Any comprehensive assessment of the management of industrial risk, and hazardous substances in particular, requires the consideration of technological, economic, environmental, and socio-political factors (Figure 3.2). Every scenario for simulation or optimization, defined interactively with this system, must ultimately be assessed, evaluated, and compared with alternatives in terms of a list of criteria. These criteria, therefore, must include economic, technical, environmental, resource-oriented, and finally socio-political descriptors.

Clearly, only a small subset of these criteria may be expressed in monetary, or even numerical terms. Most of them require the use of linguistic variables for a qualitative description. Using fuzzy set theory, qualitative verbal statements can easily be combined with numerical indicators for a joint evaluation and ranking. In the system design, the use of programming languages like LISP or PROLOG gives the user freedom to manipulate symbols and numbers within a coherent framework.

3.2 Information Management and Decision Support

The sheer complexity of the problems related to the management of hazardous substances and related risk assessment problems calls for the use of modern information processing technology. However, most problems that go beyond the immediate technical design and operational management level involve as much politics and psychology as science.

The software system described here is based on information management and model-based decision support. It envisions a broad and heterogeneous group of users, technical experts as well as decision and policy makers, and in fact, the computer is seen as a mediator and translator between expert and decision maker, between science and policy. The computer is thus not only a vehicle for analysis, but even more importantly, a vehicle for communication, learning, and experimentation.

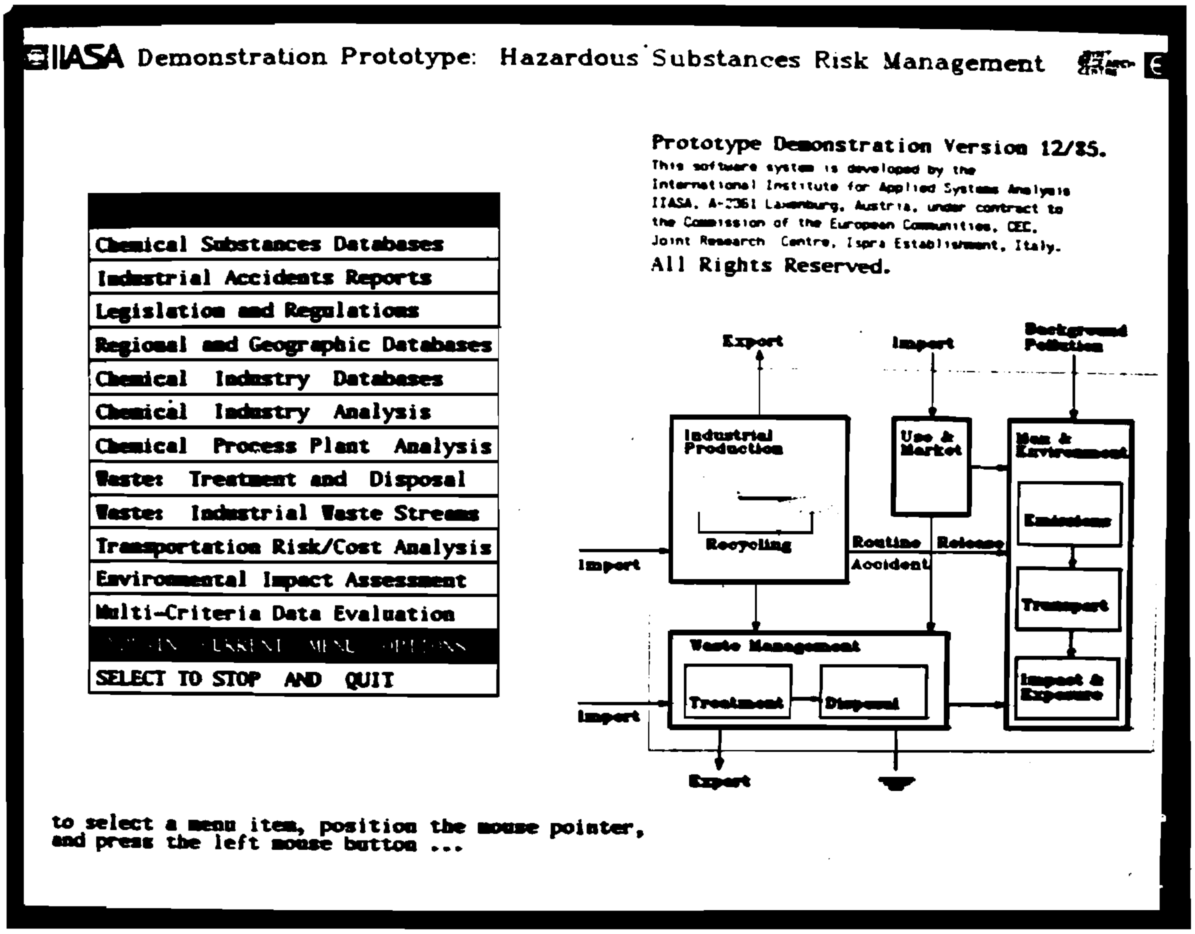

Figure 3.2: The scope of the demonstration prototype system (master menu).

The two basic elements are to supply factual information based on existing data, statistics, and scientific evidence, and to trace the likely consequences of new plans. The framework foresees the selection of criteria for assessment by the user, and the assessment of scenarios or alternative plans in terms of these criteria. The evaluation and ranking is again done partly by the user, where the machine only assists through the compilation and presentation of the information required. Alternatively, it can be done by the system on the basis of user-supplied criteria for screening and selection.

The selected approach for the design of this software system is eclectic as well as pragmatic. We use proven or promising building blocks, and we use available modules where we can find them (Zhao et al., 1985). We also exercise methodological pluralism: any "model", whether it is a simulation model, a computer language, or a knowledge representation paradigm, is by necessity incomplete. It is only valid within a small and often very specialized domain. No single method can cope with the full spectrum of phenomena, or rather points of view, called for by interdisciplinary and truly applied science.

The direct involvement of experts and decision makers shifts the emphasis from a production-oriented "off line" system to an explanatory, learning-oriented style of use. The decision support and expert system is as much a tool for the expert as it is a testing ground for the decision maker's options and ideas.

In fact, it is the *invention* and definition, i.e., the design, of options that is at least as important as the estimation of their consequences and evaluation. For planning, policy and decision making, the generation of new species of ideas is as important as the mechanisms for their selection. It is such an evolutionary understanding of planning that this software system is designed to support. Consequently, the necessary flexibility and expressive power of the software system are the central focus of development.

3.3 Model Integration and the User Interface

From a user perspective, the system must be able to assist in its own use, i.e., explain what it can do, and how it can be done. The basic elements of this self-explanatory system are the following:

- *the interactive user interface* that handles the dialog between the user(s) and the machine; this is largely menu-driven, that is, at any point the user is offered several possible actions which he can select from a menu of options provided by the system;
- *a task scheduler or control program*, that interprets the user request – and, in fact, helps to formulate and structure it – and coordinates the necessary tasks (program executions) to be performed; this

program contains the "knowledge" about the individual component software modules and their interdependencies;
the control program can translate a user request into either:

- a data/knowledge base query;
- a request for "scenario analysis"

the latter will be transferred to

- *a problem generator*, that assists in defining scenarios for simulation and/or optimization; its main task is to elicit a consistent and complete set of specifications from the user, by iteratively resorting to the data base and/or knowledge base to build up the *information context or frame* of the scenario. A scenario is defined by a delimitation in space and time, a set of (possibly recursively linked) processes, a set of control variables, and a set of criteria to describe results. It is represented by
- *a set of process-oriented models*, that can be used in either simulation or optimization modes. The results of creating a scenario and either simulating or optimizing it are passed back to the problem generator level through a
- *evaluation and comparison module*, that attempts to evaluate a scenario according to the list of criteria specified, and assists in organizing the results from several scenarios. For this comparison and the presentation of results, the system uses a
- *graphical display and report generator*, which allows selection from a variety of display styles and formats, and in particular enables the results of the scenario analysis to be viewed in graphical form. Finally, the system employs a
- *system's administration module*, which is largely responsible for housekeeping and learning: it attempts to incorporate information gained during a particular session into the permanent data/knowledge bases and thus allows the system to "learn" and improve its information background from one session to the next.

It is important to notice that most of these elements are linked recursively. For example, a scenario analysis will usually imply several data/knowledge base queries to provide the frame and necessary parameters transparently. Within each functional level, several iterations are possible, and at any decision breakpoint that the system cannot resolve from its current goal structure, the user can specify alternative branches to be followed.

The simulation models of the production system can be configured to describe the comprehensive life-cycle of hazardous substances (Figure 3.1). The major components of the simulation system are:

- the industrial production sector,
- use and market,
- waste management, including treatment and disposal,
- the cross-cutting transportation sector,
- and finally man and the environment.

Each of these major components is represented by several individual models, covering a variety of possible approaches and levels of resolution. Each element of the simulation system can be used in isolation, or it is linked with several others as pre- or post-processors into increasingly larger (sub)systems models (Figure 3.3).

It is also important to note that none of the complexities of the systems integration are obvious to the user: irrespective of the task specified, the style of the user interface and interactions with the system are always the same at the user end.

The user interface is one of the most critical elements for such a large and complex interactive system (Figure 3.4). Our interface design is based on:

- menu-driven conversational interaction, that results in a self-explanatory system that does not require the user to learn any specific command language, but always offers currently available options in a self-explanatory style;

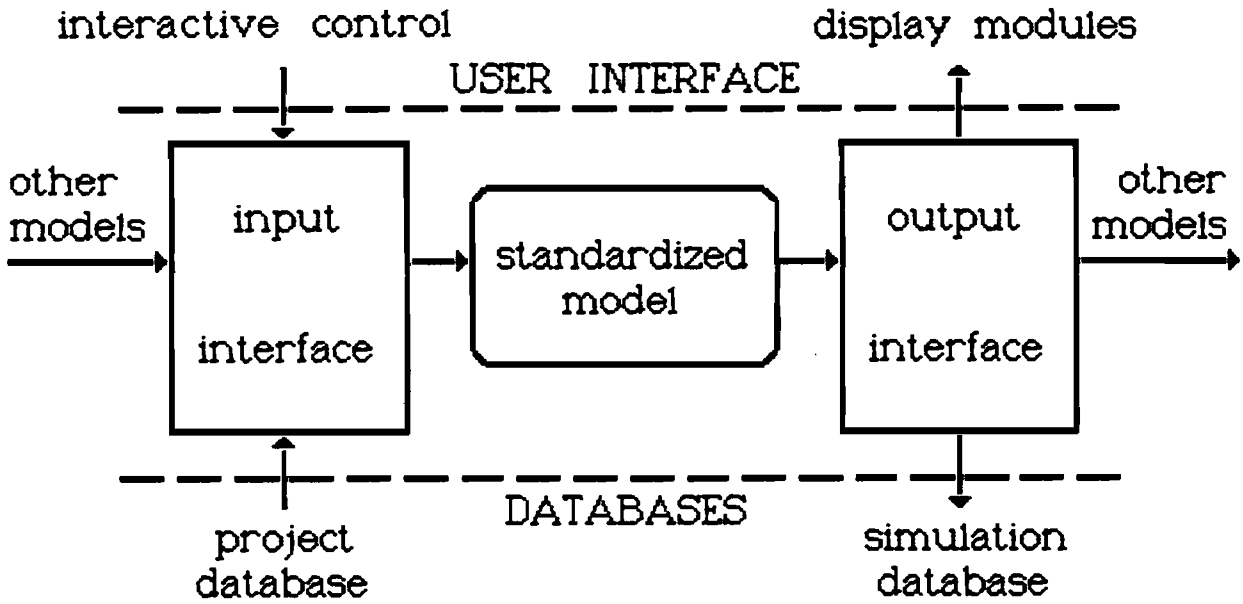

Figure 3.3: Model integration

- input error correction, language parsing, and input feasibility and consistency checking;
- a symbolic style of problem definition, starting from generic cases and default values, that can easily be modified to the user's specific requirement by relative changes and analogies;
- the automatic and transparent selection and configuration of models, estimation of parameters, connection to data bases, or other pre-and post-processors, including the automatic passing of "messages" between processes;
- a context, i.e., current-problem dependent variable structure;
- the use of bit-mapped color graphics;

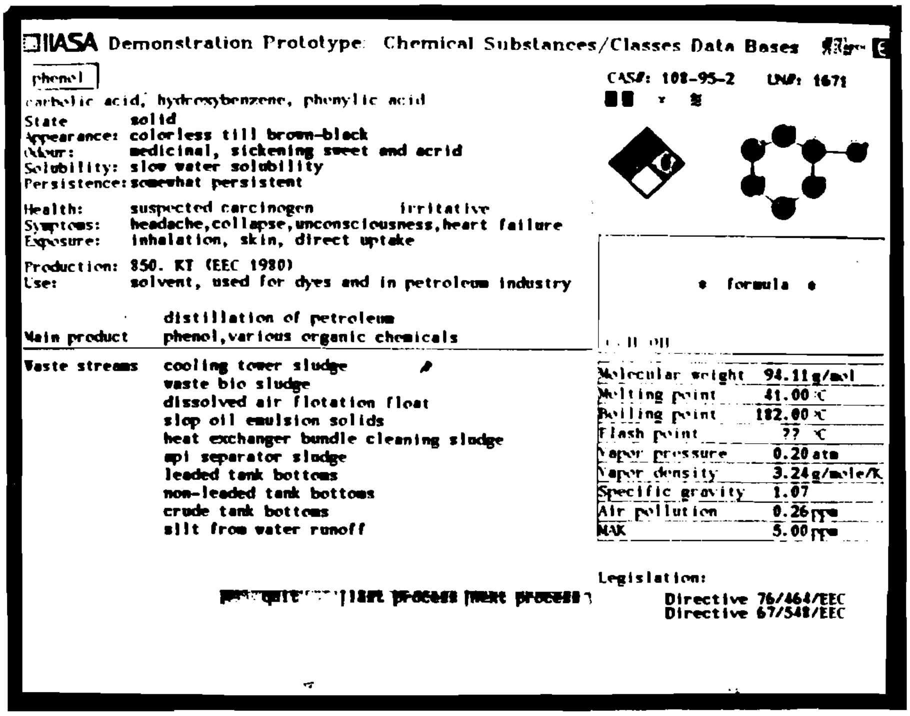

Figure 3.4a: Examples from the user interface: chemicals data base

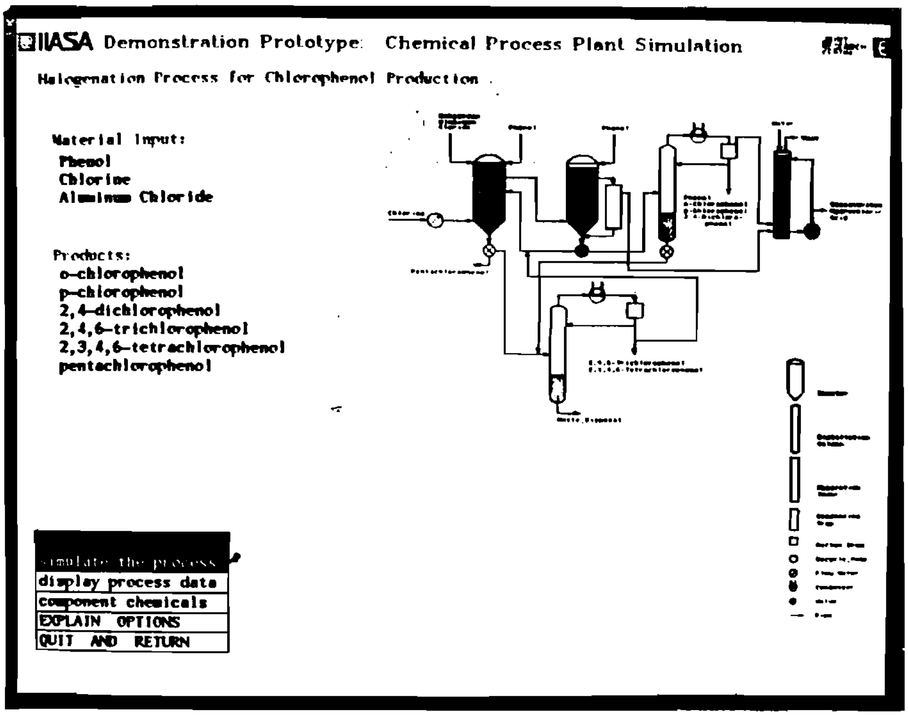

Figure 3.4b: Chemical process modeling

- a consistent screen layout, where functional blocks like menus, prompts, error messages, tables or maps, are always arranged with a similar spatial structure.

Many of the functions of the interface are entirely transparent to the user. In particular, the tasks of problem definition and output structuring involve much more than meets the eye in the color graphics displays. There are numerous small, special-purpose, rule-based intelligent interface routines between most of the numerous modules of the system, including the display modules. These enable smooth coupling of the building blocks.

An important part of the user interface's tasks is in handling uncertainty and ambiguity. Various techniques, based, for example, on fuzzy set theory (Zadeh, 1983) and a number of symbolic and probabilistic computation and estimation techniques (e.g., Goodman and Nguyen, 1985; Gupta et al., 1985; Schmucker, 1984) are used.

3.4 Data Bases, Simulation, and Optimization

The system as described above can be used in a variety of ways. These modes of operation, however, serve only as design principles. They are not seen by the user, who always interacts in the same manner through the user interface with the system. The system must, however, on request "explain" where a result comes from and how it was derived, e.g., from the data base, inferred by a rule-based production system, or as the result of a model application.

The simplest and most straightforward use of the system is as an ***interactive information system.*** Here the user "browses" through the data and knowledge bases or asks very specific questions. As an example, consider the substances data base, where the basic properties of a substance can be found. But, in addition, the system will indicate applicable regulations – which the user then can choose to read, or a history of spills and accidents that a particular substance was involved in. The latter may serve to develop a "feeling" for the order of magnitude of possible consequences of an accident.

The second mode of use is termed ***scenario analysis***. Here the user defines a special situation or scenario (e.g., the release of a certain substance from a facility), and then traces the consequences of this situation through modeling. The system will assist the user in the formulation of these "What if..." questions, largely by offering menus of options, and ensuring a complete and consistent specification.

The scenario analysis mode can use any or all models in isolation or linked together; the selection and coupling of models are automatic. The evaluation and comparison of alternatives is always performed in terms of a subset or all of a list of criteria, including monetary as well as symbolic, qualitative descriptors (Fedra, 1985). The use of certain models is implied by the selection of indicators and criteria that are chosen to describe a scenario's outcome.

Two time domains for scenario analysis with different problems addressed are supported: the models can either be used to simulate medium- to long-term phenomena, with a characteristic time scale of years, or short-term events, i.e., accidents, with a characteristic time scale of days. Switching from one mode to the other, with the necessary aggregation or disaggregation of information, must be possible.

Similar to this switching in the time domain, a change in the space domain must also be supported. There is of course a close linkage between time and space scales, in that most short-term phenomena like spills or accidents are relevant on a local to regional scale, whereas long-term phenomena like continuous routine release of hazardous substances will usually be considered on a regional to national scale.

As implied in the above listing of possible application areas, scenario analysis may be either straightforward simulation, or a combination of simulation and optimization techniques. In the latter case, the user does not have to specify concrete values for all control variables defining a scenario, but rather specifies allowable ranges on them as well as a goal structure. In the optimization mode, our system becomes a decision support system proper (Figure 3.5).

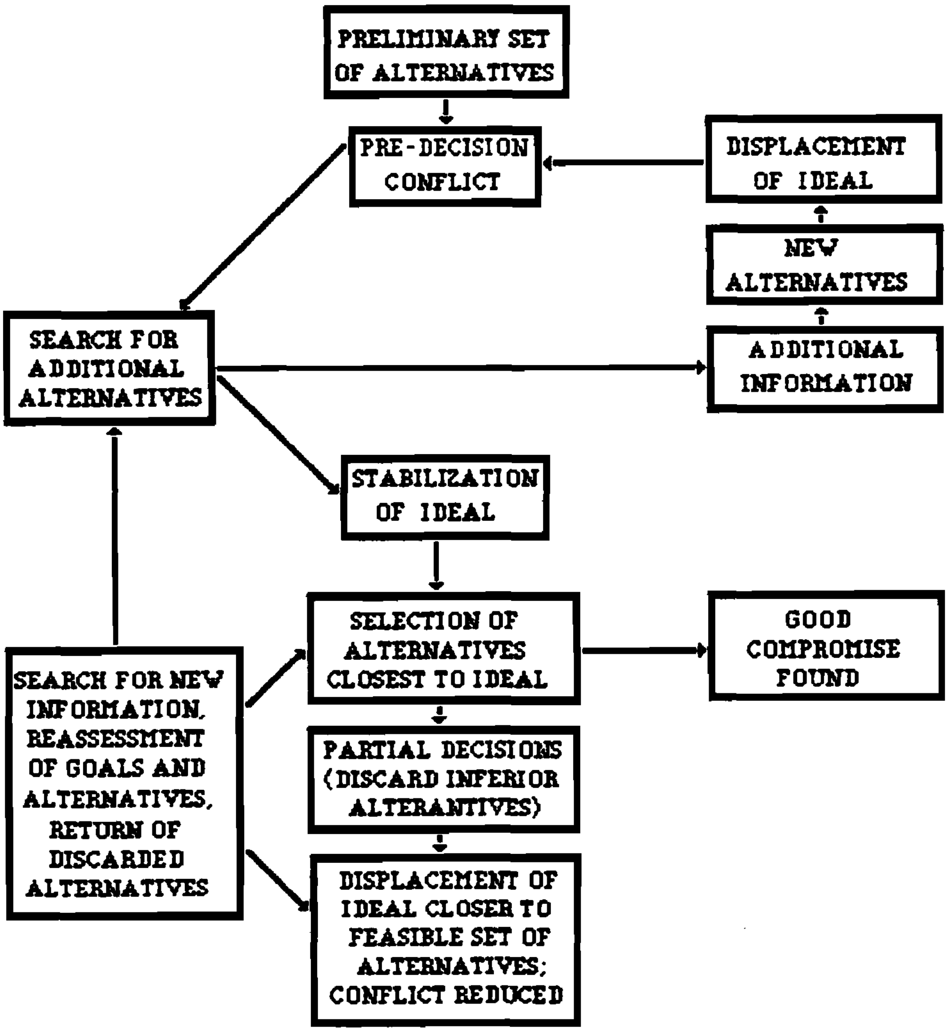

Figure 3.5: A model of decision making based on Zeleny's (1976) Theory of the Displaced Ideal (from Haustein and Weber, 1983).

Using techniques such as reference points in multi-objective problems, a framework such as DIDASS (Dynamic Interactive Decision Analysis and Support System, e.g., Grauer and Lewandowski, 1982) allows one to modify expectations interactively. The user can redefine objectives and constraints in response to first results. The human evaluator is therefore directly incorporated in the optimization process.

The optimization framework usually requires certain simplifications of the substantive production models. Reformulating a preferred alternative in terms of a more detailed dynamic simulation model with finer resolution in time and space allows for not only testing of the robustness and credibility of the optimization but also allows sensitivity analysis to be performed on the model.

A concrete example of the reference point approach (Wierzbicki, 1983) applied to a policy-oriented decision support system with parallel models of different resolution is described by Kaden et al. (1985). A planning model for dynamic multi-criteria analysis can be used alternatively with a high resolution management (stochastic simulation) model. The multi criteria-nonlinear programming system is based on the idea of ***satisficing*** (rather than ***optimizing***). Starting from the ***aspiration levels*** of the user, describing his preferred set of values for the indicators describing a certain scenario (reference point or reference scenarios), efficient systems responses are generated (Pareto points "closest" to the reference points). The best suited solution (considering the preference of the user) can be corrected by modifying the aspiration levels in an interactive procedure.

The program system is based on the nonlinear multi-criteria programming package DIDASS/N (Grauer and Kaden, 1984), coupled with the nonlinear problem solver MSPN, developed at the Institute of Automated Control, Technical University Warsaw.

In the case of numerous criteria, the reference point procedure and the comparison of alternatives becomes rather complicated. Therefore, the interactive determination of criteria should be minimized to a smaller subset of the most important ones, where the rest is considered in terms of their allowable bounds, i.e., as constraints.

An example of a DSS module in our system is described in Zhao et al. (1985).

All these refinements of the basic information and simulation system however must not complicate the users' interactions with the system. Ease of use, and the possibility of obtaining immediate answers, albeit crude and tentative, to problems the machine helps to formulate in a directly understandable, attractive and pictorial format, are seen as the most important features of the system.

3.5 Embedded Expert Systems Technology

Just as there is no definition generally agreed upon as to what a Decision Support System is, there is little agreement as to what may be called an Expert System. Trying to define it but carefully avoiding AI jargon reveals an obvious similarity between any well-designed example of interactive computer software and an expert system. In everyday language, we may define it as software that is modeled after the behavior of a human expert adviser – with obvious limitations. Thus, the system has to engage in a constructive dialog with the user and help to ask the right questions as much as try to supply meaningful answers, and explain how they were arrived at, on request.

However, technologically, there are numerous ways to achieve just that, or at least to work towards these goals. Being coded in LISP or Prolog is certainly not the only hallmark of an expert system.

As a general discriminator, we could state that expert systems are knowledge rather than data based – where the discrimination between *knowledge* (with the emphasis on structure) and *data* (with the emphasis on content) should be obvious. However, by now it should be clear that the differences between intelligent and artificially intelligent software are gradual at best, and largely in the eye of the beholder.

In our model-based decision support system (or expert system, for that matter), many concepts of artificial intelligence programming (e.g., Barstow, 1979; Charniak et al., 1980; Weiss and Kulikowski, 1984) are embedded at various levels, providing numerous and diverse functions. These range from interpreting the user's utterances when trying to spell out some description of an industrial wastestream to deciding whether or not to use an alternative algorithm to route a pollutant through an aquifer, or to supply some tentative properties for chemicals which are not described in detail in the system's data bases, or to simulate a process we only know approximately, to the overall handling of uncertainty and ambiguity (e.g., Goodman and Nguyen, 1985; Gupta et al., 1985; Schmucker, 1984). An overview of some AI technology applications in this system is given in Weigkricht and Winkelbauer (1986).

In more technical terms, the system includes or will include:

- data bases with a frame-based, heterarchical structure with property inheritance;
- a language input parser based on sideways chaining and rule values, which allows Bayesian probabilistic reasoning in identifying hypotheses (what the user really means) based on evidence (which the user spells out) and a set of *a priori* and computed *a posteriori* probabilities of what he possibly could mean, given the context of the problem;
- rule-based symbolic simulators for approximate process simulation and risk estimation;
- several heuristic search methods, e.g., to move through transportation networks or to configure process plants;
- various fuzzy set based techniques to translate uncertainty and ambiguity, either in the data bases, probabilistic model outcomes, or the user's specifications, into easy-to-grasp linguistic or graphical descriptions;
- various rule based pre- and post-processors for the individual models, defining appropriate context-dependent default values of inputs and parameters, or selecting appropriate algorithms.

However, it is important to note that these elements of expert systems technology are just part of the system, designed to make its use more effective, easier, and directly relevant to the problem situations addressed.

4. APPLICATION AREAS AND MODES OF USE

The system as described above can be used in a variety of ways. Some less technical aspects in the use of expert or decision support systems are summarized in Figure 4.1. It can also be used for a large variety of topics and problem areas. The current prototype design is based on a broad framework and attempts to include a large variety of options and possibilities, for application areas as well as for the style and mode of using the system. These options in their preliminary implementation will be the building blocks from which specific implementations will be developed. For any specific implementation (e.g., with emphasis on an industrial sector in a concrete regional context), it is important that the ultimate users are involved in the further design and development of the system.

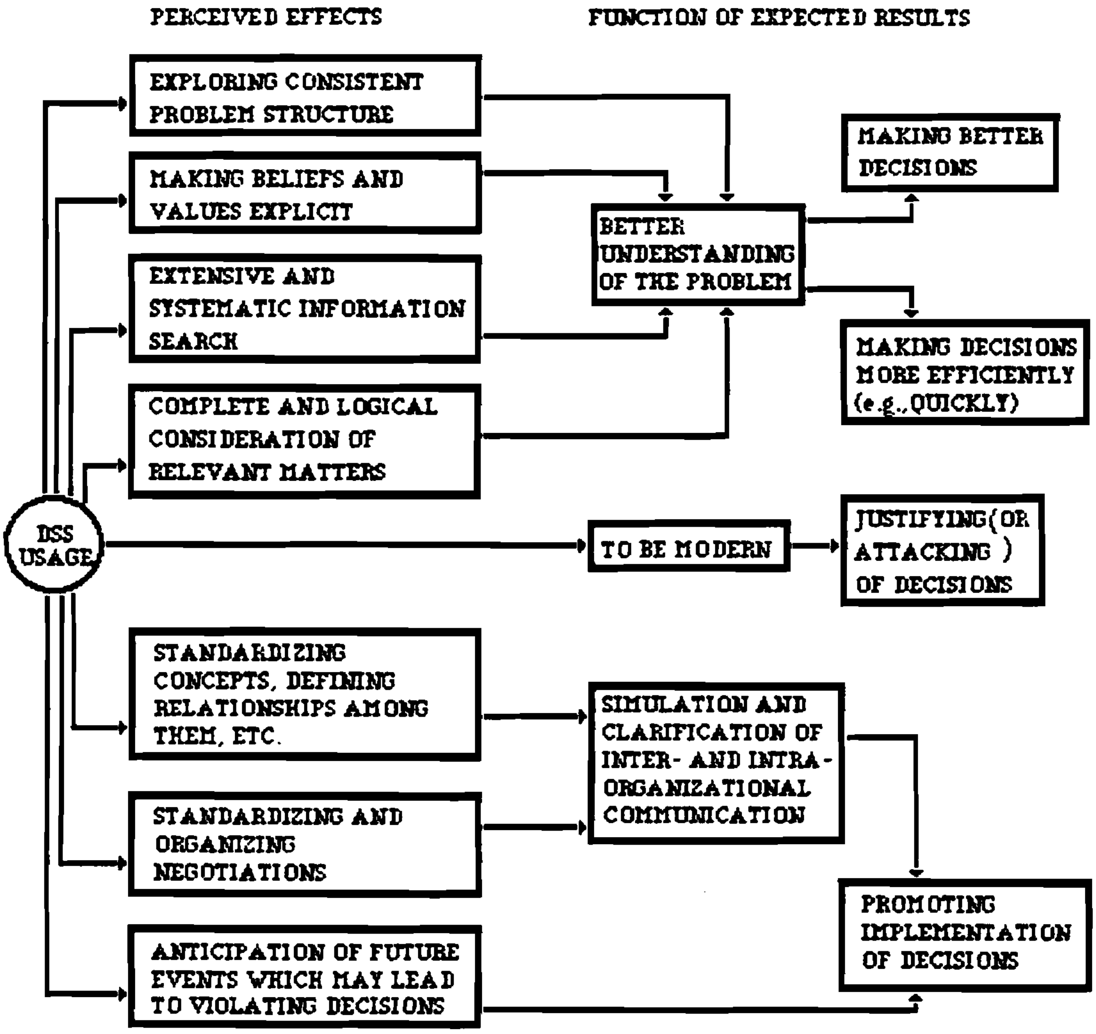

Figure 4.1: Motivations and perceived effects in the use of DSS. (after Humphreys et al., (1983)).

Since the users, however, are not expected to be computer experts, an operational prototype is essential to show what can be done and how. Only on the basis of the prototype's elements can the users then develop a sufficient understanding of the system's working to take an active role in its further design and implementation.

4.1 A Tentative List of Problem Areas

There are many specific problem areas that can be addressed with the system described above. A partial and by no means exhaustive list might include:

- estimation of **waste streams** originating from specific industrial production processes (e.g., chlorination of phenols);
- identification of **process modification requirements** (e.g., recycling, waste reduction, volume reduction) subject to waste output constraints (regulations);
- **design of alternative structures** for production and waste management systems (technological, spatial, economic);
- exploration of **siting alternatives** for production plants or treatment and/or disposal facilities, given socio-economic as well as environmental objectives and regulatory constraints;
- estimation of **trade-offs** between alternative production and treatment or disposal schemes and their implicit transportation requirements;
- analysis of alternative **regulatory policy options** (relative cost and effectiveness) for production, use, transportation, and treatment and disposal;
- **risk assessment** for given production facilities or production processes in a specific regional environment;
- simulation and **evaluation of emergency plans** for various types of accidents under a wide variety of meteorological conditions;
- risk/cost analysis for the **transportation of hazardous materials**, considering transportation mode and route alternatives, public exposure, environmental damage potential, applicable regulations, etc.;

- identification of least cost/risk **treatment and disposal alternatives** for given waste streams (amount, composition, transportation requirements);
- estimation of environmental and public health consequences of various **emission scenarios** (routine emissions from industrial production processes or dispersive use, e.g., agrochemicals, to atmosphere or water, emission from waste treatment and disposal, e.g., leaching from dumpsites); such emission scenarios might be directly user-generated or result from any of the above applications;
- long-term simulation of integrated subsystems for the description of complete **life-cycles of substances** (e.g., industrial production, treatment and disposal, environment) to identify potential problem areas e.g., disposal capacity constraints, or toxics' accumulations above thresholds in environmental media;
- estimation of **environmental hazard** (average and maximum ambient concentrations, accumulation in the food chain, human exposure), for certain substances in specific or generic environmental systems.

Many of these applications will require the linking of several of the component models of the system (compare Figure 3.3). Clearly, although many of the impact-related elements in the subsequent analysis are the same, there is an obvious dichotomy between **accident**- and **waste**- related problems.

5. IMPLICATIONS AND PROBLEMS

Expert systems, dedicated personal computers and professional workstations are relatively young phenomena, directly coupled to the rapid development of computer and communications technology over the last decade. As with the introduction of all new technology, it not only solves some old problems, it also creates its share of new ones.

5.1 The Economic Potential

Expert systems hold promise of great economic and social impact. They promise to be profitable, because they can solve problems that require the best and most expensive human expertise. In some domains, the exhaustive nature of problem solving in expert systems will assure that even remote possibilities are not overlooked. Obviously, depending on the application domain, this may be important. Also, their ability to potentially draw on very large factual data bases (e.g., on chemicals: ECDIN, developed at the JRC, Ispra, holds information on about 100,000 substances), and to trace complex consequences in simulation models by far exceed the performance of human experts in specific applications.

As was said above, our system might be useful to a regulatory agency or regional planning authority, especially in view of their typical resource constraints and the problem of maintaining technical competence vis-a-vis industry. Once developed, the software constituting the expert system can be multiplied and distributed at virtually no cost, and the hardware requirements to support this software are continuing to decrease (e.g., Fedra and Loucks, 1985).

5.2 Availability of Information

In building a computer-based information system, we clearly imply that informed decisions are "better" decisions. Expert system development poses a fundamental question concerning the nature of knowledge, both in terms of its formal representation and as an essentially social phenomenon: knowledge as something that is shared and transferred among people and machines.

The problem, obviously, is not only one of information as such, but also of interaction, communication, and of course institutional structures. What we are proposing is the development and the transfer of tools and skills rather than "solutions". We want to build the modeling approach into the decision-making process and its institutional framework. This will require close attention to customized design, on-site implementation, on-the-job training, and continuing support and maintenance.

Availability of information certainly implies a certain style, format, and ease of generating the required information quickly:

- the user may be impatient with time-consuming and stressful problem specification and assessment procedures;
- he may want to see at least tentative results promptly, in a matter of minutes, in particular if the task is sufficiently urgent;
- he may lack interest in much of the underlying technical details, and not want to directly interact with the complex quantitative procedures for analysis and decision support that are not tailored to the task structure of the problem at hand;
- consequently, he will require a format of interaction that adapts to the style of decision making appropriate to a given task and its institutional framework.

The information provided must therefore include at least:

- a set of criteria, objectives, and constraints, possibly including information on the relationship among objectives;
- a set of alternatives (scenarios), including the description of basic assumptions;
- a set of results for each alternative, describing its performance in terms of the above criteria, objectives, and constraints.

5.3 Knowledge Acquisition: a Bottleneck for Development

The transfer of knowledge from the expert system to its users is a central problem in designing its interface. Transfer of knowledge from the human expert to the system is a problem of knowledge engineering. Figure 5.1 outlines the basic structure of the knowledge acquisition process. An operational system in a dynamic application domain will require frequent updating of its factual data bases. Obvious items are new regulations, emerging products and production technologies, changes in the regional infrastructure and land use, etc.

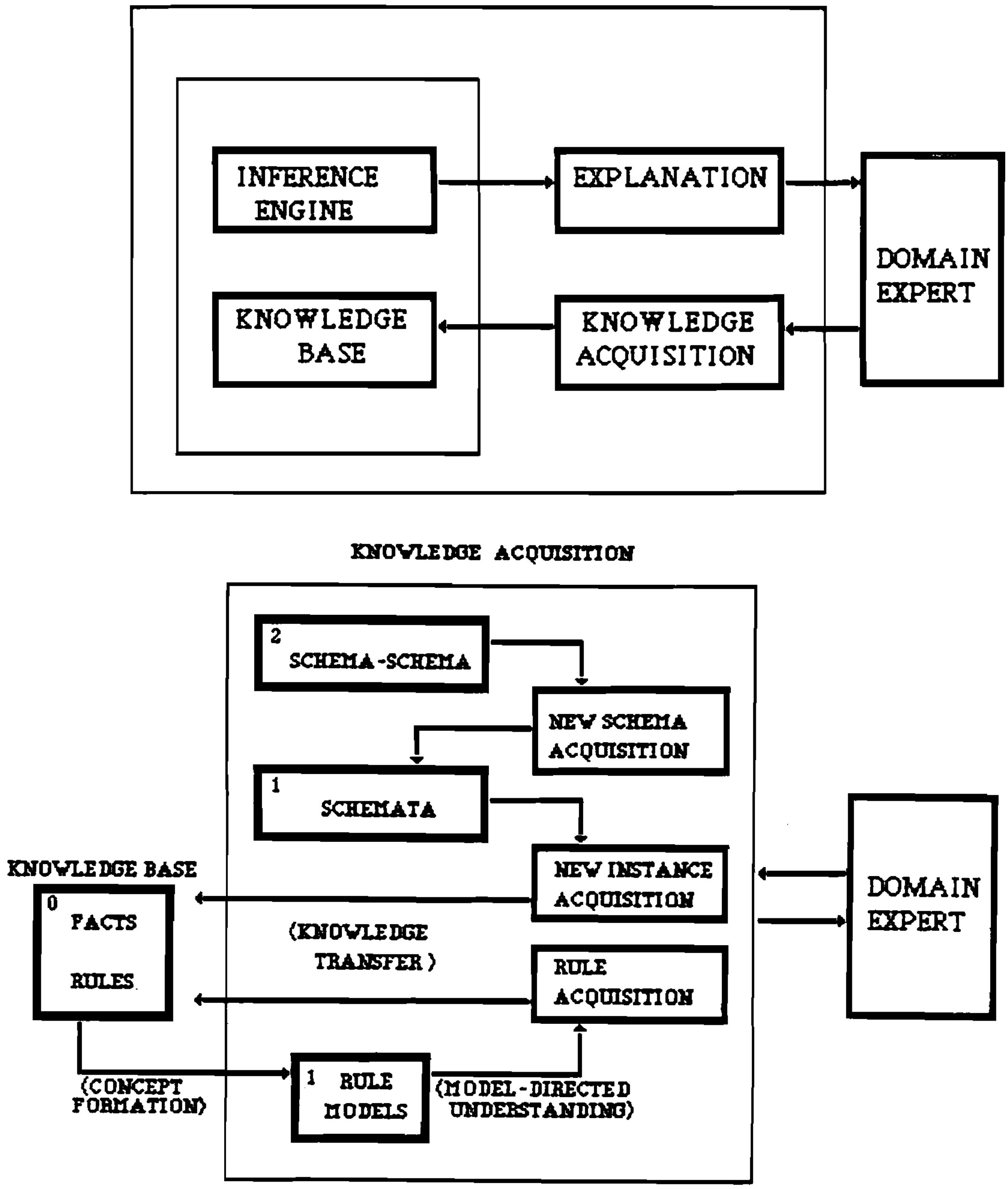

Figure 5.1: Two models of knowledge acquisition (after Davis and Lenat, 1982).

While some of these problems could be solved by connecting distributed systems into a loosely coupled network with a central site, where the updates are made, the region-specific information will require knowledge acquisition features in individual installations. Ultimately, we expect our system to be able to *learn* from the users, that is, to incorporate new information supplied by the user directly, or rules that can be inferred from a user's choices. The possible sources of information include other computers (i.e., direct access to large factual data bases), but also the system's own results of, for example, simulation runs or optimizations.

We have already briefly referred to the role of the user himself in the development of a specific implementation of such a system. In addition to the user, who may or may not be an expert on any of the domains the system covers, the expertise of numerous domain experts is required to make such a system work. It is the task of the designer and developer, the ***knowledge engineer***, to provide a framework and structure for the representation of the experts' knowledge. The knowledge engineer must extract this domain-specific knowledge, formulate it in terms of heuristics or rules, declarations, procedure, etc., and incorporate it into the system.

In our system, expert knowledge or rules are intricately merged with more traditional forms of information representation, i.e., data and algorithms or models. Their acquisition, compilation, verification, and updating is one of the more resource-consuming tasks involved.

5.4 The Hazards of Using a Hazard Management Expert System

As with any other computer program, expert systems suffer from the garbage in - garbage out syndrome. They have no ability to recognize factual errors in their data bases unless the data are inconsistent with other data or with rules stored in the system provided an appropriate ***meta-rule*** based mechanism to check the consistency of the data bases is installed. However, due to their ability to explain their results, it is much easier to identify errors than with other software. The ability to explain, on request, how a certain result was arrived at, seems critically important for decision-support software:

> *Our society's growing reliance on computer systems that were initially intended to "help" people make analyses and decisions, but which have long since both surpassed the*

> *understanding of their users and become indispensible to them, is a very serious development. ... decisions are made with the aid of, and sometimes entirely by, computers, whose programs no one any longer knows explicitly or understands. Hence no one can know the criteria or the rules on which such decisions are based (Weizenbaum 1976).*

Misinterpretation of computer processed or generated information is clearly of considerable concern.

It seems worthwhile to reiterate the potential role of the expert system concept in this setting: it is meant to support the planning, decision-making, and related communications process, and not to replace it. This support consists of making available relevant information on the technological and environmental systems in question, and the likely consequences of any action or policy considered, in a fast, reliable (at least in the sense of repeatable and open to criticism), and easy-to-comprehend way. The workstation can free planners and policy makers from the laborious and often disruptingly time-consuming tasks of non-interactive data manipulation and analysis. Besides, it also helps to clarify and formulate the problems.

The easy and fast organization of information and evidence should allow for a more creative, enjoyable, and brainstorming atmosphere. An attractive, powerful and responsive tool should invite and stimulate a more experimental, innovative attitude of "anything goes" in the sense of Feyerabend's (1978) criticism of methodological constraints. The basic idea is to provide an inviting tool that will allow a dramatic increase in the number of alternatives to be examined or, first of all, to be invented.

The expert system is supposed to provide an educational framework, as much as a professional tool. It is a LOGO-turtle* environment (Papert 1980) for industrial risk assessment and environmental systems analysis.

An important element is the direct interaction. Traditionally, computer-based approaches are used by analysts assigned to special tasks by a given client or decision-making body. The analyst, given a description

*A graphics-oriented interactive, structured and recursive computer language especially designed for children.

of the problem and the required domain of solutions, is left alone to proceed in an off-line fashion, eventually with some infrequent interaction with the client. Once the task is completed, the analyst then often learns that the client's interests have changed considerably, many of the assumptions made in the analysis no longer hold, new problems have replaced the old ones, and the results of the analysis are simply shelved. The problem, obviously, is not one of the analysis as such, but of interaction, communication, and of course, institutional structures.

The way we think models of even complex systems should be constructed, using relatively simple modules, devising a well-structured system of the modules and thoroughly documenting the model system, will help in effective model use. Remember that there are numerous examples of situations not involving computers at all, where decisions are made based on rules that are not known explicitly or fully understood. Most instinctive behavior, or the large class of individual to societal pre-judgements, falls into this category. The economy of decision-making may well require black-box decision-making tools, which, however, in the long run are always judged by the final outcome of these decisions. But this applies whether or not computers are involved.

In complex problem situations, it is next to impossible to sort out the effect of any individual decision from among the multitude of confounding influences. The success and effectiveness of computer technology and any modeling approach can only be described in terms of its use, its acceptance and contribution in the daily practice of planning and decision making. The measure of success is the contribution to a learning process, stimulating the introduction of new concepts and points of view, and new perceptions of the problems.

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