Expert Support Systems for New Product Development Decision Making: A Modeling Framework and Applications

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A modeling framework that merges knowledge-based expert systems and decision support systems with management science methods for project evaluation is presented. In particular, the strategic decision to commit to full-scale development of a new product is considered. At the core of the framework are the methods and techniques used for acquiring, modeling and processing the expert knowledge and data. Methods and techniques used include scoring models, logic tables, the analytic hierarchy process, discriminant analysis, and rule-based systems. The suggested modeling approach obtains the benefits of normative modeling as well as the flexibility and developmental advantages of expert systems. Additional benefits include reduced information processing and gathering time, which can help to accelerate the product development cycle. Potential spin-offs of this research include applications for project evaluation throughout the product development cycle and other areas such as capital budgeting. Finally, a series of related case studies that have successfully implemented this framework is described.
(*Expert Support Systems; Knowledge-Based DSS; Expert Systems; Product Development*)

1. Introduction

Success in new product introduction can be critical for a firm to maintain its competitive position. However, a variety of difficulties and uncertainties are associated with the new product development process. Firms invest in R&D knowing that only a small percentage of promising product ideas will reach commercialization. About one in seven concepts that enter the new product development process becomes a commercial success; about half of the resources that U.S. industry spends on new product development leads to failed or canceled products (Booz Allen & Hamilton 1982).

Rapid changes in technology and market demands are among the factors that are increasing the pressure on firms to accelerate the product development cycle itself. For example, Clark and Fujimoto (1991) report that Japanese auto firms spend on average about 44 months in planning and engineering, while their U.S. and European counterparts spend 62–65 months. Gupta and Wilemon (1990) have studied why development delays occur, the nature of these delays, and what can be done to avoid them. They conclude that the new product development process must be altered to address several important categories of factors, including senior management support, early integration of functional expertise into the development effort, availability of product development resources and their management, and an environment that supports teamwork. Other related managerial policies and practices are proposed by Smith and Reinertsen (1991) and Roseneau (1990).

Considering the magnitude of the resource commitments and new product failure rates, it is understandable why it is sometimes difficult to obtain top management support and sufficient resources to accelerate

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the development cycle. This combination of circumstances provides an additional incentive for the new product development manager to present senior management with a thorough and thoughtful evaluation on a given development project if support and funding are to be achieved in a timely fashion. If senior management can make a timely decision with confidence, obviating the need to require iterative evaluation cycles and additional information gathering and processing, a shorter product development cycle might be achieved. The competitive and financial benefits of even relatively short reductions in the time required for the new product development process in technology-based businesses can be quite substantial. Using a simple economic model, Reinertsen (1983) estimates that "in a high-growth market with short product-life cycles, shipping a product six months late can draw down its life-cycle profits by 33%." Profits in slow-growth markets with long product-life cycles are also affected negatively but to a much lesser extent.

In what follows, we describe a modeling framework that merges knowledge-based expert systems (ES) and decision support systems (DSS) technology with management science methods for the evaluation of new product development projects. We focus on the strategic decision to commit to full-scale development of the product. In particular, the project is presumed to be at the stage on the development cycle where a major resource commitment is required to "prove" the product and its technology. This may occur when the product concept moves from preliminary development and testing to scale-up, where piloting or either small-scale or contract manufacturing is required.

Such new product development decisions are often addressed by groups such as business strategic planning teams, and require gathering, processing and evaluating information from diverse functional groups in the organization. Thus, the framework we propose incorporates the expertise of the decision-making group into a project evaluation system that provides a normative evaluation and supporting diagnostics with application for individual and group decision-making. The objectives of the systems development process are to design an evaluation system which when implemented will help reduce the time required for decision-making, while improving decision quality and consistency. The anticipated result is that the development cycle can be accelerated through the application of an evaluation system based on the proposed framework. Further, formalizing our understanding of how the various issues and criteria interact and influence the new product development evaluation process should also help bridge the communication gap between project managers and the decision-maker(s).

After a review and critique of evaluation methods and approaches, the modeling framework and architecture are presented. This is followed by several related case studies that describe evaluation systems that are successful implementations of the proposed framework.

2. Literature Review and Critique

Since our proposed modeling framework incorporates management science methods and knowledge-based systems, it is necessary to review and critique the contributions of the literature in both of these areas.

2.1. Traditional Management Science Approaches

The development of models and methods for the evaluation and selection of both research and development projects has been of interest to both academics and practitioners for over thirty years. Periodically, these models and their contributions have been reviewed in various surveys (see, e.g., Baker and Pound 1964; Cetron, Martino and Roepke 1967; Dean 1968; Souder 1972; Augood 1973; Baker 1974; and Gupta and Taube 1985).

Fahrni and Spatig (1990) have conducted an extensive literature review and have identified five key issues that should be considered before selecting an appropriate model. These are as follows: 1) determine if there are more good proposals than the available resources could fund (really a screen); 2) the extent to which the relevant information can be quantified; 3) the degree of project interdependence; 4) the presence of single vs. multiple objectives; and 5) the importance of risk. Using a simple decision tree, the authors provide a guide as to what subset of the available models are appropriate given your answers to the five questions.

A number of the studies reported and reviewed in the literature describe successful single-site applications of specific models. A few studies have been undertaken to determine the extent of use of these models (see

Liberatore and Titus 1983, and Watts and Higgins 1987). The findings suggest that conceptually simple models such as checklists and scoring approaches are widely used, while more sophisticated methods such as mathematical programming have had limited impact in practice. Also, many managers do not perceive that the available models appreciably improve their decision making (Liberatore and Titus 1983).

These findings lead to three related conclusions concerning the development of project selection methods and systems (see also Liberatore 1989, and Gupta and Taube 1985):

(1) consider the characteristics of the organization conducting the research and development (R&D), such as business strategies and goals and data availability;

(2) include both qualitative and quantitative criteria as appropriate; and

(3) use methods which measure and aggregate multiple criteria.

In line with the findings concerning management practice, scoring models offer one approach that meets the concerns expressed above. Scoring models such as Dean and Nishry's (1965) and Dean and Sengupta's (1962) were developed to consider the diversity of project selection criteria. Several authors (e.g., Merrifield 1981; Paolini and Glaser 1977; Plebani and Jain 1981; and Cooper 1985) have identified different sets of selection factors, and present methods for scoring and aggregating these to obtain a single criterion. Scoring models are easy to use and understand, systematize the review of projects, and focus attention on the most important issues (Cooper 1985).

Scoring models, however, do have certain limitations. Scoring models are seen as oversimplifications when they attempt to reduce complicated decisions to a product score based on a small number of criteria. Also, the final project scores may not be cardinal measures, if each criterion's weight is multiplied by an ordinal rating.

The analytic hierarchy process (AHP) of Saaty (1980) can be used to determine criteria weights and scores using a process of ratio-scale measurement. The AHP offers an advantage over standard scoring models in that the resulting project scores can be used in both funding and ranking decisions. The advantages and disadvantages of AHP over utility theory, and technical issues such as rank reversal, are dealt with elsewhere (Winkler 1990, Saaty 1990; Dyer 1990a and 1990b, and Harker and Vargas 1990). The basic AHP approach can be extended using a rating scale for each criterion, again based on a ratio-scale of measurement. More details on AHP applications in project selection and evaluation can be found in Liberatore (1987, 1989).

An important limitation of both the AHP and scoring models is the assumption concerning independence for both the criteria and the projects. One approach for addressing the independence issue is given by Cooper (1985). His NEWPROD scoring-type model is based on a factor analysis of project characteristic data of almost 200 projects from 100 companies. This model was developed for product screening and not detailed evaluation.

In developing methods and systems for project selection and evaluation, it is important to explicitly recognize and incorporate the knowledge and expertise of project and development managers. As early as the mid-seventies Baker and Freeland (1975) stated that "the trend in application appears to be away from decision models and toward 'decision information systems'." One approach for developing decision information systems with the capabilities necessary to support product development decisions is through the use of knowledge-based approaches such as expert systems.

2.2. Knowledge-Based Approaches

Simply defined, an expert system is "a computer program that has built into it the knowledge and capability that will allow it to operate at an expert level" (Feigenbaum and McCorduck 1983). The program should exhibit "a high degree of performance on problems that are difficult enough to require significant human expertise for their solution" (Feigenbaum 1985).

Unlike other expert system applications in fields such as manufacturing, the goal here is not to "replace" the evaluation of expert(s) by a computer program. Rather, the goal is to capture the knowledge of expert(s) and make it available in a standardized form to the expert(s), as well as others in the organization.

Expert systems technology can provide an effective approach for encoding the knowledge of both development managers and the decision-maker(s). Such encoded knowledge can be made available for decision-making over the course of the development cycle. A knowledge-based (KB) approach for product development decision-making can offer an organization several key advantages including:

(1) flexibility in capturing and representing information, knowledge and managerial judgments;

(2) the ability to formally capture and systematize expert knowledge, which can be more broadly disseminated throughout the organization and become a source of competitive advantage;

(3) enhanced understanding of the decision-making process which can lead to its improvement (i.e., the KB approach is not merely descriptive);

(4) improved organizational understanding and communications, and improved consistency in decision-making by providing a common platform for many users at different levels; and

(5) compatibility with traditional management science multi-criteria methods.

In addition, expert system shells—the software tool kits used to develop expert systems—provide important developmental advantages including:

(1) user interfaces which provide a more natural approach for structuring the dialogue between the system and the user; the shell's explanation facility, which can also be accessed through the user interface, can help users better understand the intent of the questions asked, and how conclusions are derived;

(2) rapid prototyping capabilities which lead to iterative development and increased user involvement and confidence with the system and its outputs;

(3) special systems modeling capabilities, such as intelligent branching to avoid unnecessary questions, metarules to validate the user's responses and ensure consistency, and the ability to easily access multiple databases and external programs as needed; and

(4) freedom in structuring the knowledge base, which also minimizes maintenance.

There are some limitations to using expert systems, however. The utility of the system is highly dependent on the expert(s)' knowledge and the skill of the knowledge engineer. Also, a substantial effort by developers, users, and experts is usually required for successful systems development.

The application of expert systems to product development evaluation has been limited. Balachandra (1989) has developed an expert system for the decision to terminate or continue an R&D project in the development stage. He uses the inductive approach, which requires collecting a set of example cases with all relevant information for situations in which an expert has drawn specific conclusions and made specific decisions. A decision tree and/or rules can then be induced from these examples.

Wilkinson (1991) has suggested the development of an expert system for product evaluation. The evaluation would occur in two stages. First, a project would be classified according to its position along three dimensions: 1) normal or probable time to completion; 2) corporate urgency to have the project completed; and 3) the need for technological innovation. Second, based on case analysis, successful projects and their characteristics would be identified according to the project's position in the "cube." An evaluation could be completed once the project is classified.

Ram and Ram (1988, 1989) developed an expert system called INNOVATOR for screening new product ideas in the financial services industry. Five financial experts were used to generate the list of financial products represented in the knowledge base, the key attributes for each product and the relative weight for each attribute. The system makes recommendations regarding two specific product lines, and products and brands within these lines. Once the user inputs the necessary attribute values, a score is computed, and based on certain cutoff values a recommendation of GO/REEVALUATE/NO-GO is given.

In summary, Balachandra's model (1989) and Wilkinson's approach (1991) are targeted for ongoing project evaluation and use data collected from a variety of projects from different organizations and environments for their knowledge bases. The Ram and Ram model (1988, 1989) is targeted for project screening, not evaluation. All three models are "generic" expert systems and do not capture the knowledge required to develop a model suitable for strategic new product development decision-making within a particular organization.

After reviewing the benefits and limitations of the management science and knowledge-based approaches, we conclude that a new integrated project evaluation framework is needed. This framework must be flexible in order to accommodate organizational and decision-making differences. Evaluation systems based on this framework should be able to capture expert knowledge and provide a normative-type project evaluation along with suitable diagnostics, and allow for learning. Such systems should be designed for strategic decision-making, and could serve as a common platform for executives and product development managers. A framework for the design of an evaluation system based on these guidelines is described in the next section.

3. Expert Support System for Project Evaluation

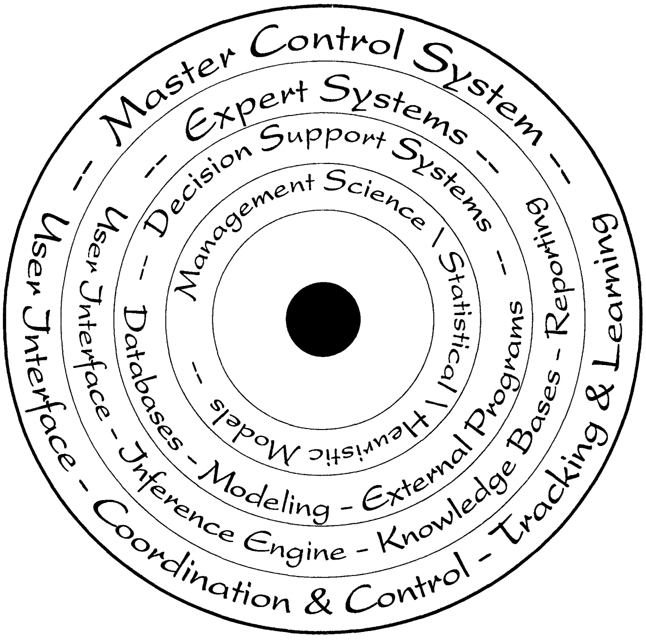
As described in the previous section, one of the important advantages of expert systems technology derives from is its ability to enhance decision support by introducing heuristic elements that are inherent to the experts' decision process. New product development evaluation, although a good candidate for a knowledge-based system, has many features and requirements that make necessary the extension of the knowledge-based system paradigm. The traditional management science approaches used in project evaluation are usually more structured and more quantitatively oriented than the assessment produced by an expert system. Such quantitative modeling support can be best handled by a different type of system, i.e., a DSS.

Expert Support Systems (ESS) combine capabilities from both Decision Support Systems and knowledge-based approaches such as Expert Systems. Generic, conceptual models of Expert Support Systems (also known as Knowledge-Based Support Systems, Intelligent DSS, Expert DSS, or Intelligent Support Systems) have been described by many researchers in the DSS/ES fields (Bonczek et al. 1980, Courtney et al. 1987, El-Najdawi and Stylianou 1993, Holtzman 1989, Lee 1986, Luconi et al. 1986, Stylianou and El-Najdawi 1989, Turban and Watkins 1986). A key issue considered by this literature is the need for integration of DSS and ES, due to the inherent weaknesses of each, and the potential benefits of synergy. Other issues considered by the literature include descriptions of general approaches and models of integration and discussions of implementation issues. Although it is both important and useful to discuss DSS/ES integration issues in general terms, it should be recognized that different problems in various domains could require different ways to combine and integrate the various ESS components. Therefore, the model presented here can be considered as the next phase in the evolution of ESS. As this particular ESS model has been specifically designed and implemented to support new product development decision-making, it represents a refinement and an extension of the generic, conceptual models presented before. However, the basic structures and interrelationships incorporated within this ESS model can, with minor modifications, be applied to other problem domains requiring complex evaluations (such as capital budgeting).

Figure 1 illustrates the hierarchical composition of the ESS. At the core of the ESS are the various models that are responsible for supporting the acquisition, modeling, and processing of the required problem solving knowledge. These include management science models (such as scoring models, mathematical programming, AHP and utility theory), statistical models (such as regression and discriminant analysis), and heuristic models (such as if-then-and-or-else rules). The models are accessed and processed by expert systems, decision support systems, and other support programs.

The DSS ring represents the capabilities of the system to access and use various databases, external programs,

Figure 1 **ESS Composition**



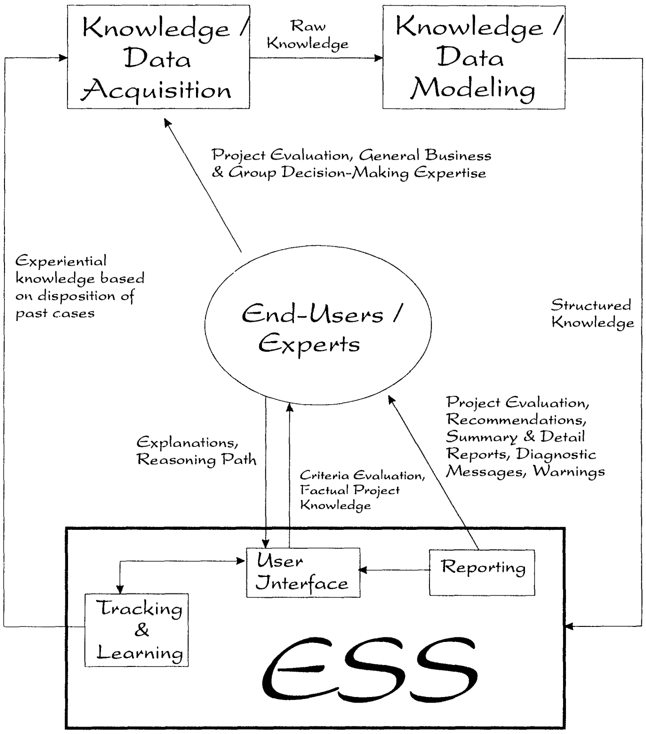
and the underlying models. Most of the modeling and processing involved at this level is quantitatively oriented.

The DSS programs and databases are called as a result of the firing of heuristic rules contained within the various expert systems that are part of the ESS. This approach allows for the representation of problem solving knowledge in the form of heuristic rules. The knowledge is processed by inference engines that have AI inference and control capabilities. Communication with the user is provided through the user interface and the ES reporting facilities.

The Master Control System (MCS) is another expert system with the specific responsibilities of integrating, coordinating and controlling the individual expert systems. The MCS also contains a tracking and learning facility that is used to follow up on the implementation of past system advice in order to identify any need for knowledge modification as a result of environmental changes.

The specific interaction among the various components of the ESS is further described in the next section.

Figure 2 Project Evaluation ESS



4. A Project Evaluation Framework

We have used the ESS model described above as the foundation for developing an integrative project evaluation framework that merges management science models with expert support systems (Figure 2). This framework proposes a process for evaluating new product development projects as well as an architecture for an evaluation system. The remainder of this section discusses the components of the proposed framework.

4.1. Knowledge and Data Acquisition

As mentioned above, decision support for evaluating product development projects requires a capability to extract knowledge from one or more experts, design a knowledge structure based on the decisional models used, integrate the modeled knowledge into a common system, and disseminate it to decision makers at the various organizational levels. Knowledge acquisition and knowledge engineering techniques commonly used in the development of knowledge-based expert systems offer an excellent starting point for these activities.

Expert knowledge includes the selection of the appropriate criteria, subcriteria, and factors; the weights attached to each of these; the interrelationships among them; and the reasoning path for making project evaluation decisions given the knowledge and data associated with a specific project.

Sometimes, the individual possessing the primary expertise within an area (e.g., the VP of Manufacturing) may have on his/her staff an individual with recognized expertise within a specific manufacturing function (e.g., logistics). In this situation, the Manufacturing VP is considered to be the primary expert and the head of logistics is a secondary expert. Primary and secondary experts can be interviewed using both structured and free form approaches. This process is time consuming and requires intensive and frequent interaction between developers and experts. Inductive expert system shells, such as 1STCLASS, can help identify key factors that influence the project evaluation decision. Also, decision tree-based tools, such as TI's Procedure Consultant, can be used to develop an initial model of the expert(s)' decision process. Other knowledge acquisition techniques, such as protocol analysis, may also be quite useful. Once a satisfactory model structure is agreed upon, questionnaires and other input forms can be distributed to the experts to help them organize and refine their ideas and at the same time reduce the contact required with the knowledge engineering team. Techniques such as pairwise comparisons of evaluation criteria, logic tables, and direct assessment methods can be used extensively to extract knowledge from the experts. Customer satisfaction surveys and other market research can also be used to incorporate important customer driven aspects of the new product evaluation decision.

Strategic product development decision-making often involves a group of executives. As a result, in addition to the interviews with each expert, a number of consensus-building, free-form interviews are required with the experts. These sessions are critical not only because of the group knowledge that they yield but also because they serve as a group bonding agent, they provide team training, and promote a sense of system ownership for the decision-making group.

4.2. Knowledge and Data Modeling

A variety of models can be used during each phase of the project evaluation. During knowledge acquisition, logic tables, pairwise comparisons, sampling, and direct assessment techniques can be used to extract knowledge from the experts. The raw knowledge can then be modeled using AHP, utility theory, or other modeling techniques. Rating scales and weighted choice sets used for measuring the major criteria, subcriteria, and factors can be determined. The resulting knowledge can be encoded in expert system production rules, DSS models, and other support programs. The evaluation weights can be stored in databases making the system more flexible and easier to maintain. For reasons described in §2, the proposed model for processing the user responses is a scoring model.

In situations where the volume of criteria and factors make it difficult for the experts to evaluate all possible cases, representative samples can be used as surrogates. For these cases, knowledge can be generated dynamically during the processing phase using statistical models such as regression or discriminant analysis.

4.3. End Users and End-User Interface

The system's end-users could include the experts themselves, as well as other non-expert decision makers. Specifically, the major users will be the business strategy team and / or the business unit tactical teams. Note that the term "business planning teams" will be used when a reference is being made to both of these groups.

Expert system shells provide easy to use, user friendly interfaces. The more sophisticated shells allow the developer to choose among alternative interfaces, to customize an existing interface, or even to create a new one. Availability of alternative user interfaces is especially important when the user population is diverse, as measured by background, cognitive styles, and preferences.

A front-end expert system could keep track of individual, as well as group user preferences and requirements. Given a particular user, or group of users, the system can then display the appropriate interface. An AI program could be added to this front-end to provide natural language capabilities.

The user interface allows the system to question the users as to their preferences and assessments relating to the various factors and criteria affecting project evaluation. System output is also routed through the user interface. In addition, the user interface facility allows the user to demand explanations from the system as to why certain questions are being asked, how conclusions were derived, and what is known at any time during the consultation. The user could also choose to consult with a single specific ES or DSS or can use the MCS, which will engage all necessary ES and DSS subsystems (see next section).

4.4. Knowledge Processing

Key project characteristics, such as development project classification and target market, can be solicited from the user. These can then be used to select the correct databases and to determine the relevant knowledge-base partitions which represent the appropriate structure for evaluating projects with such characteristics. As a result, the system can identify and pursue a set of major criteria that can be measured directly or indirectly by the results of subcriteria and factors, as dictated by the evaluation structure. In turn, subcriteria and factors can be pursued as necessary.

4.5. Reporting

Desirable system outputs consist of:

(a) Final project evaluation and recommendation;

(b) Diagnostic messages and warnings; these include warnings resulting from a check of the consistency of the user's responses;

(c) Summary and detailed reports of the rating scales results and the weighted choice sets assessments; and

(d) Explanations of system actions, reasoning path, and conclusions (available on user request).

4.6. Tracking and Learning

Product development decision making is very dynamic with constant environmental changes that the experts have to consider. Changes can be initiated externally by competitors, customers, the government, and consumer groups, or they may be caused as a result of internal organizational policy and strategy changes or employee actions. A system can only be successful if it can support the expert in dealing with these changes. Support, at the minimum, denotes a system that can be modified easily to include new decision criteria and changes in priorities. A more sophisticated system should help the expert recognize when changes are necessary based on environmental feedback from the disposition of past decisions. The Tracking & Learning Facility shown in Figure 2 is the mechanism used in this framework to support a dynamic link between the system and the environment.

The system could maintain a case history database for tracking cases that have been previously run. Case data includes the user's assessments and responses to system questions, as well as the system's conclusions and advice. At the beginning of every new session the system asks the user if any final decisions were made on any of the past cases and what those decisions were. For projects that have already been decided, the system requests user feedback as to their success or failure. This information is appended to the case history database. The original system conclusions and advice are compared to the final decision taken and to the post implementation evaluation of the project's success or failure. The user is alerted for any detected discrepancies and is asked to reconcile them.

The case history database can eventually be processed by an inductive expert system or a neural network to better isolate those factors and relationships that lead to acceptance or termination of specific product development projects. This may allow the future development of simpler, normative evaluation systems.

In the next section we will discuss several case studies of successful implementations of the proposed project evaluation framework and ESS model.

5. Implementation

The framework presented above has been successfully applied in several system development efforts. We will now present two major system development efforts: the first is based on a single expert, while the second is based on a team of experts operating in a group decision-making environment at the strategic level. A third implementation that is a modification of the second will be mentioned briefly in the extensions section. Table 1 summarizes the specific techniques, tools, and models used by all of these systems.

Before continuing, it is important to note that the development and implementation processes described

Table 1 Project Evaluation ESS: Methods and Models Used

Knowledge & Data Acquisition
Interviews (Case examples; formal/informal approaches)
Logic Tables
Questionnaires
Market Research
Group Decision-making
Consensus-building Sessions
Pairwise Comparisons
Direct Assessment Techniques
Decision Trees
Statistical Sampling
Customer-based Strategic
Planning (documented knowledge)
Rapid Prototyping
Knowledge & Data Modeling
Rating Scales
Weighted Choice Sets
Discriminant Analysis
Expert Support System (Knowledge Processing)
Heuristic Rules
External DSS Programs
Databases
Expert System Shells
Analytic Hierarchy Process
Scoring Model

here were quite extensive and occurred over a multiyear period. As a result, many details have been omitted. The interested reader is referred to Liberatore and Stylianou (1991) for a more detailed discussion.

5.1. Background

The testing and implementation site for the two systems we describe below is the Floor Products Operations of Armstrong World Industries. Armstrong is the recognized industry leader in the development and commercialization of new flooring technologies and products. The Armstrong floor products strategy team is charged with the responsibility of evaluating product concepts as they move from research and early development to full-scale development. The strategy team consists of seven individuals: the operations manufacturing general manager, the residential and commercial sales and marketing managers, the operations general manager of engineering, the operations product styling and design general manager, the operations general manager of research and development, and the general manager of marketing information. As a result of the team's evaluation, for example, a product concept could be moved to the piloting stage or in-house manufacturing to help prove the product concept. These evaluations are strategic decisions for Armstrong, since they affect the mix of products that will be offered to customers in the future.

Each floor products development project is assigned a product development manager or project leader who is responsible for gathering the necessary information to support the business planning teams' decision-making process. The business planning teams had been using an evaluation under an overall process called customer-based strategic planning (CBSP) to guide their evaluation. The CBSP evaluation process required responses to a variety of questions leading to a final product score. As part of the CBSP process, the strategy team members engaged in lengthy meetings held over a series of several months to assess the value of projects, sometimes in the presence of the product development manager and / or project leader.

Both the strategy team and several of the product development managers and project leaders interviewed felt that the questions asked and the scoring approach used by CBSP were not enabling the team to make timely decisions, since many important issues were not adequately addressed. As a result, many meetings were required before all necessary information was obtained, lengthening the time required for decision-making. The team also felt that they were not consistently addressing the same issues, and that different factors seemed to weigh, often arbitrarily, on the final decision. For these reasons the strategy team was dissatisfied with the CBSP evaluation process and wanted a new support system that would consider the issues they felt should be addressed in their group discussions of each product development project. Each team member wanted his / her expertise incorporated into the system, and desired a normative evaluation as well as other supporting information before making a final decision. Each team member also desired the capability to use the part of the system containing his / her expertise without having to complete the full evaluation process.

Our systems development effort was initially sponsored and supported internally by Armstrong's General Manager for Pioneering Research. This individual appointed the senior scientist responsible for expert systems as the study liaison.

5.2. Single-Expert System: DMAS

The systems development process began by identifying a product development manager who was willing to commit the necessary time and energy toward the development of an evaluation system. Through a series of initial personal interviews we began to determine the key project characteristics and criteria that influenced the selected product development manager's recommendation. We also discovered that the system was required to ask certain screening questions that could lead to an early decision or would lead to warnings or comments about the project under consideration. During this period we learned that the notion of a normative evaluation obtained through a scoring model was strongly ingrained throughout Armstrong. We therefore decided that a key output of the system should be a score as well as a verbal interpretation of that score: GO / NO-GO / UNCERTAIN.

A hierarchical structure was found to be useful in representing the relationships indicated by the development manager concerning the criteria, subcriteria, factors, and ratings scales. After extensive interviews, questionnaires, and some initial modeling using Procedure Consultant, a system structure chart was developed and approved. The development manager also used the expertise of several other individuals, including a marketing manager and the controller, before finalizing the system's structure.

Key modules of this system include technology/manufacturing, financial and marketing assessments, with the overall evaluation moderated by the project's environmental impact. Questions relating to such issues as strategic fit and capital availability produced warnings or diagnostics depending upon the user's responses. A series of rules and checks were included to help monitor and improve the consistency of the data captured by the system.

The AHP with the ratings scale method mentioned in §2 (Liberatore 1987) was initially considered as a candidate model that would drive the development of the numerical evaluation score. However, the development manager was not comfortable in using pairwise comparisons in every situation where items required weights. Logic tables were sometimes found to more easily model his evaluation process when there were dependencies between the items being evaluated.

For example, a logic table was used to combine the results of the probability of technical success (five ratings) with technical familiarity (four cases) into an evaluation of the twenty cases for technological certainty. Each of these twenty cases was rated as high, good, moderate, fair, or poor by the development manager. Based on the user's responses to questions concerning probability of technical success and technical familiarity, a series of if-then rules determines the rating for technological certainty. Weights were assigned to the technological certainty ratings based on pairwise comparisons.

The Development Manager's Advisory System (DMAS) then views AHP as a knowledge engineering tool that can be used in conjunction with logic tables or direct numerical assessment to obtain the necessary weights. Expert Choice was used to process those subcomponents that were modeled using pairwise comparisons. The criteria weights and cutoff values assigned to individual ratings were placed in a database file (DBASE III+) which was accessed by the expert system.

After experimentation and initial prototypes with several expert system shells, such as VP-Expert, we found that Level5 possessed the level of flexibility suitable for our needs. The development manager, previously not a computer user, became an enthusiastic user and proponent of the system. He found that he could easily test and play "what if" games with DMAS. This allowed the rapid development of a number of prototypes which eventually led to the final model and system.

The completed system was demonstrated to the strategy team using several past and current projects that were previously evaluated. In each case, the system responded with an evaluation that matched the strategy team's decision, providing some measure of satisfaction with, and confidence in the system. The development manager has since used DMAS to support his recommendation for several ongoing projects. The strategy team members decided to develop a similar evaluation system based on their joint expertise.

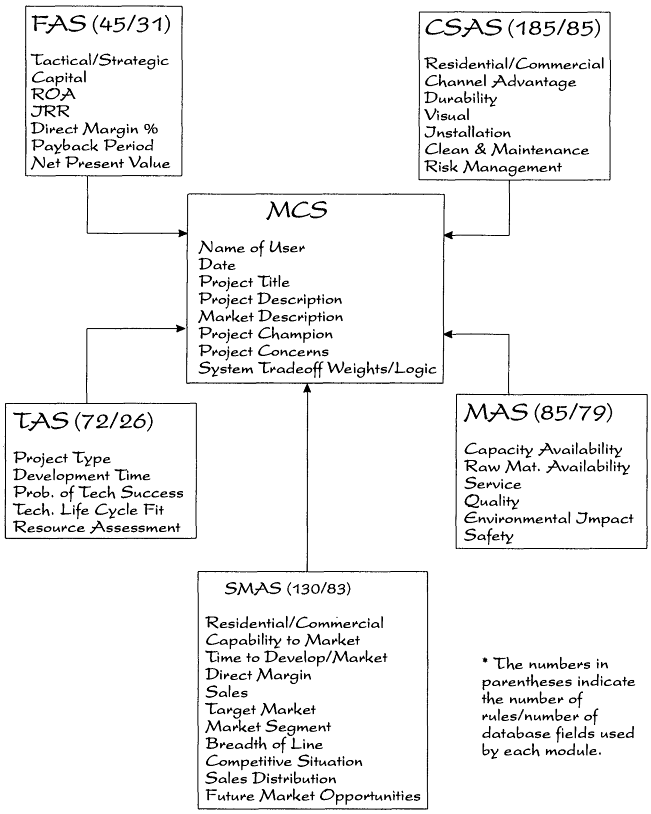
5.3. Multi-Expert System: PRAS

After several meetings with the strategy team, it was decided that a strategic product development evaluation system for the floor products operation required five major systems: technology, manufacturing, marketing, customer satisfaction, and finance. Figure 3 provides a diagram of the overall structure of the Project Assessment System (PRAS). The systems design process mandated that each system be capable of being used as a stand-alone system, or as a supporting system for an overall product evaluation. The intended users of PRAS are the business planning team members individually or as a group, as well as those development managers and/or project leaders who present their projects to the business planning teams for evaluation.

The first phase of system development required that prototype systems be developed based on the expertise of those individuals on the strategy team representing each area of responsibility. The technology and manufacturing systems were based on the expertise of their respective general managers. The operations manager of planning and distribution also participated in the development of the manufacturing system.

In floor products operations, development products are classified as either targeted to the residential or commercial markets. Thus, both residential and

Figure 3 PRAS Structure Chart



commercial sales and marketing managers participated in the development of the marketing system, with the residential manager assuming the lead position. The general manager of engineering, who is responsible for capital expenditures, was the primary expert for the financial system. During the course of the development cycle, the operations controller became a secondary expert to make sure that the system was consistent with operations and corporate financial standards. The general manager of marketing information was the key expert in the customer satisfaction system. The product styling and design general manager was responsible for developing a portion of the customer satisfaction system addressing this area.

The development process for the various systems was similar to that of the development manager's model (DMAS), with several exceptions. First, periodic meetings of the entire strategy team were convened to review the five system structure charts. During these meetings, team members would question and critique each other's systems, leading to further modifications. This step was necessary to ensure that the entire team was satisfied with each system since the team as a group made the final decision on each new product development project.

Second, discriminant analysis was used as a knowledge processing tool whenever the logic tables had too many entries requiring evaluation by the expert. For example, consider the durability assessment required in the customer satisfaction system. The discriminant function was developed to provide an overall durability assessment of excellent, very good, good, fair or poor based upon the user-supplied assessments of four durability subfactors. Each subfactor is rated by a PRAS user on a four-point scale: positive (as compared to current products on the market), neutral (or similar to current products), negative (worse than current products) or don't know. Thus, there are $4 \times 4 \times 4 \times 4 = 256$ durability cases which PRAS must be capable of evaluating to cover all the possibilities. To simplify the knowledge acquisition activity, an orthogonal sample of the cases was rated by the expert and a discriminant function was developed based on the results. The discriminant analysis was refined after experimentation by the expert. This resulted in either altered judgments for specific cases, or the addition of one or more evaluated cases that were added to the original sample.

Each discriminant function (such as the one used for durability assessment) was coded into an external program accessed by the expert system whenever an evaluation was required. For example, once the user interface obtained the ratings for each of the four durability subcriteria, the expert system passed this information to the discriminant function program, which then returned a durability rating by applying the coefficients of the subfactor values. These discriminant function coefficients remain fixed unless a revision is desired by the strategy team. In this situation, the expert would adjust his/her ratings of the cases in the original sample and/or add additional rated cases as needed.

Third, during one group session, each strategy team member was asked to allocate 100 points across the scores produced by the five systems. The results were obtained by secret ballot during the meeting and reported back to the group. The allocations offered by the team members had minor differences, with customer

Figure 4 **Technology Assessment System (TAS) Structure Chart**

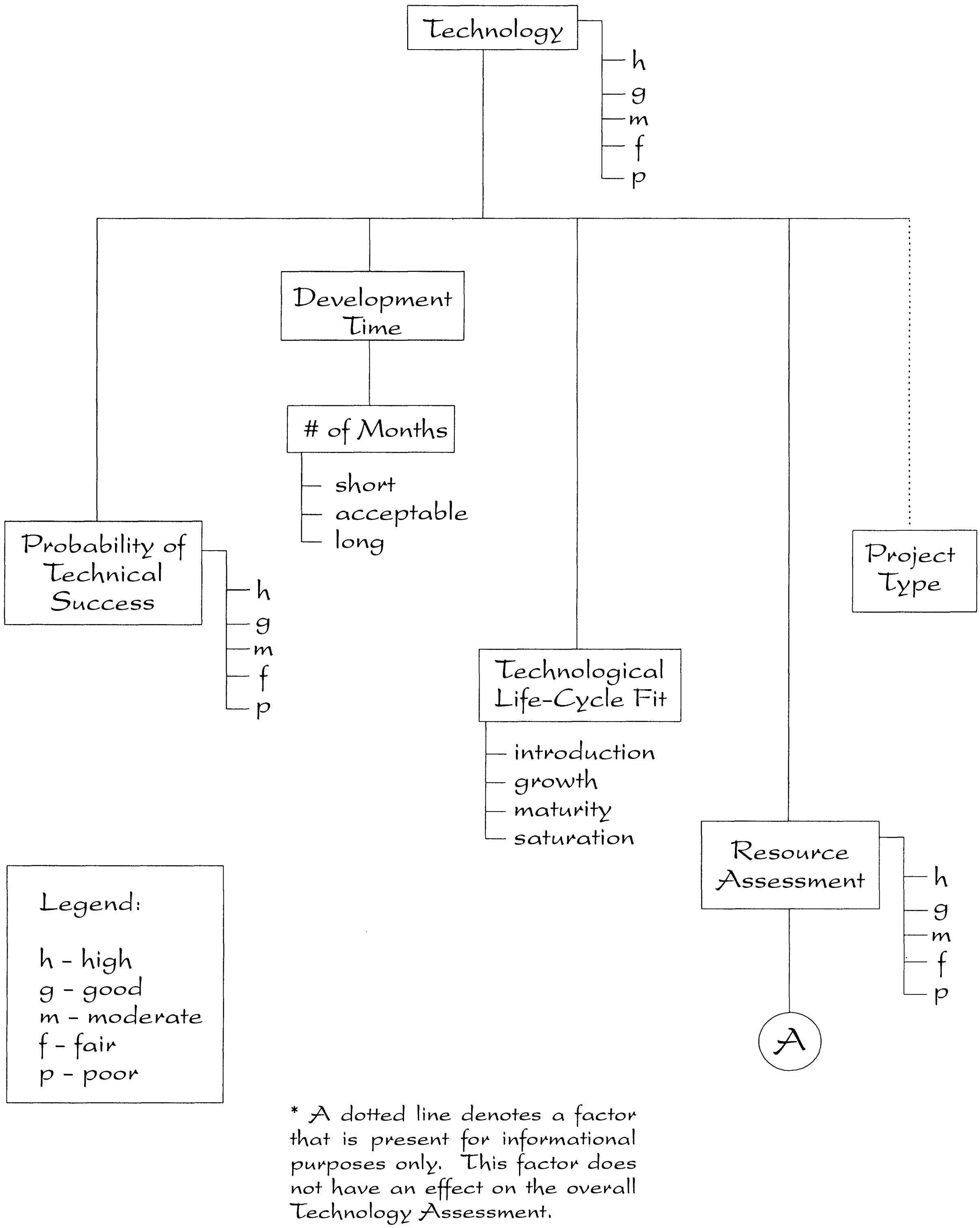
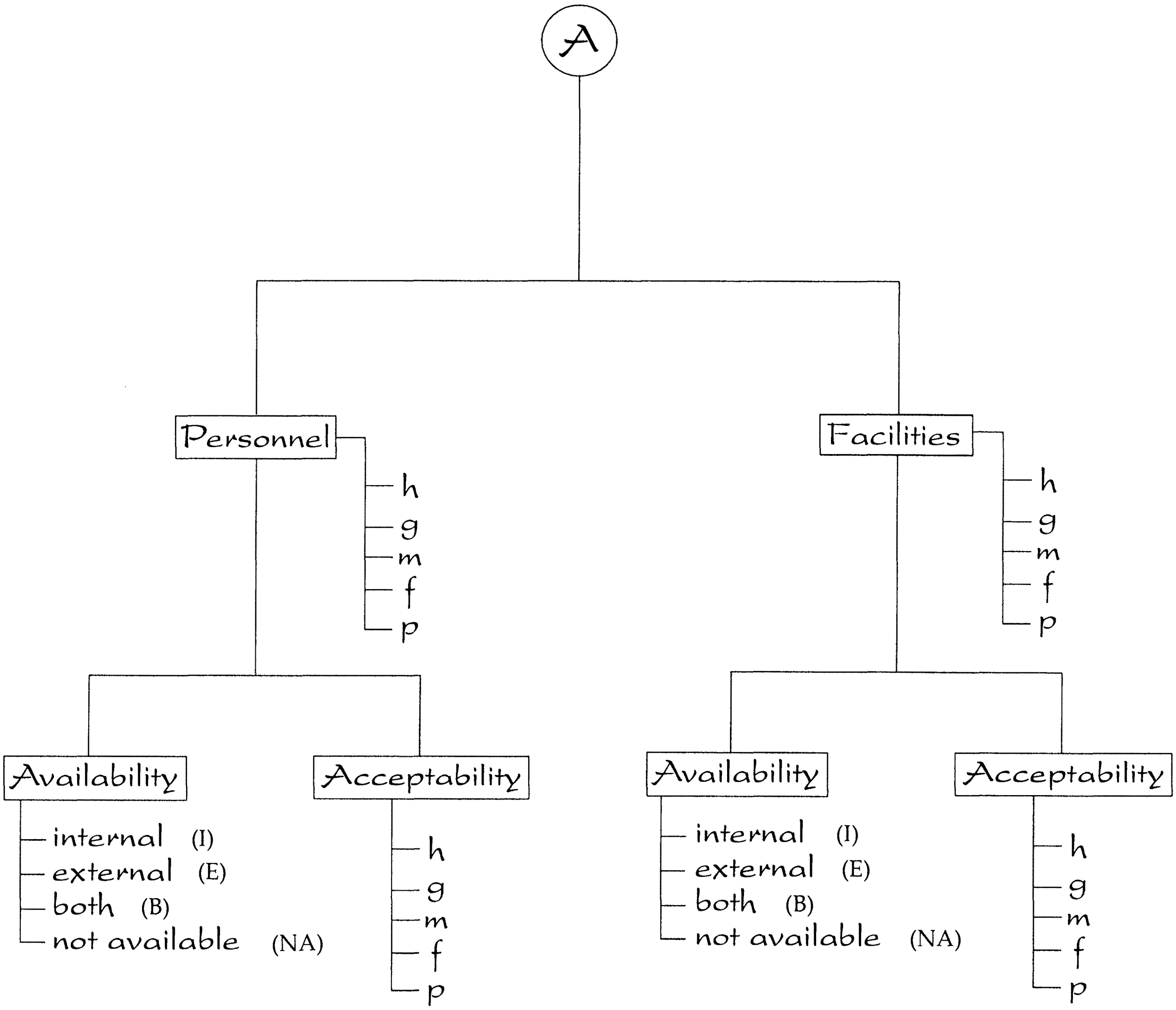


Figure 4 *Continued*



satisfaction receiving the largest weight, in consonance with Armstrong's strategic objectives. The group accepted an allocation of weights based on the median scores for each system. These system weights were incorporated into a master control system (MCS) which provides an overall evaluation of the project (see Figure 3). Together the MCS and the five expert support systems form a system for new product development evaluation, called PRAS. The MCS collects additional information about the development project (project champion, description, etc.) and integrates the results and diagnostics from each of the five systems.

5.4. The Technology Assessment System (TAS)

To illustrate the pertinent modeling and user interface issues addressed by each of the PRAS systems, we now consider the technology assessment system in some detail. Figure 4 provides a structure chart for the technology system, Table 2 displays sample rules, and Figure 5 shows a sample conclusion/summary screen from this system. Some of the questions asked of end-users concerning development time relate to division standards and lead to certain diagnostics. The development time ratings themselves, namely, short, acceptable, and long (which are defined in the system) influence the

Table 2 PRAS Sample Rules for Technology Assessment System (TAS)

RULE T1.5
IF Probability of Technical Success IS Poor . . . . 0 to 14
THEN Probability of Technical Success Assessment Has Been Done
AND Total_Tech := Total_Tech + (TECH_BASE.TSUCC*TECH_BASE.TSUCC_P)

RULE T2.0.1
IF Personnel Assessment IS High
AND Facilities Assessment IS High
OR Facilities Assessment IS Good
THEN Resource Assessment IS High
AND Total_Tech := Total_Tech + (TECH_BASE.RESOUR*TECH_BASE.RESOUR_H)

RULE T2.1.1
IF Personnel Availability IS Internally Only
AND Personnel Acceptability IS High . . . . 85 to 100
THEN Personnel Assessment IS High

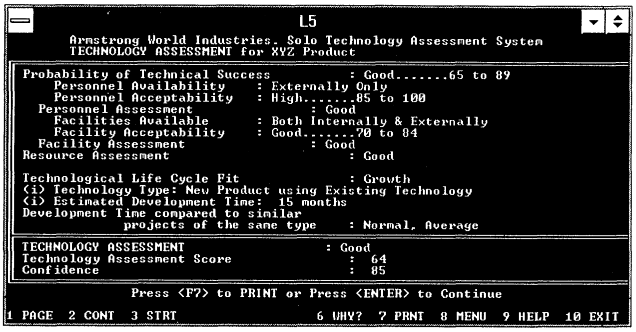
RULE T2.2.1
IF Facilities Availability IS Internally Only
AND Facilities Acceptability IS High . . . . 85 to 100
THEN Facilities Assessment IS High

RULE T3.1
IF Lifecycle Fit IS Introduction
THEN Lifecycle Assessment Has Been Done
AND Total_Tech := Total_Tech + (TECH_BASE.LIFE*TECH_BASE.LIFE_I)

RULE T5.0
IF Development Time < > 0
OR Development Time = 0
AND Comparison Has Been Done
AND Development Time Assessed
THEN Development Time Assessment Has Been Done

RULE T5.1
IF Development Time Comparison IS Shorter Than Average
THEN Development Time Assessed
AND Total_Tech := Total_Tech + (TECH_BASE.DTIME*TECH_BASE.DTIME_S)

Figure 5 Technology Assessment System (TAS) Summary Screen



evaluation through weights that are based on pairwise comparisons. On the other hand, the project type questions are informative in nature (and are included in the diagnostics) and do not influence the evaluation of the project under consideration.

The AHP was used to develop weights for the key criteria, namely probability of technical success (PTS), development time (DT), technological life cycle (TLC), and resource assessment (RA). A hypothetical set of pairwise comparisons and weights is given in Table 3. The AHP also was used to develop the weights for the

Table 3 Deriving Adjusted AHP Weights for the Technology Assessment System (Excluding Resource Assessment)

Overall Technology Criteria

	PTS	DT	TLC	RA	WTS
PTS		3	2	3	0.459
DT			1	1/3	0.119
TLC				1/3	0.137
RA					0.285

Inconsistency Ratio = 0.089

Probability of Technical Success (PTS)*

	HIGH	GOOD	MODERATE	FAIR	POOR	WTS	ADJ WTS*
HIGH		2	4	5	6	0.446	1.000
GOOD			2	3	4	0.240	0.538
MODERATE				4	5	0.185	0.415
FAIR					3	0.083	0.186
POOR						0.046	0.103

Inconsistency Ratio = 0.065

Development Time (DT)*

	SHORT	ACCEPT	LONG	WTS	ADJ WTS**
SHORT		2	5	0.595	1.000
ACCEPT			2	0.276	0.464
LONG				0.128	0.215

Inconsistency Ratio = 0.005

Technological Lifecycle (TLC)*

	INTRO.	GROWTH	MATURITY	SATURATION	WTS	ADJ WTS**
INTRODUCTION		1/2	5	7	0.346	0.672
GROWTH			6	7	0.515	1.000
MATURITY				2	0.086	0.167
SATURATION					0.054	0.105

Inconsistency Ratio = 0.027

* All of the categories are defined and illustrated within PRAS e.g., a high PTS may be defined as an estimate over 80%.
** Adjusted weights are obtained by dividing the AHP-derived weights by the maximum AHP weight.

scales or categories associated with PTS, DT and TLC as shown in Table 3. In each of these three cases the AHP-derived weights (also called local weights) had to be adjusted so that an absolute rating could be assigned to the project under evaluation. For example, if a candidate project was judged to be in the Growth phase of the TLC, an AHP local weight of .515 is appropriate in our example (last matrix in Table 3). Since Growth is the highest TLC category, then 100% of TLC's overall weight of .137 (first matrix in Table 3) should be scored. Similarly, if Introduction is selected, then .346/.515 = .672 of TLC's weight should be scored. This leads to an adjustment rule that requires dividing the local AHP weights for a criterion's category or scales by the maximum local AHP weight associated with that criterion. This adjustment was consistently applied throughout PRAS.[1]

The development of rating scale weights for the RA criterion required the use of several logic tables and the AHP as summarized in Table 4. The various combinations of the availability cases and acceptability scales lead to personnel and facilities assessments (see Table 4). These two assessments are combined through a logic table to provide overall resource assessment ratings. The weights attached to the resource assessment ratings were developed using pairwise comparisons. Consider the following example.

In the hypothetical example given in Table 4, a user response of Both for personnel availability and Fair for personnel acceptability lead to a personnel assessment of Good. For facilities, corresponding availability and acceptability responses of External and Fair, respectively, lead to a facilities assessment of Moderate. The Good personnel assessment and Moderate facilities assessment lead to a resource assessment of Good. Finally, using the adjusted AHP weights, a Good resource assessment is worth .806 of the total resource assessment (RA) criteria's weight (from Table 3), or a score of (.806)(.285) = .230.

The user responses to the various technology rating and subcriteria questions fire a series of if-then rules eventually leading to a normative evaluation (i.e., score) as illustrated above as well as other supporting outputs. The other systems, such as the customer satisfaction assessment system, operate in a similar fashion. The remaining system structure charts are omitted because of space considerations. The five evaluation systems along with the MCS are represented in knowledge bases containing a total of 518 rules. In addition, supporting databases containing AHP and scoring weights consist of 309 data elements.

[1] This same adjustment procedure can be used at the lowest level of any AHP hierarchy and thus avoid potential rank reversal problems. This adjustment procedure has been added to Expert Choice.

Table 4 Developing the Resource Assessment (RA) Ratings and Score

Personnel Logic Table			Facilities Logic Table		
Avail.	Accept.	Assess.	Avail.	Accept.	Assess.
I	H	H	I	H	H
I	G	H	I	G	G
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
$\boxed{B}$	$\boxed{F}$	$\boxed{G}$	$\boxed{E}$	$\boxed{F}$	$\boxed{M}$
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
NA	P	P	NA	P	F

Resource Logic Table

Pers.	Facil.	Assess.
H	H	H
H	G	H
•	•	•
•	•	•
•	•	•
$\boxed{G}$	$\boxed{M}$	$\boxed{G}$
•	•	•
•	•	•
•	•	•
P	P	P

Resource Ratings Weights

AHP MATRIX	H	G	M	F	P	Wts.	Adj. Wts.*
H		2	3	4	6	.403	1.000
G			3	5	7	.325	$\boxed{.806}$
M				2	5	.149	.370
F					2	.079	.196
P						.044	.109

Inconsistency Ratio = .036

* Adjusted Weights obtained by dividing the AHP-Derived Weights by the maximum AHP Weight.

Legend: I = Internal, E = External, B = Both, NA = Not Available; H = High, G = Good, M = Moderate, F = Fair, P = Poor.

5.5. System Validation and Verification

Validation is the process of determining if the system under development satisfies its stated purposes and user requirements (Landauer 1990, O'Leary 1987). Verification is a closely related process targeted towards testing the accuracy, consistency and completeness of the system's knowledge base (Nguyen et al. 1987) and ascertaining the degree to which the system can achieve acceptable performance levels reliably with sufficient accuracy (Radwan et al. 1989).

It is widely recognized and well documented (Gaschnig et al. 1983, Henderson 1987, O'Keefe et al. 1987, O'Leary et al. 1990, Nguyen et al. 1987) that verification and validation are "critical to the design and implementation of decision-making ESs" (O'Leary

1987). It is also a fact and a continuing source of criticism that many ES developers still fail to properly establish the validity of their systems (Eliot 1992, O'Keefe 1988).

Throughout the PRAS development life cycle we have integrated formal verification and validation procedures consistent with the frameworks and guidelines proposed by O'Leary (1987) and O'Keefe et al. (1987) and the paradigms described by O'Leary et al. (1990) and Radwan et al. (1989). These procedures included content, construct, subsystem, and input validity procedures, and are summarized in Figure 6.

In addition to the knowledge engineering team, participants in the validation and verification process included the individual experts, a special strategy team subcommittee, and other potential users. The work of the strategy team subcommittee has proved particularly important to the acceptance of PRAS. This committee, in cooperation with the development team, conducted an intensive effort to test and validate PRAS. Their efforts had three principal objectives: 1) to establish the validity of PRAS; 2) to determine their level of comfort with PRAS; and 3) to identify what changes (if any) were required before a decision on full-scale implementation. The subcommittee used PRAS to analyze in depth and assess twelve projects representing the spectrum of project types which PRAS will be expected to handle. The project mix included two technology assessment projects, seven completed and new product projects spread over the residential and commercial market segments, and three hybrid (product enhancement) projects. Some of these projects were evaluated during different runs of PRAS by different evaluators for an additional level of comparison. As a result of these runs, the following conclusions were reached by the subcommittee regarding PRAS's effectiveness:

(1) PRAS performs very well with accurate results when a project has a clear product and market focus.

(2) For new technology projects, the technology and customer satisfaction assessments are most useful, while the quality of the other assessments depends on the extent of knowledge about product and market focus.

(3) For process improvement projects, the usefulness of the customer satisfaction assessment depends on whether the change is visible to the customer. For example, if a new coating placed on the flooring product cannot be seen or felt (perceived) by the consumer, then, as one might expect, a customer satisfaction assessment at this stage in the development cycle is difficult. In addition, the financial assessment is affected differently by the multi-product focus associated with some process improvements.

(4) PRAS is especially useful for scenario analysis where the options for a given project are compared (e.g., residential vs. commercial markets, different manufacturing processes, etc.).

(5) The numeric assessment scores generated by PRAS become increasingly useful as more projects are run.

(6) PRAS helps to pinpoint issues that require resolution before decisions are made. For example, the need for a clearer product or market focus, or more details on the manufacturing process becomes evident after running PRAS.

(7) PRAS is not useful for analyzing maintenance projects (as discussed later, these are difficult for Armstrong to analyze under any circumstances), and is not sensitive to environmental issues. In the most recent version of PRAS, this latter limitation was corrected.

As a result of these conclusions, some minor modifications were suggested. Overall, the subcommittee was very pleased with PRAS's performance, and decided to recommend full-scale implementation.

To summarize, PRAS was subject to extensive and formal evaluation efforts throughout the system development process, all of which led the users to have confidence in the system's performance as a support tool. Based on the strategy subcommittee's strong supportive recommendation, PRAS is now on-line and being used by the strategy team.

PRAS is used to support critical strategic decisions in a volatile environment and the dynamic domain of R&D project evaluation. Such systems need to be continuously maintained and refined to reflect any new realities resulting from changes in the marketplace, the available technologies, or the organization's priorities. As a result, verification and validation needs to be a continuous process extending beyond the initial implementation. The effectiveness of PRAS is being re-evaluated with every new project processed and adjustments are made as necessary. Additional information regarding PRAS's success record is contained in the following section.

Figure 6 **PRAS Validation/Verification Activities**

Content Validity	
Direct Examination	On a regular basis during development the prototype rules, models, and factors were evaluated by the experts.
I/O Comparison	System outputs were compared with inputs given under a wide variety of scenarios.
Face Validation	The system's performance was compared with that of different experts.
Predictive Validation	Historic test cases were used to compare the system's performance with known results.
Sensitivity Analysis	The system's response was tested to variations in the input.
AHP Inconsistency Ratio	Where applied, AHP allowed the measurement of the consistency of the experts' judgements.
Construct Validity AHP Scoring Model Discriminant Analysis	This type of validity examines the underlying theory on which the system is based. Scoring models and AHP provide the underlying construct for PRAS. These are proven techniques for evaluation. PRAS also uses discriminant analysis which is a well known statistical classification technique.
Subsystem Validity Sensitivity Analysis I/O Comparison	PRAS was developed using a modular design. Modules were validated by running a range of input values representing different scenarios through each and evaluating the results.
Input Validity	Users are provided with a PRAS Input Guide specifying input requirements and procedures. The PRAS facilitator assists users with data preparation and related activities.

Knowledge Engineering Team

Experts

Strategy Team Validation Subcommittee

Users

5.6. System Use and Extensions

Once PRAS's implementation was approved, Armstrong appointed a system facilitator to assist all PRAS users with data preparation and related procedures and to coordinate the system's usage. Thus far, the strategy team has run all the active strategic projects through PRAS with excellent results. These projects included an exploratory project dealing with recycled materials, a technology project with no clear product focus, a maintenance project, a project at the pilot stage involving the use of alternative materials, and two projects with specific product-oriented focus at key decision points. For many of these projects, PRAS is used at various decision points to identify information requirements or to provide advice as additional information becomes available. Based on these runs, the strategy team verified its previous conclusion that PRAS works best with projects having a clear product focus. For three of these projects, the team adopted PRAS's recommendations: 1) one strong GO, project went to full-scale development; 2) one NO-GO, project was put on the shelf; and 3) one UNCERTAIN, more information was sought which led to an eventual NO-GO. For the two projects with no clear product focus (i.e., the exploratory and technology projects), PRAS's ability to highlight the various information requirements and evaluation criteria, as well as the assessments resulting from PRAS's individual modules were still found to be quite useful. The strategy team found the maintenance project difficult to analyze with or without PRAS, and subsequently decided to fold it into another project.

In addition to the strategic projects run through PRAS, four of the six tactical teams have made multiple runs for six active tactical projects and found that PRAS worked very well for decision support and scenario analysis. PRAS was also well received by the newly established global team that tested the system with one "live" project. They concluded that PRAS's output was quite helpful to their deliberations and indicated their interest in pursuing continued development of the system so that it can provide complete decision support for global projects.

The ceramic tile tactical team for residential products has implemented a modified version of PRAS called CT^3AS, the Ceramic Tile Tactical Team's Assessment System. This system uses the same basic structure of PRAS as illustrated in Figure 3. However, substantial modifications in the knowledge and rule bases were made in the customer satisfaction assessment system, while the changes required in the other component systems were relatively minor. Armstrong's development team has used a neural network to process the judgments contained in the logic table of the ceramic customer satisfaction module and is considering the pros and cons of integrating this network within the CT^3AS system. The development of CT^3AS and the ability to embed and integrate additional technologies (such as neural networks) attests to the basic soundness and flexibility of the framework presented here.

In addition, Armstrong is implementing a New Product Delivery (NPD) Process that will govern new product development activities at all levels—global, strategic and tactical. PRAS is being recommended for use as part of this process. The questions and issues that must be considered as part of this NPD process will require data that are needed for running PRAS. Thus, PRAS usage is projected to increase further, especially at the tactical level, once this new process is fully implemented. More details on the use of PRAS will follow in the next section.

6. Summary and Conclusions

The principal contributions of this research are threefold:

(1) a framework for the application of expert support systems for the strategic evaluation of new product development projects has been developed and described; this framework can be applied to a broader range of evaluation problems;

(2) new approaches for utilizing the analytic hierarchy process and discriminant analysis for knowledge acquisition and processing have been presented; and

(3) a series of related case studies that have successfully applied this framework have been described.

This research has demonstrated that management science can be successfully merged with knowledge-based and decision support systems. At the core of the proposed modeling framework are the methods and techniques used for acquiring, modeling and processing the expert knowledge and data. The suggested approach obtains the normative modeling benefits of traditional management science evaluation methods as well as the flexibility and developmental advantages of expert systems and related technologies. Additional hypothesized benefits of the proposed approach include the ability to reduce information processing and gathering time, which can help to accelerate the product development cycle.

Potential spinoffs of this research are applications of this framework and modifications of the systems designs for project evaluation throughout the product development cycle. Of course, the precise mix of factors and their interactions, as well as the level of knowledge concerning the issues addressed and questions asked change somewhat as one proceeds through the development cycle. However, the framework is still appropriate, and the methods and the techniques used in this research are still applicable. More broadly, the framework itself may be useful in other areas of project evaluation such as capital budgeting.

A series of related case studies that have successfully applied this framework were described. Decision support at the strategic level requires intense systems development efforts to achieve successful implementation. Users have expressed satisfaction and commitment to the systems developed, and have indicated that the systems offer them a competitive advantage. More detailed measurements concerning decision quality and cycle time reduction will be forthcoming in future research. The collection of such data will enable the testing of hypotheses relating to the use and effectiveness of expert support systems for new product development decision making across different industries and environments.[2]

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References

Augood, D., "A Review of R&D Evaluation Methods," *IEEE Transactions on Engineering Management*, EM-20 (1973), 114–120.

Baker, N. R., "R&D Project Selection Models: An Assessment," *IEEE Transactions on Engineering Management*, EM-21 (1974), 165–171.

—— and J. Freeland, "Recent Advances in R&D Benefit Measurement and Project Selection Methods," *Management Sci*., 21 (1975), 1164–1175.

—— and W. H. Pound, "R&D Project Selection: Where We Stand," *IEEE Transactions on Engineering Management*, EM-11 (1964), 124–134.

Balachandra, R., *Early Warning Signals for R&D Projects*, Lexington Books, Lexington, MA, 1989.

Bonczek, R. H., C. W. Holsapple, and A. B. Whinston, "Future Directions for Developing Decision Support Systems," *Decision Sciences*, 11, 4 (1980), 616–631.

Booz Allen & Hamilton, *New Product Management for the* 1980's, Booz Allen & Hamilton, Inc., 1982.

Cetron, M. J., J. Martino and L. Roepke, "The Selection of R&D Program Content—Survey of Quantitative Methods," *IEEE Transactions on Engineering Management*, EM-14 (1967), 4–13.

Clark, K. B. and T. Fujimoto, *Product Development Performance: Strategy, Organization and Management in the World Auto Industry*, Harvard Business School Press, Cambridge, MA, 1991.

Cooper, R. G., "A Process Model for Industrial New Product Development," *IEEE Transactions on Engineering Management*, EM-30 (1983), 2–11.

——, "Selecting Winning New Product Projects Using the NewProd System," *J. of Product Innovation Management*, 2 (1985), 34–44.

Courtney, J. F., D. B. Paradice and N. H. Ata Mohammed, "A Knowledge-Based DSS for Managerial Problem Diagnosis," *Decision Sciences*, 18, 3 (1987), 373–399.

Dean, B. V., *Evaluating, Selecting and Controlling R&D Projects*, AMA Research Study 89, American Management Association, 1968.

—— and M. Nishry, "Scoring and Profitability Models for Evaluation and Selecting Engineering Projects," *Oper. Res*., 13 (1965), 550–569.

—— and S. S. Sengupta, "Research Budgeting and Project Selection," *IEEE Transactions on Engineering Management*, EM-9 (1962), 158–169.

Dyer, J. S., "Remarks on the Analytic Hierarchy Process," *Management Sci*., 36 (1990a), 249–258.

——, "A Clarification of 'Remarks on the Analytic Hierarchy Process,' " *Management Sci*., 36 (1990b), 274–275.

El-Najdawi, M. K. and A. C. Stylianou, "Expert Support Systems: An Integration of Decision Support Systems, Expert Systems, and Other AI Technologies," *Communications of the ACM*, 36, 12 (1993), 55–65.

Fahrni, P. and M. Spatig, "An Application-Oriented Guide to R&D Project Selection and Evaluation Methods," *R&D Management*, 20 (1990), 155–171.

Feigenbaum, E. A., "Themes and Case Studies in Knowledge Engineering," in D. Michie (Ed), *Expert Systems in the Microelectronic Age*, Edinburgh University, Scotland, 1979.

—— and P. McCorduck, *The Fifth Generation*, Addison-Wesley, Reading, MA, 1983.

Gaschnig, J., et al., "Evaluation of Expert Systems: Issues and Case Studies," in F. Hayes-Roth, D. Waterman and D. Lenat, (Eds.), *Building Expert Systems*, Addison-Wesley, Reading, MA, 1983.

Gupta, A. K. and D. L. Wilemon, "Accelerating the Development of Technology-Based New Products," *California Management Review*, (Winter 1990), 24–44.

Gupta, S. K. and L. R. Taube, "State of the Art Survey on Project Management," in B. V. Dean (Ed), *Project Management: Methods and Studies*, North-Holland, Amsterdam, 1985.

Harker, P. T. and L. G. Vargas, "Reply to 'Remarks on the Analytic Hierarchy Process' by J. C. Dyer," *Management Sci.*, 36 (1990), 269–273.

Henderson, J. C., "Finding Synergy Between Decision Support Systems and Expert Systems Research," *Decision Sciences*, 18, 3 (1987), 333–349.

Holtzman, S., *Intelligent Decision Systems*, Addison-Wesley, Reading, MA, 1989.

Landauer, C., "Correctness Principles for Rule-Based Expert Systems," *Expert Systems with Applications*, 1, 3 (1990), 291–316.

Lee, J. B., *Intelligent Decision Support Systems for Business Applications: With an Example of Portfolio Management Decision Making*, Ph.D. Dissertation, New York University, New York 1986.

Liberatore, M. J., "A Decision Support Approach for R&D Project Selection," in B. L. Golden, E. A. Wasil and P. T. Harker (Eds), *The Analytic Hierarchy Process: Applications and Studies*, Springer-Verlag, Heidelberg, Germany, 1989.

——, "An Extension of the Analytic Hierarchy Process for Industrial R&D Project Selection and Resource Allocation," *IEEE Transactions on Engineering Management*, EM-34 (1987), 12–18.

—— and G. J. Titus, "The Practice of Management Science in R&D Project Management," *Management Sci.*, 29 (1983), 962–974.

—— and A. C. Stylianou, "Applying Expert Systems to Shorten the Product Development Cycle," final report submitted to the National Science Foundation and the Center for Innovation Management Studies, Lehigh University, Bethlehem, PA, October, 1991.

Luconi, F. L., T. W. Malone and M. S. Scott-Morton, "Expert Systems: The Next Challenge for Managers," *Sloan Management Review*, 27, 4 (1986), 3–14.

Merrifield, D. B., "Selecting Projects for Commercial Success," *Res. Management*, 24 (1981), 13–18.

Nguyen, T. A., W. A. Perkins, T. J. Laffey and D. Pecora, "Knowledge Base Verification," *AI Magazine*, 8, 2 (1987), 69–75.

O'Keefe, R. M., "Artificial Intelligence and the Management Science Practitioner: Expert Systems and MS/OR Methodology (Good News and Bad)," *Interfaces*, 18, 6 (1988), 105–113.

——, O. Balci and E. P. Smith, "Validating Expert System Performance," *IEEE Expert*, 2, 4 (1987), 81–89.

O'Leary, T. J., M. Goul, K. E. Moffitt and A. E. Radwan, "Validating Expert Systems," *IEEE Expert*, (1990), 51–58.

O'Leary, D. E., "Validation of Expert Systems—With Applications to Auditing and Accounting Expert Systems," *Decision Sciences*, 18, 3 (1987), 468–486.

Paolini, A., Jr. and M. A. Glaser, "Project Selection That Pick Winners," *Res. Management*, 20 (1977), 26–29.

Plebani, L. P., Jr. and H. K. Jain, "Evaluating Research Proposals with Group Techniques," *Res. Management*, 24 (1981), 34–38.

Quinlan, J. R., "Learning Efficient Classification Procedures and Their Application to Chess End Games," in R. S. Michalski, J. Carbonell and T. Mitchell (Eds), *Machine Learning, An Artificial Intelligence Approach*, Tioga Publishing Co., Palo Alto, CA, 1983.

Radwan, A. E., M. Goul, T. J. O'Leary and K. E. Moffitt, "A Verification Approach for Knowledge-Based Systems," *Transportation Res.*, 23A, 4 (1989), 287–300.

Ram, S. and S. Ram, "INNOVATOR: An Expert System for New Product Launch Decisions," *Applied Artificial Intelligence*, 2 (1988), 129–148.

—— and ——, "Expert Systems: An Emerging Technology for Selecting New Product Winners," *J. Product Innovation Management*, 6 (1989), 89–98.

Reinertsen, D. G., "Whodunit? The Search for the New-Product Killers," *Electronic Business*, July 1983, 62–66.

Roseneau, M., *Faster New Product Development*, Amacom, New York, 1990.

Saaty, T. L., "An Exposition of the AHP in Reply to the Paper 'Remarks on the Analytic Hierarchy Process,' " *Management Sci.*, 36 (1990), 259–268.

——, *The Analytic Hierarchy Process*, McGraw-Hill, New York, 1980.

Smith, P. G. and D. C. Reinertsen, *Developing Products in Half the Time*, Van Nostrum Reinhold, New York, 1991.

Souder, W. E., "Comparative Analysis of R&D Investment Models," *AIIE Transactions*, 4 (1972), 57–64.

Stylianou, A. C. and M. K. El-Najdawi, "Integration of ES into Strategic Planning Processes: A Conceptual Model and Managerial Implications," paper presented at TIMS/ORSA National Meeting, New York, October, 1989.

Turban, E. and P. R. Watkins, "Integrating Expert Systems and Decision Support Systems," *MIS Quarterly*, June 1986, 121–136.

Watts, K. M. and J. C. Higgins, "The Use of Advanced Management Techniques in R&D," *Omega*, 15 (1987), 21–29.

Wilkinson, A., "Developing an Expert System on Project Evaluation," *R&D Management*, 21 (1991), 19–29.

Winkler, R. L., "Decision Modeling and Rational Choice: AHP and Utility Theory," *Management Sci.*, (March 1990), 247–248.

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