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APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGY TO INCREASE PRODUCTIVITY, QUALITY AND ENERGY EFFICIENCY IN HEAVY INDUSTRY

Canada Centre for Mineral and Energy Technology

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CANADA'S GREEN PLAN
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APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGY TO INCREASE PRODUCTIVITY, QUALITY AND ENERGY EFFICIENCY IN HEAVY INDUSTRY

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EXECUTIVE SUMMARY

Automate or emigrate have become the practices of North American heavy industry during the 1990's in order to compete with the inexpensive labour, rich resource base and low regulatory environments in Asia and South America. To automate means to develop human/machine systems with specialized problem-solving capabilities. It also means to capture human expertise and knowledge on a computer. A key element in heavy industry's automation strategies has been advanced system control technologies and, lately, Artificial Intelligence (AI) technologies.

This study assesses the applications and benefits of AI systems implemented in heavy industry. It focuses on intelligent systems aimed at increased productivity, quality and energy efficiency in five industrial sectors: iron and steel, cement, mining and metallurgy, oil and gas, and pulp and paper. The study identified 177 applications of intelligent technologies in the areas of process control and monitoring, scheduling and planning, fault diagnosis and maintenance, and design. It evaluated the benefits to be accrued from intelligent systems and listed examples of improvements in productivity, quality and energy efficiency in each of the above application areas. The study also assessed the critical issues associated with, and barriers to, application of intelligent systems in the industry, based on interviews and a survey of developers and users of intelligent systems.

In addition to the industry-wide assessment, the study looked at intelligent systems implemented or demonstrated in each of the five sectors. For each sector, a summary of the systems implemented by the application type, geographic location and technology used has been compiled including descriptions of the systems. In total, 177 intelligent applications are described for the five sectors - 57 systems with detailed information on developers, implementation methods, and cost and benefits, and 120 systems with general information on solutions applied and benefits reported. As a supplement to this study, two appendices were prepared containing a comprehensive review of the AI tools available for development of intelligent systems, and the current AI trends and markets.

The study shows that although they are relatively new to the industry, AI technologies offer attractive solutions for the development of advanced control systems, management of production workflow, and training of staff. In addition to productivity and quality improvements, intelligent systems can significantly reduce energy use in energy intensive operations through better control and scheduling of production, and reduction of work disruptions. Intelligent technologies are no longer a concept or a program for tomorrow. They are a realistic solution for today's problems in heavy industry.

TECHNICAL SUMMARY

The specific objectives of this study have been to: 1) assess current uses of Artificial Intelligence (AI) in heavy industry and related industries; 2) identify where and how AI may increase productivity, quality and energy efficiency in industry; 3) identify key barriers to the development and implementation of intelligent systems in heavy industry; and 4) identify application targets in five industrial sectors: iron and steel, cement, mining and metallurgy, oil and gas, and pulp and paper.

The study identified three major challenges facing heavy industry in 1990's (Table 1). AI's role in meeting those challenges is to provide computer technology for management of production knowledge and for further development of systems control and automation. Rationale for the application of AI in heavy industry are listed in Table 2.

Table 1. CHALLENGES FACING HEAVY INDUSTRY IN 1990'S

1. Structural Changes: increased competition, movement of capital, worldwide access to technology, regulatory barriers.
2. Production Challenges: increased speed of production, smaller and more varied orders, just-in-time production, demand for high quality products.
3. Competitive Issues: shift of emphasis from production technology, capital and labor costs to management of knowledge.

Table 2. RATIONALE FOR AI IN HEAVY INDUSTRY

1. need to further automate and/or develop systems with specialized problem-solving capabilities.
2. limitations of conventional computer technologies which are difficult and often ineffective for automation of complex plant operations.
3. AI advantages such as the ability to manage information, knowledge and production decisions, provide advice on how to optimize production, make inferences and implement control decisions.
4. AI roles as an extension of conventional control technologies, new technologies for management of operational know-how and expertise, new technologies for efficient computer programming of complex systems.

The study identified 177 intelligent systems prototyped and/or applied in heavy industry. Figure 1 shows the systems applied in each sector by application but does not include the 6 cross-cutting applications which can be applied in all sectors. Key application areas identified and unique capabilities offered by AI were:

- Process Control: low level control, fault detection, diagnosis and alarming, handling control devices, and sensor diagnostics. Includes capabilities to acquire, analyze and display data intelligently, make inferences and reason about the process, and implement complex control decisions.

- Process Monitoring: high level control, improving access to process information, on-line decision support, and analysis of crucial events. Includes capabilities to model decision processes instead of equipment or operations, provide consistent shift-to-shift operations, and promote better understanding of processes and training.

- Scheduling and Planning: integration of orders, production planning, cost accounting, market forecasting, and planning equipment status. Includes capabilities to generate several feasible solutions, implement high level reasoning, mimic the expert's mapping out methods, and handle uncertainties and conflicting constraints.

- Fault Diagnosis and Maintenance: reduction of equipment downtime, process mishaps and production loss, monitor hundreds of machines, and systematic analysis of information about equipment failure. Includes capabilities to make the expertise of the best maintenance personnel available at all times and to apply this expertise, and to handle large amounts of information.

- Design: generation of alternative designs.

Typical benefits gained from the implemented intelligent systems are listed in Table 3. These benefits and performance were confirmed by a worldwide survey of developers and users of intelligent systems (Table 4).

The report demonstrates that intelligent technologies are no longer a concept or a program for tomorrow. They are a realistic solution for today's problems in heavy industry.

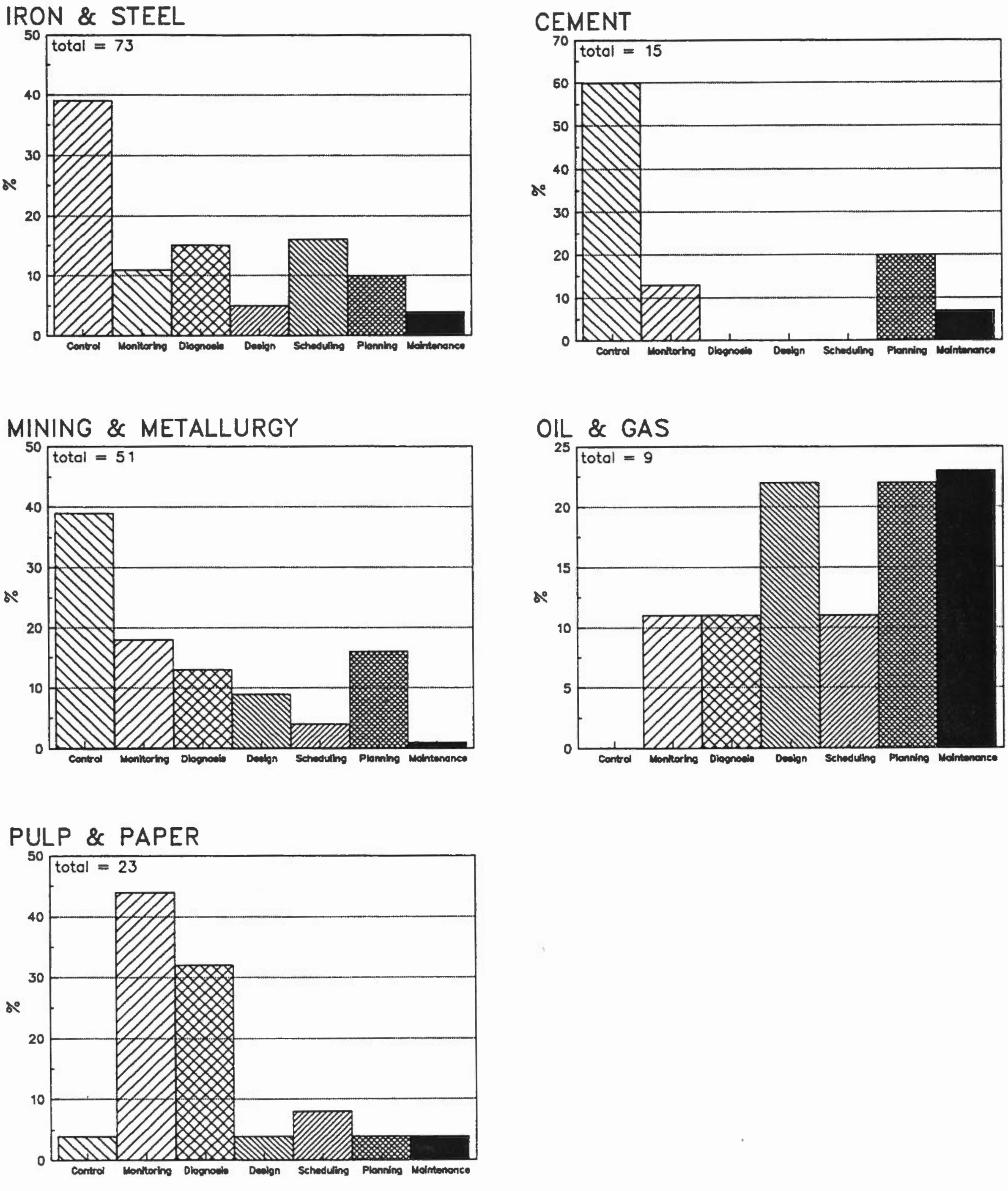

Figure 1. EXPERT SYSTEMS USED IN HEAVY INDUSTRY BY SECTOR AND APPLICATION

Table 3. AI PERFORMANCE AND BENEFITS

1. Productivity (control): improved stability of the process, quick adaptation to process changes, improved control of plant disturbances, elimination of the effects of shift changes, reduced work disruptions, increased efficiency of materials flow.

2. Productivity (monitoring and diagnosis): process diagnosis is improved, more consistent decisions by non-experts, decreased quality variation, expertise retained in the company, reduced downtime and repair time.

3. Productivity (scheduling): improved staff scheduling, quick rescheduling of new, urgent orders, reduction of machine waiting time, improved schedule quality, increased yield.

4. Quality Improvement: better understanding of process and equipment, improved diagnosis of quality problems, more consistent quality though better training of staff, increased quality.

5. Energy efficiency: reduced energy waste due to work disruptions, energy optimization due to better response to operating changes, reduced peak and average processing temperatures, improved consistency of heat control, reduced peak demand of electricity.

Table 4. Percentage of Developers/Users Reporting Specific Benefits

Benefit	Percent of Respondents
Quality	63
Productivity	50
Reliability	41
Labour Efficiency	32
Maintenance	23
Safety	18
Energy Use	14

RÉSUMÉ

Pour pouvoir concurrencer l'Asie et l'Amérique du Sud, qui possèdent une main d'oeuvre bon marché, des ressources abondantes et une réglementation peu rigoureuse, l'industrie lourde nord-américaine doit, pendant les années 1990, s'automatiser ou émigrer. Choisir l'automatisation signifie concevoir des systèmes homme-machine capables de résoudre des problèmes précis et traduire sous forme informatisée les connaissances et l'expertise humaines. Parmi les éléments essentiels des stratégies d'automatisation de l'industrie lourde figurent les technologies perfectionnées de contrôle des systèmes et les technologies de l'intelligence artificielle (IA) (apparues plus tard).

La présente étude évalue les applications et les avantages des systèmes d'IA utilisés dans l'industrie lourde. Elle met l'accent sur les systèmes intelligents visant à augmenter la productivité, la qualité et l'efficacité énergétique dans cinq secteurs industriels : le fer et l'acier, le ciment, l'exploitation minière et la métallurgie, le pétrole et le gaz et les pâtes et papiers. L'étude a recensé 177 applications des technologies intelligentes dans les domaines de la surveillance et du contrôle des procédés, de l'ordonnancement et de la planification, des diagnostics de panne et de l'entretien et, enfin, de la conception. Elle comporte une évaluation des avantages à tirer des systèmes intelligents et cite des exemples d'amélioration de la productivité, de la qualité et de l'efficacité énergétique dans chacun des domaines d'application susmentionnés. L'étude comprend en outre une évaluation (fondée sur des entrevues et un sondage auprès des fabricants et des utilisateurs de ces systèmes) des principales questions liées à l'application des systèmes intelligents dans l'industrie, ainsi que des obstacles à cette application.

Les responsables de l'étude, en plus de faire une évaluation dans l'ensemble de l'industrie, se sont penchés sur les systèmes intelligents appliqués ou démontrés dans chacun des cinq secteurs. Ils ont fait, pour chaque secteur, un résumé des systèmes exploités en les décrivant et en indiquant leur genre d'application, leur situation géographique et la technologie utilisée. En tout, ils ont décrit 177 applications intelligentes pour les cinq secteurs : 57 systèmes avec des renseignements détaillés sur les responsables de leur mise au point, les méthodes de mise en application, les coûts et les avantages, et 120 systèmes avec des renseignements généraux sur les solutions appliquées et les avantages retirés. Deux annexes complètent l'étude : un examen exhaustif des outils (IA) disponibles pour la conception des systèmes intelligents ainsi qu'un aperçu des tendances et de la situation actuelle des marchés de l'IA.

Il ressort du document que même si les technologies d'IA sont relativement nouvelles sur le marché, elles constituent une solution intéressante pour le développement de systèmes de contrôle perfectionnés, la gestion du volume de travail et la formation des employés. En plus de contribuer à l'amélioration de la productivité et de la qualité, les systèmes intelligents peuvent réduire considérablement la consommation d'énergie des activités énergivores en assurant un meilleur contrôle et un ordonnancement amélioré de la production ainsi qu'une réduction des interruptions de travail. Les technologies intelligentes ne sont plus des concepts d'avenir, elles constituent une solution réaliste aux problèmes de l'industrie lourde aujourd'hui.

RÉSUMÉ TECHNIQUE

La présente étude avait quatre objectifs précis : 1) évaluer les diverses utilisations de l'intelligence artificielle (IA) dans l'industrie lourde et les industries connexes, 2) déterminer où et comment l'IA peut accroître la productivité, la qualité et l'efficacité énergétique dans l'industrie, 3) trouver les principaux obstacles au développement et à la mise en application des systèmes intelligents dans l'industrie lourde et 4) préciser les objectifs d'application dans cinq secteurs industriels : le fer et l'acier, le ciment, l'exploitation minière et la métallurgie, le pétrole et le gaz et les pâtes et papiers.

Selon l'étude, trois défis de taille attendent l'industrie cours des années 1990 (tableau 1). Le rôle de la TA, dans ce contexte, est de fournir la technologie informatique pour la gestion des connaissances sur la production et pour le perfectionnement du contrôle et de l'automatisation des systèmes. Vous trouverez au tableau 2 les raisons qui justifient l'application de l'IA à l'industrie lourde.

Tableau 1. DÉFIS QUE L'INDUSTRIE LOURDE AURA À RELEVER DANS LES ANNÉES 1990

1.	Changements structuraux : concurrence accrue, mouvement de capitaux, accès mondial à la technologie, obstacles réglementaires.
2.	Production : rythme de production accru, commandes plus petites et plus variées, production au moment adéquat, demande pour des produits d'excellente qualité.
3.	Concurrence : changement de priorités : la technologie de production ainsi que les coûts des investissements et de la main-d'oeuvre cèdent la place à la gestion des connaissances.

Tableau 2. RAISONS JUSTIFIANT L'UTILISATION DE L'IA DANS L'INDUSTRIE LOURDE

1.	Nécessité d'automatiser davantage et de créer des systèmes capables de résoudre des problèmes.
2.	Limites des technologies informatiques classiques difficiles à adapter et souvent inefficaces lorsqu'il s'agit d'automatiser des opérations industrielles compliquées.
3.	Les avantages de l'IA, comme la capacité de gérer de l'information, des connaissances et des décisions en matière de production, de fournir des conseils sur la façon d'optimiser la production, de faire des inférences et d'appliquer des décisions sur le plan du contrôle.
4.	Les rôles de l'IA comme prolongement des technologies de contrôle, les nouvelles technologies pour la gestion du savoir-faire et de l'expertise sur le plan des opérations, les nouvelles technologies pour une programmation efficiente des systèmes complexes.

L'étude a permis de dénombrer 177 systèmes intelligents utilisés dans l'industrie lourde, sous forme de prototype ou sous leur forme définitive. Le Tableau 1 indique les systèmes appliqués dans chaque secteur selon leur application, mais n'inclus pas les 6 applications qui peuvent être utilisées dans tous les secteurs. Les principaux domaines d'application retenus et les capacités uniques offertes par l'IA sont les suivants :

- Contrôle des processus : contrôle de bas niveau, détection des pannes, établissement d'un diagnostic et avertissement, manipulation des dispositifs de contrôle et utilisation des diagnostics des capteurs. Nécessite la capacité d'acquérir, d'analyser et d'afficher des données avec intelligence, de faire des inférences et des raisonnements au sujet des processus et d'appliquer des décisions de contrôle complexes.

- Surveillance des processus : contrôle de haut niveau, amélioration de l'accès à l'information sur les processus, aide à la prise de décisions en direct et analyse des faits importants. Nécessite la capacité de modéliser les processus décisionnels plutôt que l'équipement ou les opérations, d'assurer un fonctionnement constant et de favoriser une meilleure compréhension des processus et de la formation.

- Ordonnancement et planification : intégration des commandes, planification de la production, comptabilisation des coûts, établissement des prévisions de marché et des prévisions sur l'état de l'équipement. Nécessite la capacité de trouver plusieurs possibilités de solutions réalisables, d'appliquer un raisonnement poussé, de reproduire les méthodes de planification des experts et de régler les problèmes attribuables aux incertitudes et aux contraintes conflictuelles.

- Diagnostic sur les pannes et entretien : réduction du temps de panne de l'équipement, des contretemps et des pertes sur le plan de la production, surveillance de centaines de machines et analyse systématique des renseignements sur les pannes d'équipement. Nécessite la capacité de rendre accessibles en tout temps les compétences des meilleurs employés spécialisés en entretien, d'utiliser ces compétences et de traiter de grandes quantités d'informations.

- Conception : génération de concepts alternatifs.

Les avantages de l'utilisation des systèmes intelligents sont énumérés au tableau 3. Ces avantages ainsi que les renseignements sur le rendement ont été confirmés par un sondage fait auprès de responsables du développement et d'utilisateurs de systèmes intelligents du monde entier (tableau 4).

Le rapport démontre bien que les technologies intelligentes ne sont plus des concepts d'avenir, elles constituent une solution réaliste aux problèmes de l'industrie lourde aujourd'hui.

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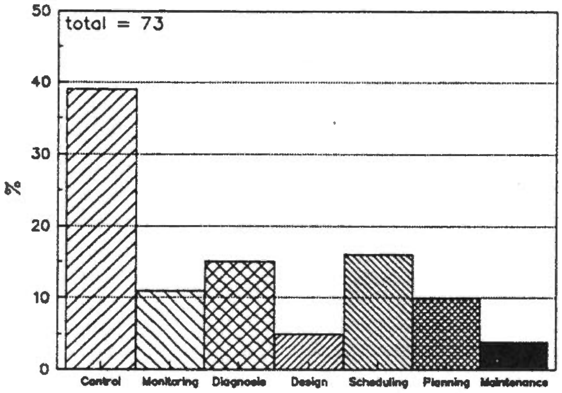

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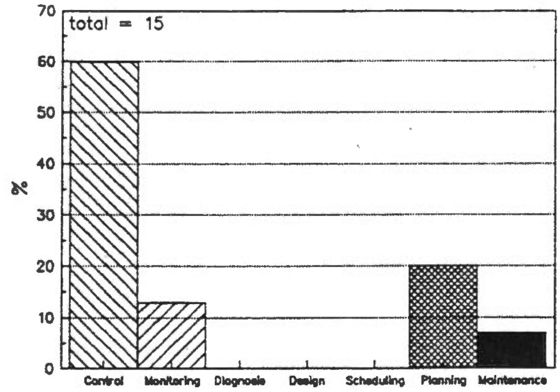

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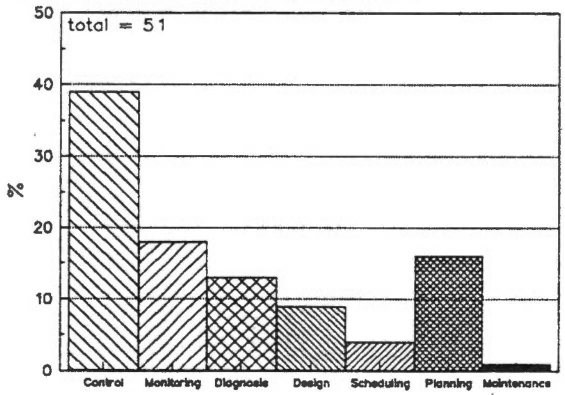

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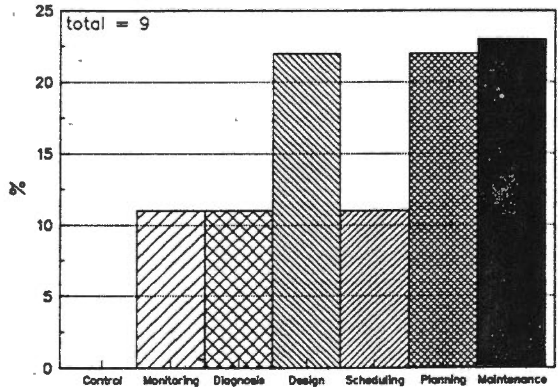

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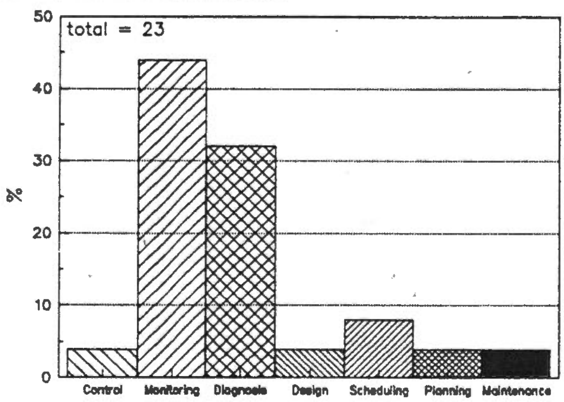

Tableau 1. SYSTÈMES EXPERTS UTILISÉS DANS L'INDUSTRIE LOURDE PAR SECTEUR ET APPLICATION

Tableau 3. RENDEMENT ET AVANTAGES DE L'IA

1. Productivité (contrôle) : amélioration de la stabilité des processus, adaptation rapide aux changements de processus, amélioration du contrôle des perturbations dans les usines, élimination des effets des changements de quarts, réduction des interruptions de travail, augmentation de l'efficience du traitement des matières.

2. Productivité (contrôle et diagnostic) : amélioration du diagnostic et de l'uniformité des décisions prises par des personnes qui ne sont pas expertes, diminution des fluctuations dans la qualité, maintien des personnes compétentes dans l'entreprise, réduction des temps de panne et de réparation.

3. Productivité (ordonnancement) : amélioration de l'établissement des horaires de travail des employés, rapidité de l'ordonnancement des nouvelles commandes urgentes, réduction du temps d'attente, amélioration de la qualité du calendrier, accroissement de la production.

4. Amélioration de la qualité : meilleure compréhension des processus et de l'équipement, amélioration du diagnostic sur les problèmes de qualité, uniformisation accrue de la qualité grâce à une meilleure formation des employés, amélioration de la qualité.

5. Efficacité énergétique : réduction du gaspillage d'énergie causé par les interruptions de travail, optimisation de l'utilisation d'énergie attribuable à une meilleure réponse aux changements opérationnels, à une réduction des températures de traitement élevées et moyennes, à une amélioration de la constance du réglage de la chaleur et à une réduction de la demande de pointe d'électricité.

Tableau 4. Pourcentage de responsables du développement et d'utilisateurs qui rapportent des avantages précis

Avantage	Pourcentage des répondants
Qualité	63
Productivité	50
Fiabilité	41
Efficacité de la main-d'oeuvre	32
Entretien	23
Sécurité	18
Consommation d'énergie	14

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1. SUMMARY

1.1. Introduction

Significant structural changes have been occurring in heavy industry over the last 10 years. Increased competition, movement of capital, and worldwide access to technology have exerted pressure on the industry to restructure its operations and business. The industry has had to respond to challenges like increased scale and speed of production, smaller and more varied orders, just-in-time production and delivery, and rapid changes in technology. To meet these challenges the industry sought strategies which would reduce production costs and time, improve product quality, and save energy. A key element in these strategies has been advanced system control technologies.

Control technologies have always played an important role in increasing the competitiveness of heavy industry. In the 1960's, on-line computer systems were introduced to centralize plant process control and information flow. In the 1970's and 1980's microprocessor technology brought distributed computing and cost effective redundancy to computerized control systems. Microprocessor-based programmable logic controllers replaced most of the analog logic systems and allowed introduction of advanced, modern control theory in industrial practices. As a result, in the 1990's, computer-based control systems are common in the industry. Today's computer-based process control systems acquire data, and perform complex analysis and control actions based on process models or statistical process control. The systems are networked to provide specific information at various technical and managerial levels.

During the 1990's, in the search for further improvements in production and scheduling methods, the industry is increasingly seeking computer-assisted management of human assets including management of production expertise, staff training, etc. Many companies have recognized that their competitive advantages are no longer based on production technology, capital or labour costs. Instead, their competitive advantages are based on the knowledge of their employees, i.e. on employees' ability to process information and data in all aspects of production and business including marketing, scheduling, and control of production processes. A key computer technology applied to management of knowledge and human resources has been Artificial Intelligence, specifically its application fields of expert systems, machine learning, neural networks, and fuzzy logic, all referred to in this report as intelligent systems.

This study assesses the applications and benefits of the intelligent systems implemented in heavy industry. It does this by evaluating existing applications of intelligent systems in five industry sectors: iron and steel, cement, mining and metallurgy, oil and gas, and pulp and paper. The study focuses on intelligent systems aimed at increased productivity, quality and energy efficiency. These three issues - productivity, quality and energy efficiency - are considered to be interdependent and are treated as the key components in heavy industry's strategy to achieve higher competitiveness. Therefore, it also has an impact on electrical utilities and other energy suppliers.

1.1.1. Report Organization

Chapter 1 summarizes the main results of this study in the context of all heavy industry sectors. It starts with an analysis of the rationale for the implementation of intelligent systems and a description of the type of AI applications and solutions used in the industry. This is followed by a review of the reported performance and benefits of the AI systems. This chapter also identifies the changes needed and issues to be addressed in the implementation of intelligent systems in heavy industry. The examples and conclusions in the chapter are based on the AI systems implemented and a survey of developers and users of AI systems conducted especially for this study.

Chapters 2 through 6 review intelligent systems applications in iron and steel (Chapter 2), cement (Chapter 3), mining and metallurgy (Chapter 4), oil and gas (Chapter 5), and pulp and paper (Chapter 6). Each chapter provides an overall analysis of the application types and technologies used in the sector. It also lists selected application targets, other systems implemented, and related applications. A definition of each category is given in the respective chapters.

Chapter 7 lists selected cross-cutting applications of intelligent systems, i.e., systems that are relevant to all sectors.

In addition, two appendices were prepared in support of this study. Appendix A: AI Primer, provides a historical overview of AI, and an analysis of current AI markets and trends and Appendix B: Intelligent Tools, reviews in detail technologies and tools available for developing intelligent systems.

1.2. AI Applications in Heavy Industry

1.2.1. <u>Rationale for AI in Heavy Industry</u>

Automate or emigrate have become the practices of North American heavy industry during the 1990's in order to compete with the inexpensive labour, rich resource base and low regulatory environments in Asia and South America. To automate means to develop human/machine systems with specialized problem-solving capabilities. It also means to capture human expertise and knowledge in a computer.

Automation helps prevent costly shutdowns, can increase yield and quality, and can result in operating the process and equipment more effectively and efficiently. However, automation of some production aspects is often not easy because plant operations exhibit complex interactions under rapidly changing circumstances. Many of the plant operations can not be mimicked by simple models or are not well understood. The actions of operators are ambiguous, imprecise, and based on experience and intuitive knowledge that can not be programmed or modeled using mathematical methods or simple algorithms. All of these factors make the use of conventional computer technologies difficult and often ineffective for automation of production processes. To derive better performance from computers and to supplement the conventional control technologies with more advanced features, the industry has turned, therefore, to artificial intelligence methods which can facilitate the management of information, knowledge and production decisions.

Artificial Intelligence (AI) is a branch of computer science that studies human-like intelligence and capabilities of reasoning. (For background information on AI see Appendix A: AI Primer). Intelligent systems discussed in this study are computer programs and hardware that offer specialized capabilities in analyzing data, information and knowledge to make production decisions or implement control actions. They offer a number of benefits for automating production processes and procedures. They can:

- manipulate large amounts of information
- detect operating irregularities
- suggest adequate remedies and provide advice on how to optimize the production
- make inferences and implement control decisions.

They can be viewed as:

- an extension of conventional control technologies
- new technologies for management of operational know-how and expertise
- new technologies for more efficient computer programming of complex systems.

All three views of AI technologies are correct, yet they also limit our understanding of intelligent systems' capabilities. For example, one of the key motivations behind the use of intelligent technologies is the fact that they can deal with human cognitive limitations, i.e., human failure to monitor all information, to resolve complex and conflicting situations, to identify high-revenue opportunities or to prevent high-cost mistakes. Another motivation behind the use of intelligent systems is the increasing need for higher quality and greater availability of production expertise to deal with the increased complexity of production problems. Intelligent systems assist in training novice operators, provide decision support, or mimic human reasoning in narrowly defined domains. They have the ability to keep track of thousands of pieces of information while commanding the knowledge of several experts.

1.2.2. Application Types and Situations

Intelligent systems can play a number of roles in heavy industry. These roles are as diverse as tuning control loops or providing expert diagnostic advice (Figure 1.1).

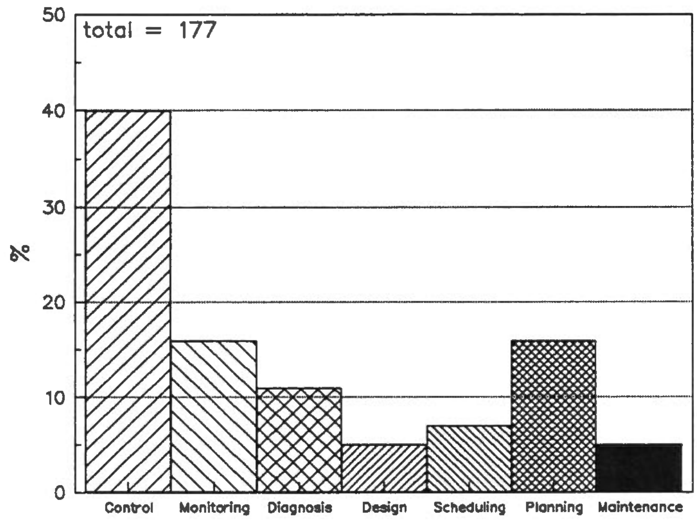

Figure 1.1. AI USE IN HEAVY INDUSTRY BY APPLICATION

Intelligent systems have been used in major industrial countries worldwide (Figure 1.2) and employ a number of different technologies (Figure 1.3).

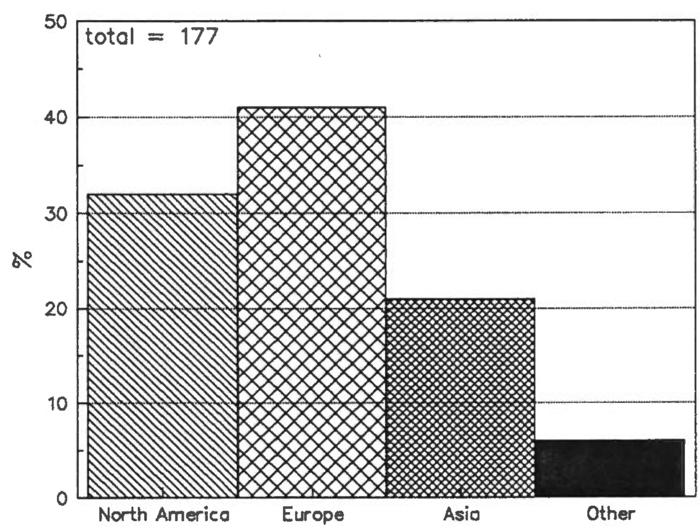

Figure 1.2. AI USE IN HEAVY INDUSTRY BY CONTINENT

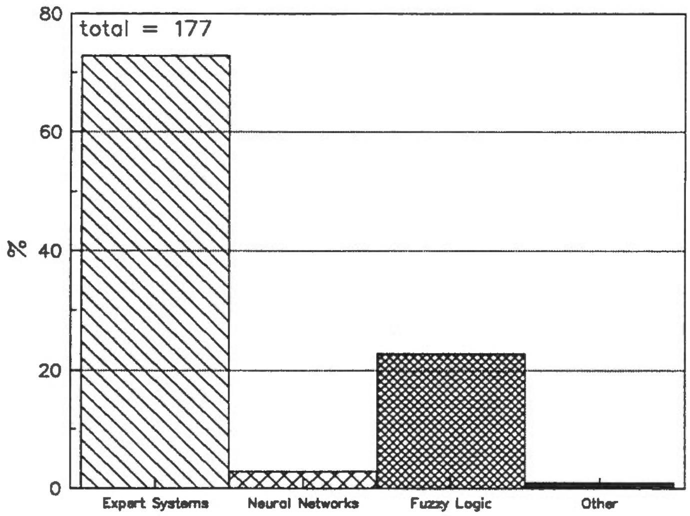

Figure 1.3. AI USE IN HEAVY INDUSTRY BY TECHNOLOGY

From the application point of view, intelligent systems usually perform one of the following functions:

- process control
- process monitoring
- scheduling and planning
- maintenance and diagnosis
- design.

The following sections discuss the application of intelligent systems for heavy industry in terms of these functions. The discussion and examples are based on experiences and benefits reported in over 200 intelligent systems implemented in the sector.

Process Control

These tasks usually involve automation of low-level control (loop control) in a real-time system. The implemented systems are concerned with fault detection, diagnosis and alarming, and with operating the control devices in the control loops. The systems can run in several modes including continuous scanning, executed only when new data are available, or activated by specific external events, e.g., change of feed properties. Integral parts of intelligent systems' functions are sensor diagnostics, handling of erroneous or missing data, performing temporary reasoning, etc. The systems often incorporate mathematical models of unit processes and operations, and empirical control rules acquired from the operators.

Examples of intelligent systems applications in process control are Nippon Steel's system for preventing caster break-outs during the continuous casting of steel (**Iron & Steel**, p. 49), the Control International system for tuning controllers to correct for highly non-linear dynamics in the operation of semi-autogenous grinding mills (**Mining and Metallurgy**, p. 93) and the Automation Technology system for updating control models as process conditions change in brownstock operations (**Pulp & Paper**, p. 123).

Real-time intelligent systems are complex and expensive. They have to contain some understanding of the process, handle a large number of external variables and control devices, have access to the control system's database, and be integrated with large distributed data handling systems. They also must model the fine details of the plant, need high power computers, and need time-critical integration with existing system control methods and algorithms. Their implementation is difficult because of the number of sentry tasks and the burden of maintaining these tasks in real-time.

Despite the level of skill needed and the high cost of implementing real-time intelligent control systems, a significant number of these systems has been implemented in heavy industry. About 40 percent of all intelligent systems identified in this study have been applied in process control (Figure 1.1). This is especially true for the iron and steel, cement and metallurgical sectors where real-time systems offer unique capabilities, i.e. they:

- acquire, analyze and display data intelligently
- make inferences and reason about the process
- implement complex control decisions in real time.

One of the key issues in implementing intelligent systems is choosing an appropriate AI application. As a general rule, it is less risky to improve on an existing process application than to look for a new one. Since intelligent control applications improve or enhance existing conventional control systems, they are considered to be good application candidates in spite of their high cost and complexity.

Process Monitoring

The application of advanced, model-based process control in heavy industry has brought better optimization, stability and control quality to industrial processes. Yet not all processes and unit operations can be described by detailed control models. Processes are often too complex or not sufficiently understood to write mathematical equations describing multivariable interactions. The same processes are, however, often controlled well by human operators using experience and mental models of the process.

A major problem of control based on the operator's mental model of the process is frequent inconsistency of the control actions. This inconsistency leads to quality variations and to yield and product losses among different operators and shifts. Variability due to human factors can be effectively reduced, however, by improving operators' knowledge and by providing operators with better access to process information.

Improving production control by improving operators' access to knowledge and process information is part of the supervisory control or control monitoring (top-down approach), where operators are provided with on-line decision support but are not replaced by automation. In general, control monitoring systems compare and analyze the process behavior of events that are crucial to successful operation. They identify potential and existing malfunctions and suggest any corrective actions that should be implemented by the operators.

The top-down approach to production control has a number of advantages. By modeling decision-making processes and not equipment or operations, on-line decision-support systems provide consistent shift-to-shift quality, higher productivity, and lower product cost executed at the performance level of the best operator. The systems monitor plant information and make recommendations only where they are needed, thus preventing cognitive overload. They may automate some tasks (usually repetitive tasks requiring less skill) to allow operators to concentrate on the major tasks. Supervisory type intelligent systems are event-driven, interactive and responsive tools for decision-making. They can be built and maintained at a lower cost than real-time control systems and can access other plant information like data concerning process and equipment troubleshooting, and statistical process control.

Decision-support systems are easier to implement than real-time systems especially for complex, less understood processes. They result in better formalization of domain knowledge and better understanding of tasks and processes. The top-down approach separates knowledge from logic of control, and thus makes the knowledge easier to understand, learn and update.

Intelligent applications for control monitoring constitute about 20 percent of the intelligent systems implemented in heavy industry and are implemented about evenly in all heavy industry sectors. Good examples of advanced, on-line supervisory control systems are POSCO's system for diagnosing abnormal blast furnace conditions (**Iron and Steel**, p. 42), the Outukump Oy system for control of flotation cells at copper mines (**Mining and Metallurgy**, p. 87), the Kemira Oy expert system for optimization of phosphate flotation (**Mining and Metallurgy**, p. 89), and the Wiggins system for control of coater/paper machines (**Pulp & Paper**, p. 121).

A note of caution is due with regard to decision-support systems. They can be easily ignored by operators since they do not perform any direct control actions. When operators find the decision system less knowledgeable than themselves, they are likely to stop using it.

Decision-support or supervisory-control systems are both communication tools and learning tools, making the knowledge of experienced operators available when and where it is needed. They can act as off-line advisory systems that use information from databases or information provided by questions-and-answers from keyboard input. Because these systems can explain the logic of their control actions, they are excellent vehicles for learning and training.

At most plants, training tends to be carried out on the job. This often results in perpetuating misunderstandings and misinformation about the process from one generation of operators to another. These difficulties in the training tasks are further compounded by high turnover rates, slow transfer of knowledge from existing personnel to new staff, and loss of know-how with loss of experienced personnel. Also, the detailed operational knowledge required to run a plant is frequently buried in the plant manuals rather then being easily accessible to novice operators.

Intelligent training systems allow operators to train onsite but off-line. Examples of such systems are Paprican's system for training operators to solve quality problems in a boxboard mill (**Pulp and Paper**, p. 115), Chevron's supervisory control of refinery operations (**Oil and Gas**, p. 107), and the Kemira Oy supervisory system for grinding and flotation control (**Mining and Metallurgy**, p. 89). Intelligent systems assist in training by :1) making essential operating knowledge accessible; 2) diagnosing and correcting students' behavior including their weaknesses in knowledge; 3) recommending information that needs to be learned through tutorial interactions.

Scheduling and Planning

More varied orders, just-in-time manufacturing, and the desire to ensure delivery times and good end-product quality are some factors that have increased the need for operational flexibility and underscore the importance of scheduling and planning in the industry. Traditional approaches to production scheduling used intermediate buffers to cope with poor production coordination. Today, buffers are often eliminated in an attempt to react to variations in order size and specifications. Also, production scheduling is considered in the context of a complex analysis of incoming orders, production processes, cost accounting, market forecasting, and plant equipment state.

Although a number of computer-based approaches claim to provide fully automated scheduling, in practice, this is rarely the case because of poorly defined constraints, ambiguous evaluation criteria, and a vast number of available possibilities. Also, it is not always possible to develop accurate mathematical models of target objectives and organizational goals, which are required by the operational research approach. A practical approach to scheduling generates feasible solutions that satisfy local constraints while the user ensures that global constraints are also satisfied. This approach is called cooperative scheduling. The computer generates several schedules, but the user has the final choice in selecting the preferred schedule. After selection, the preferred schedule can be modified further.

Intelligent systems offer several advantages in developing computerized scheduling systems. They:

- can represent symbolic and non-mathematical knowledge
- can use expert heuristics to reduce the search space
- offer easy implementation of high level reasoning
- can mimic the expert's mapping out methods in scheduling
- can carry on distributed processing to implement specific tasks at appropriate locations
- can include information on limitation bottlenecks, quality variables, strategy changes, etc.
- are more flexible than conventional scheduling systems
- can handle uncertainties, vagueness, and conflicting constraints.

Instead of presenting one optimization schedule, AI-based scheduling systems present several schedules with their evaluation indexes. The operator can then select the optimum schedule. The advantage of intelligent schedulers is reduced scheduling time which allows more frequent production rescheduling as new orders and requirements arrive.

This study identified over forty intelligent scheduling and planning systems implemented in heavy industry. The systems are used in all sectors and constitute about 20 percent of the systems implemented (Figure 1.1). Examples of the diversity of intelligent scheduling systems are the Voest-Alpine system for planning operations of a continuous slab caster (**Iron & Steel**, p. 48), the Yukong Ltd expert system for delivering crude oil to its refineries (**Oil and Gas**, p. 105), the Tanoma Coal systems for selecting staff for different shifts in underground mining (**Mining and Metallurgy**, p. 86), and the Oji Paper Co. scheduling expert system for paper production (**Pulp and Paper**, p. 120).

Fault Diagnosis and Maintenance

Fault diagnosis and maintenance constitute a significant fraction of operating cost. Maintenance costs can reach up to 50 percent of the equipment cost while the time spent on diagnosis often approaches 60 percent of the total time required to correct operational problems. The problem of fault diagnostics is further compounded by the fact that good diagnostic expertise is rare and not available 24 hours a day.

To reduce operational costs due to equipment downtime, process mishaps, and production loss, industry has implemented preventive maintenance programs such as condition-monitoring techniques to diagnose damaged components and estimate lifetime expectancy before breakdowns occur. However, these tasks can be quite complex because hundreds of machines may need to be monitored, data have to be interpreted by qualified maintenance personnel, and complex diagnostic problems are time consuming to solve even by the experts. These problems can be compounded by the fact that primary defects can lead to secondary defects and it may not be apparent which defects initiated the problem. All of the above call for a systematic approach to analyzing information about failures in order to identify the true causes of process mishaps.

Artificial Intelligence systems offer a number of advantages for working with diagnostic problems. First, they can monitor and analyze hundreds of sensors, determine any anomalies in their functions and identify probable causes of the discrepancies between expected and actual operating conditions. They can incorporate the expertise of the best maintenance personnel, information from equipment manuals, previous records of equipment/process failures, etc. The systems can be available to the operators and maintenance personnel at all times and at the right locations. They can have embedded human expert reasoning and heuristics about diagnostic problem solving including detailed information on process and equipment performance and possible malfunctions.

Diagnostic and maintenance applications constitute about 15 percent of all intelligent applications in heavy industry (Figure 1.1). The number is quite low for all sectors with the exception of Pulp and Paper where diagnosis and maintenance constitute over 30 percent of AI applications. Examples of diagnostic expert systems in the industry are Nippon Steel's expert system for preventive maintenance of over 500 pieces of electrical and mechanical equipment (**Iron and Steel**, p. 60), LKAB's use of AI for diagnosing transmission of load-haul-dump mine vehicles (**Mining and Metallurgy**, p. 88), the Wiggins Teape Appleton system for paper machine fault diagnosis (**Pulp and Paper**, p. 114), and the PAPRICAN system for diagnosing pitch formation in kraft pulp plants (**Pulp and Paper**, p. 117).

Design

Opportunities for using intelligent systems in design are the least understood and explored of all AI applications in heavy industry. There are several barriers to the introduction of computerized systems in design beyond the drafting, cataloguing, or visualization of the designs. The process of design involves a large number of combinations, and, often, subjective judgements. Design problems are similar to scheduling and planning problems, yet they also involve more than a simple configuration of objects that can satisfy defined constraints of the problem.

Progress has been made in the application of AI in design where the objective of the systems is to assist the designer in generating alternative designs for further refinement by the human expert. Examples of implemented systems are the Nippon Steel Felt system for design of wet felts for paper machines (**Pulp and Paper**, p. 116) and the Schlumberger system for design of cement slurry for oil well casings (**Oil and Gas**, p. 106). However, in total the design systems constitute less than 5 percent of the identified intelligent applications in heavy industry (Figure 1.1).

1.2.3. Performance and Benefits of Intelligent Systems

Because AI is a new technology in heavy industry, many of the application areas are still difficult to quantify and there are no industry-wide studies documenting the costs and benefits of intelligent systems applications. However, a number of case studies report significant benefits accrued due to intelligent systems, such as reducing plant cost and improving customer services.

A survey of users and developers of intelligent systems, conducted as a part of this study, showed that the majority of intelligent applications are less than three years old. The survey included over 50 respondents active in implementing and developing intelligent systems in industry. They each have applied/developed, on average, three intelligent systems and 60 percent of the respondents identified applications in heavy industry specifically.

The following is a summary of the benefits and performance of intelligent system applications identified and evaluated in this study.

Productivity (Control)

Improved stability of the process, quick adaptation to process changes and feed variation, and improved control of plant disturbances are the most frequent benefits reported from the implementation of intelligent systems. Other reported benefits are elimination of the effects of shift changes, reduced duration of work disruptions, and increased efficiency of materials flow and utilization. The value of these benefits depends on the case or situation, but good indications of typical gains in productivity are given below:

- Wiggins Teape Appleton, UK (**Pulp and Paper**, p. 114) improved productivity by 2 percent and reliability by 1 percent through implementation of Level Expert for diagnosis and control of "level" problems in paper machines. Wiggins also improved (Pulp and Paper p. 6-12) plant uptime by 2 percent by implementing an AI system for control of paper coater machines.

- Kemira Oy, Finland (**Mining and Metallurgy**, p. 89) increased phosphates flotation concentrate recovery by 1.5 percent by application of intelligent control systems at its Siilinjarvi plant.

- Control International, US (**Mining and Metallurgy**, p. 93) increased copper ore plant throughput by 5 to 8 percent and productivity of mills by 6 to 15 percent with the application of an expert system for control of semi-autogenous grinding circuits.

- Cementos Cruz Azul, Mexico (**Cement**, p. 74) increased plant productivity by 1.7 percent after implementing a kiln optimization expert system.

- Ciments Francais, France (**Cement**, p. 76) improved kiln availability by 10 percent and throughput by 5 percent by the use of fuzzy logic expert systems at its cement plants.

- General Cement Co., Greece (**Cement**, p. 77) improved plant productivity by 4 to 5 percent with the use of an intelligent system for supervisory control of cement manufacturing.

Productivity (Monitoring & Diagnosis)

The most frequently reported benefits from the implementation of intelligent systems for process diagnosis are improved, more consistent decisions by non-experts, decreased quality variation in the product, expertise being kept in the company, and reduced downtime and repair time, the net result being higher productivity. Good examples of these benefits are:

- Nippon Steel, Japan (**Iron and Steel**, p. 49) breakout detection in a continuous caster improved by about 6.5 seconds over a conventional system. Nippon Steel also reports (**Iron and Steel**, p. 60) the reduction of maintenance staff by 35 people at its Oita Works by implementing intelligent diagnosis of equipment faults in steel manufacturing.

- PAPRICAN, Canada (**Pulp and Paper**, p. 117) showed 90 percent accuracy in diagnosis of pitch problems in kraft pulp mills by using its Pitch Expert System.

Productivity (Scheduling)

Increased productivity due to improved staffing scheduling; the ability to reschedule production for new, urgent orders; and improved schedule quality, such as reduction of machine waiting time are the most frequently reported benefits of intelligent scheduling. Examples of more flexible, optimized production scheduling are:

- Kawasaki Steel (**Iron and Steel,** p. 53) reduced schedule development time for seamless steel pipe production from 11 hours to 2-3 hours by implementing intelligent systems for planning the hot rolling processes.

- NKK Corp., Japan (**Iron and Steel**, p. 56) reports they reduced scheduling time for steel making from 4 hours to less than 30 minutes by implementing intelligent system Scheplan.

- Oji Paper, Japan (**Pulp and Paper**, p. 120) reduced the time required to develop the monthly schedule for paper production from 3 days to 2 hours.

Quality

Better training of new staff and service personnel, development of better understanding of process issues and equipment behavior, and improved diagnosis of quality problems are examples of how implementation of intelligent systems can result in quality improvement. Examples of the magnitudes of those gains are given below:

- Nippon Steel, Japan (**Iron and Steel**, p. 45) improved optimization of BOF operations and reduced the variance of carbon, phosphorous and manganese in its steel products with the use of a hybrid expert system.
- Sumitomo Metal, Japan (**Iron and Steel**, p. 47) reports reduction of melt level fluctuation in a continuous caster by 40 percent through application of a real-time expert system.
- Kawasaki Steel, Japan (**Iron and Steel**, p. 50) reports the correct classification of stenciled characters on slabs increased to 99 percent through the use of a neural network-based intelligent character recognition system.
- Hitachi, Japan (**Iron and Steel**, p. 52) improved shape control of rolling mills by reducing the degree of steepness from 1.8 to 1.4 percent with an intelligent system.
- ABB LINKman, UK (**Cement**, p. 75) improved klinker grindability by 2.5 to 5 percent through its expert control of a cement manufacturing plant.

Energy

Energy use in energy intensive industries can be affected by a number of production faults. When production stops, large amounts of energy can be wasted in terminating operations and then resuming them. If a production line stops for a long period of time, material and product flows throughout the entire plant can be disturbed requiring rescheduling of production plans. Intelligent systems can offer significant direct and indirect energy savings by improving process diagnosis, stability and consistency in operations and by improving the control response to operating changes.

Typical operational benefits reported by high energy users (iron and steel, cement, and metallurgical sectors) from implementing intelligent systems are:

- reduced peak and average processing temperatures
- more stable and efficient furnace operations
- improved consistency of heat control
- reduced peak demand electricity charges
- reduced discharge of nitrogen oxides and other emissions.

These operational gains result in significant energy savings and energy efficiency improvements. Examples of the magnitude of energy savings achieved are:

- Kawasaki Steel, Japan (**Iron and Steel**, p. 38) reports an increase of 3 percent in hot stove efficiency through the use of fuzzy logic for automatic control of hot stove combustion.

- British Steel, UK (**Iron and Steel**, p. 61) reports energy savings of 1.5 percent from the implementation of an expert system for optimization of boilers at its steel plants.

- Cementos Cruz Azul, Mexico (**Cement**, p. 74) reports a 8.2 percent reduction in energy use including a 7.6 percent reduction in electricity consumption from implementation of its TOP EXPERT system.

- ABB LINKman, UK (**Cement**, p. 75) reduced fuel consumption by 2.5 to 5 percent (10 percent best) by the application of a fuzzy logic expert system for control of cement kilns.

- Ciment Francais, France (**Cement**, p. 76) reported a 3 percent reduction in heat consumption and a 8 percent reduction in electricity use from the implementation of BATEXPERT system.

- Control International, US (**Mining and Metallurgy**, p. 93) reports a decrease in energy consumption of 4 to 5 percent from the implementation of an expert system for control of grinding circuits.

In general, for the systems studied, the reported energy efficiency improvements were 2 to 5 percent. It was difficult, however, to evaluate the distribution of the efficiency gains by the type of energy, e.g., fossil fuels vs electricity, because only a few companies provided detailed enough information on the distribution of the energy used.

Other

Additional information about the benefits of intelligent systems (Table 1.1) has been provided by a worldwide survey of over 50 developers and users of AI systems. Sixty-three percent of the developers and users reported their applications resulted in quality improvement and fifty percent reported productivity improvement. Twenty-seven percent of the respondents could not determine or did not see any benefits from at least one of their applications.

Table 1.1. PERCENTAGE OF DEVELOPERS/USERS REPORTING SPECIFIC BENEFITS

Benefit	Percent of Respondents
Quality	63
Productivity	50
Reliability	41
Labour Efficiency	32
Maintenance	23
Safety	18
Energy Use	14

Over sixty percent of the respondents rated the success of their applications as high or very high. Less than 20 percent of respondents rated the success of their applications as low or very low. Responses further confirmed the case specific benefits of intelligent systems, as listed in Selected Application Targets for each sector.

1.3. Implementation of AI Systems

1.3.1. Changes Needed

Heavy industry is, in general, cautious and conservative when it comes to the introduction of new technologies. This is understandable, for any misapplication of technology can have serious consequences in terms of production or capital losses. Another rationale often given in explaining the conservative attitude of the industry is the possible loss of opportunities in capital utilization, especially in times of capital shortage. In practice, however, the cost of introducing AI technologies is small in comparison to typical capital layouts in the industry.

It appears that the most important factor affecting implementation of intelligent technologies in the industry is management's understanding of the issues involved in technology transfer. In the early stages of use, it is often difficult to comprehend the range of applications offered by the new technology. However, with each new application, the benefits and risks of the new technology become easier to assess. Eventually, companies that are able to tailor the new technology to their needs benefit most. It is important, therefore, that in implementing intelligent technologies, management takes a long-term view of technology transfer and understands that operating staff will need considerable time to feel comfortable with the new systems.

Heavy industry has some cultural characteristics that do not favour intelligent technologies. The industry often views those who can quickly fix operational problems as heroes, yet those who prevent failures from happening in the first place are often not noticed. The industry also values control tools more than decision-support tools, because control tools can decrease the number of people needed for plant operation.

Today's state-of-the-art computerized control technologies suggest that the bottom-to-top approach to automation of the operator tasks, which involves removing the operator from the control loop, will be increasingly more complex and expensive. What seems to be less recognized is that by giving operators more responsibility (top-to-bottom approach), industry can achieve better, less costly productivity improvements. However, this approach requires that management provide operators with better decision-support tools, share more information and delegate more decision-making.

1.3.2. Stages of Implementation

Although development of intelligent systems differs in many aspects from the development of conventional software, in general, introduction of AI systems follows three stages: exploration, interaction and implementation (Figure 1.4). A detailed description of these phases is beyond the scope of this report. For more information, the reader is referred to the textbooks listed in Appendix C.

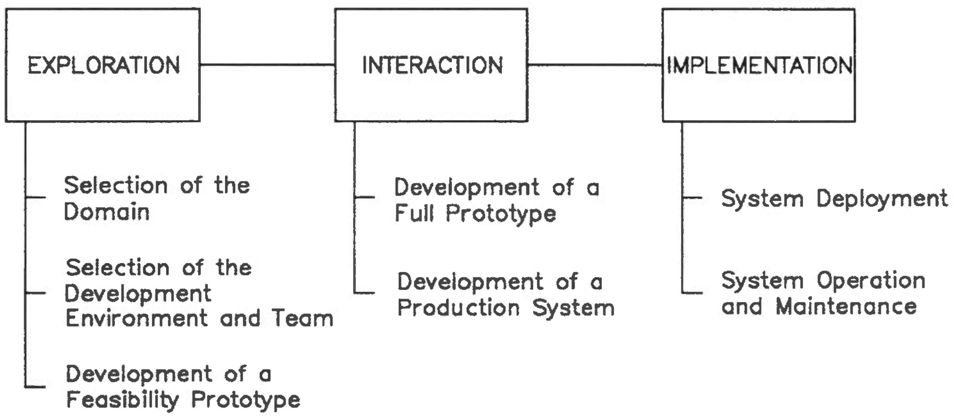

Figure 1.4. STAGES OF IMPLEMENTATION

1.3.3. Issues in Implementation

The issues in implementing intelligent systems are strongly dependent on:

- the objective of the project: is it to introduce technology into the organization or to solve a specific problem that other methods can not solve?
- resources available: can the organization develop its own group that will act as a technology broker within the organization or will it have to rely on an outside group?
- specific barriers: these tend to be plant specific.

The objective of each specific AI project determines a number of implementation issues. The early applications of intelligent systems were usually designed as one-of-a-kind solutions for solving critical problems and required non-routine development which made the projects expensive and risky. To reduce the risk, several systems have been developed that screen potential applications using elaborate criteria. The approach of screening potential AI applications has, however, some inherent problems. First, choosing an appropriate application can take from 10 to 50 percent of total resources. Second, the focus on a set of defined criteria for project selection, although useful, does overemphasize the requirement that each project has to stand on its own. This may be acceptable if isolated problems are being solved. However, experience shows that isolated applications, even if technically successful, often fail because of the lack of a technology transfer strategy by the user and low acceptance of the developed solution by the operating staff. One should note, however, that isolated projects are often successful when implemented to automate process control. In these situations, the intelligent methods are embedded or integrated within the process control system and do not require operators' support.

This study indicates that the best application results have been obtained when a comprehensive strategy is developed for transferring AI technologies into the plant culture. In such situations, every project, whether successful or not, adds to the body of knowledge and experience upon which the next applications are built. For example, it may be better initially to use AI technologies to assist in more mundane tasks like sensor validation, and signal processing while preparing to solve larger problems.

The resources available for introducing AI technologies into operations determine, to a large extent, the long-term benefits accrued from intelligent systems. This study shows that the amount of resources allocated to introducing intelligent systems varies significantly among sectors and even more among geographic locations (Figure 1.2). In Asia, in the iron and steel sector (e.g., Nippon Steel, Kawasaki Steel, NKK Corp., Sumitomo) most of the intelligent applications have been developed by in-house groups. In Europe, in the pulp and paper, metallurgy and cement sectors (e.g., Outokumpu, Rautaruukki, Ciments Francais) most intelligent applications were developed by in-house groups which identify the applications and oversee the transfer of AI technologies. In North America, intelligent applications are more likely to be introduced by research institutes, consultants and European engineering companies which developed/acquired key AI technologies. An exception to this rule is the oil and gas sector where many North American companies have in-house groups specializing in advanced control and intelligent systems.

A strong reliance on outside groups for implementing new technologies like AI has some potential pitfalls. For example, this approach may implement AI solutions but not transfer the technology, or it may preclude accumulation of expertise at the plant level. The success of the application also depends heavily on selection of the right application and on acceptance of the solution by the operating staff.

The development of in-house groups, knowledgeable in AI, contributes to the orderly and effective introduction of intelligent systems. It can also have other positive benefits such as ensuring that expertise is available to train production staff in identifying benefits and suitability of AI applications. This approach has been taken even further by companies like Kawasaki, Monsanto and Du Pont which stress the need for operational staff to develop and implement intelligent systems. The underlying rationale is that in many applications the process domain experience outweighs the AI experience. Providing process engineers with the proper tools and knowledge would result in better applications and implementations. The duties of in-house specialists include training and assisting process engineers, identifying portability of intelligent solutions to similar problems in other plants, and conducting organization-wide research on the application of AI.

Another strategy for introducing intelligent systems is the use of sector-wide, jointly-funded projects, the results of which are later shared by the funding companies. Experience shows that for common industry problems the sector-wide approach can be effective. Examples of this approach are ABB LINKman's system for control and optimization of kilns in cement plants (**Cement**, p. 75), and PAPRICAN's system for control of pitch formation in kraft pulp mills (**Pulp and Paper**, p. 117). The sector-wide approach can be successful if the developed intelligent systems can be implemented at different plants with only minor changes. Many of the process applications are unique, however, because of different technologies, equipment, etc. at the various plants and are thus not easily amenable to sector-wide solutions.

There is an expectation in the industry that equipment manufacturers and control system vendors will be providing AI technologies in the future. Indeed, some of this is already occurring in the area of control loop automation where many vendors have introduced fuzzy logic. However, in the areas of supervisory control, diagnostics, scheduling and design, the most important part of intelligent systems is the knowledge base which contains the knowledge and experience of skilled operators and plant experts. Obviously, it would be difficult for the equipment vendors to provide industry with such supervisory control type of knowledge. Many of the potential intelligent applications also do not represent markets large enough to be of interest to the equipment vendors.

This study identified a few situations where an equipment vendor offers intelligent systems, e.g., ABB LINKman (**Cement**, p. 75). One should note, however, that ABB did not develop the LINKman technology but bought it in 1991 after it had been proven at a number of cement plants.

The survey of the developers and users of existing systems identified a number of barriers to the development of intelligent systems. They are depicted in Table 1.2.

Table 1.2. BARRIERS TO DEVELOPMENT

Barrier	percent of respondents
Limited Funds and Time	45
Difficulty in Quantifying Payoffs	36
Lack of Support from Operating Personnel	36
Lack of Top-Level Support	36
Lack of Expertise	23
Difficulty in Identifying Application	18
Other	5

Interesting enough, almost half of the respondents identified "limited funds and time" as a major barrier to development of intelligent systems. This underscores the limited availability of resources in heavy industry for introduction of new technologies. A relatively high proportion (36%) of the respondents identifying "lack of support from operating personnel and/or top-level" suggests that intelligent technologies are not viewed by the operational staff as high priority items in plant quality and productivity improvement programs. However, the reduction of resistance by operating personnel from 36 percent in development to 18 percent in implementation (Table 1.3) suggests that these barriers can be overcome by better understanding of the technology.

Table 1.3. BARRIERS TO IMPLEMENTATION

Barrier	percent of respondents
Difficulty in Integrating into Operations	45
Resistance of Operating Personnel	18
Insufficient Training of Operating Personnel	14
Unclear/Unquantifiable Benefits	14
Poor Reliability of the Systems	9
Other	14

Table 1.3 shows the percentages of respondents reporting different barriers to the implementation of intelligent systems. The barrier with the highest number of respondents was "difficulty of integrating into operations". This could be because many of the applications listed by the respondents were real-time applications which require a high level of integration with the plant control systems. Because of the complexity of real-time applications, it is not surprising that the respondents found it difficult.

It is also interesting to note the high percentage of respondents reporting unclear benefits (14 percent of respondents had such implementation barriers). This underscores the importance of clearly identifying the benefits from AI projects. On the other hand, the low percentage of respondents reporting poor reliability of the systems implemented is a good testimony to the technical capabilities of intelligent systems.

Analysis of the barriers reported versus the respondents' rating of the success of their applications, showed a strong correlation of those factors. Respondents who indicated high success also indicated a low number of barriers to development and implementation and vice versa.

1.4. Structure of the Remaining Chapters

Four essential elements are required for the successful implementation of intelligent systems: management commitment, having the right people, choosing the right application, and choosing the right tools. This report addresses the last two requirements: the right applications (Chapters 2 to 7) and tools (Appendix B).

Chapters 2 to 7 describe applications of intelligent systems in five heavy industry sectors: iron and steel, cement, mining and metallurgy, oil and gas, and pulp and paper, and cross-cutting applications. They provide examples of intelligent systems implemented in industry and can assist readers in selecting suitable applications for their own use. In each sector, the examples identified are divided into three sections:

1) Selected Application Targets: includes descriptions of the applications, names of users and developers/vendors, estimated cost to implement the system (order of magnitude, excluding hardware and other requirements), additional requirements like mathematical models, software, etc., hardware requirements, and a list of actual, reported benefits by the users.

2) Other Systems Implemented: lists additional applications including their objective, user's name, and benefits where available.

3) Related Applications: includes references to applications in other sectors that may be of interest to this sector.

The systems listed in Selected Application Targets were chosen on the basis of several criteria, namely:

- productivity and quality improvements by the system
- energy efficiency improvements (direct and indirect)
- methodologies used (unique solutions)
- benefits reported by the user
- potential for implementation in the sector.

The applications listed in Other Systems Implemented are related to the study's objectives (productivity, quality and energy efficiency) but their benefits could not be confirmed. Some of the descriptions in Other Systems Implemented are expanded to present interesting implementation methodologies or benefits.

The intelligent systems in the Related Sectors were listed using a broad judgement as to what can constitute similar operational problems, equipment and/or AI methodologies.

This study reports on 177 different intelligent systems implemented in heavy industry. It does not report on university prototypes, research prototypes, and other AI systems or software that have not been implemented or tested in an industrial environment. The total number of systems identified is estimated to be 250 if multiple sites are counted for systems like ABB LINKman and Pitch Experts. Including university prototypes, research prototypes, and industrial systems not reported here, the total number of intelligent systems studied or implemented by the industry worldwide is estimated to be more than 1000 systems as of 1994. This number is estimated to grow more than 20 percent a year.

The reported benefits listed in Selected Application Targets are for information purposes only. Since each plant's situation is unique, any company interested in implementing an expert system should do a thorough analysis of expected benefits before proceeding.

The costs listed for application targets are based on development by knowledgeable people (except where purchase price is indicated). Actual costs could be less if the system is already available for purchase. All costs are listed in Canadian dollars.

2. IRON AND STEEL

2.1. Summary

More than 70 intelligent systems were found to be applied in the iron and steel industry. These do not include expert system prototypes not tested in the industry or those which are kept confidential. Nippon Steel Corporation, alone, reports over 70 expert systems developed at its plants and laboratories, while Kawasaki Steel Corporation reports over 30 intelligent systems. A review of all these systems would be beyond the scope of this project. However, the systems identified in this report represent a broad cross-section of intelligent system applications in the iron and steel sector.

The iron and steel sector has implemented more intelligent systems than other heavy industry sectors. There are a number of reasons for this. The process control problems in this sector are well suited for the application of Artificial Intelligence, i.e., they are often too difficult to be described in terms of mathematical models, the operators use heuristics in decision-making, and many process control strategies are based on experience. AI is viewed in the industry as technology that can assist, rather than replace, the operators in process automation.

Figure 2.1 is a schematic of steel manufacturing including the number of AI systems in each process area (numbers in the circles). The process areas are divided as follows:

- ironmaking (14 systems)
- steelmaking (5 systems)
- continuous casting (12 systems)
- rolling (18 systems)
- other (24 systems)

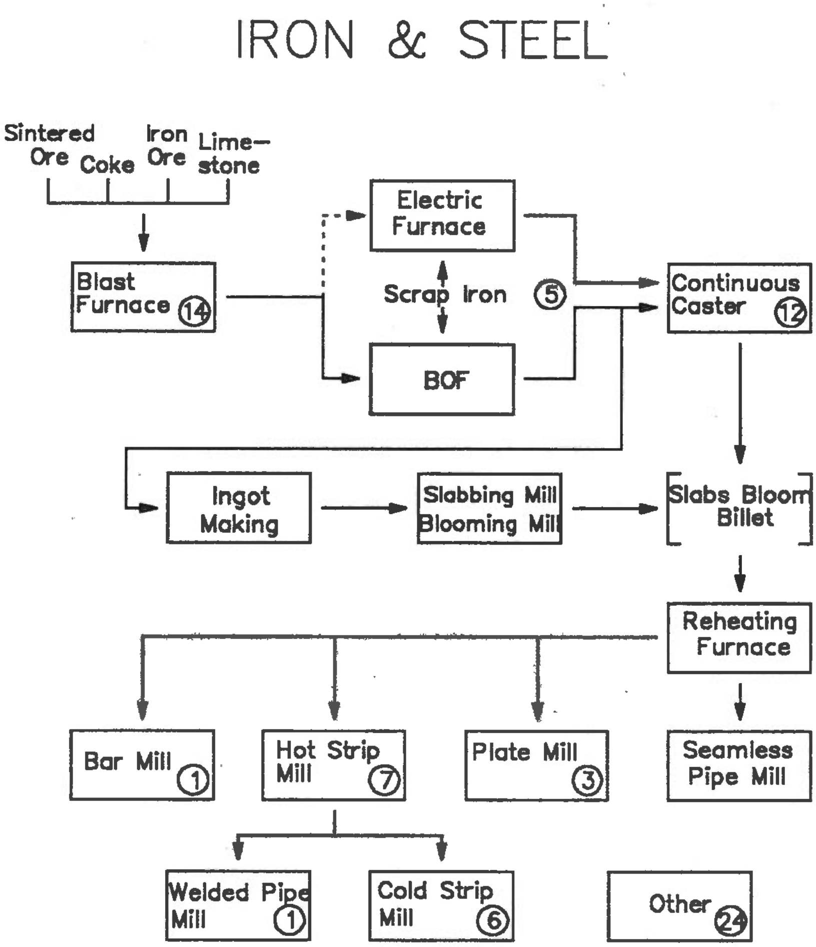

Figure 2.1. SCHEMATIC OF STEEL MANUFACTURING

Figures 2.2 to 2.4 show the distribution of intelligent systems by the type of application, the geographic region and the technology applied. The key conclusions from these figures are:

- The largest application domain is control (39 percent) followed by scheduling (16 percent) and diagnosis (15 percent). If monitoring is combined with control, these applications account for about half of all intelligent systems applications.
- The smallest number of applications is in maintenance and design (3 percent). The small number of applications in maintenance is surprising. One could expect significant benefits to be accrued by the industry from using intelligent systems in the area of maintenance.
- The geographical distribution shows that half of the applications are in Asia (mainly in Japan). Europe has about 31 percent of the identified applications, and North American applications were a distant third at 13 percent. This indicates slow acceptance of AI technologies and, based on discussions with some developers, a

reluctance on the part of North American industry to disclose information about existing systems.

- The majority of intelligent systems applied in the iron and steel industry are expert systems (Figure 2.4). This was expected since expert system technology is the most mature of the AI technologies and it addresses well the type of problems encountered in the iron and steel industry.

- Neural networks and fuzzy logic are a distant second and third, respectively, in technology applications. But both are beginning to have an impact in such areas as continuous casting.

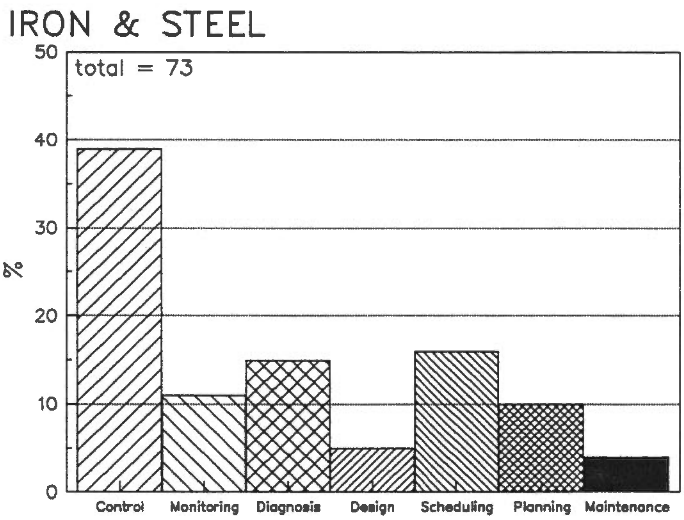

Figure 2.2. AI USE IN IRON AND STEEL PRODUCTION/ PROCESSING BY APPLICATION

An interesting characteristic of the intelligent systems applied in iron and steel is that many applications are small to medium in size (<24 person-months of effort). The members of the Japanese Steel Industry (Kobe, Nippon Steel, etc.) developed their own expert system shells that allow their engineers and plant operators to build expert systems without knowledge engineers or specialists in AI. A similar approach was taken in Australia by BHP which developed a system that allows the integration of a variety of expert system modules, resulting in rapid development of intelligent systems at a low cost.

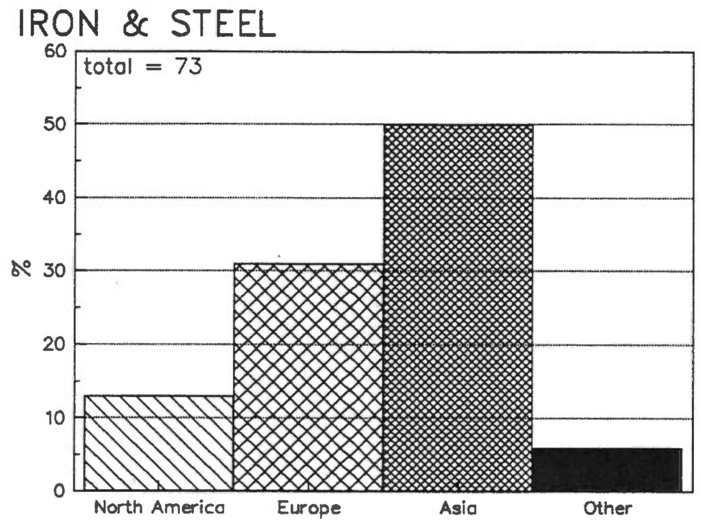

Figure 2.3. AI USE IN IRON AND STEEL PRODUCTION/ PROCESSING BY CONTINENT

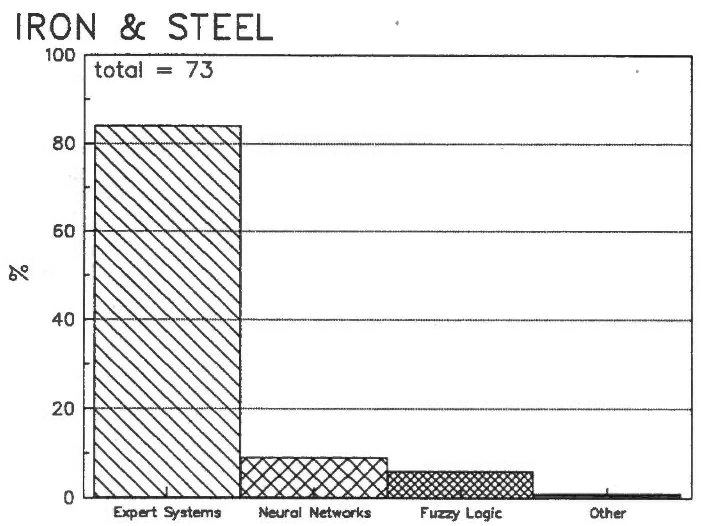

Figure 2.4. AI USE IN IRON AND STEEL PRODUCTION/ PROCESSING BY TECHNOLOGY

Intelligent systems have been applied in all major areas of iron and steel plants. The most promising applications are:

Ironmaking: energy management, blast furnace control and optimization, diagnosis of misoperations.

Steelmaking: BOF control and optimization, electric furnace diagnosis and electrode drive control and optimization, steel quality control, waste gas recovery (energy management).

Continuous Casting: mold bath level control and optimization, breakout forecasting and diagnosis, scheduling casting sequences.

Rolling: optimization and control of the rolling mill, scheduling of rolling sequences, product quality control, energy management.

Other: scheduling of steelmaking processes, design of product properties, equipment fault diagnosis, energy management.

The following three sections provide examples of intelligent systems being applied in the iron and steel sector. These sections are provided not as a comprehensive review, but to show the types of problems being solved by the industry through AI technologies:

- Section 2.2 "Selected Application Targets" describes 24 applications and gives detailed information on developers, vendors, costs and benefits.

- Section 2.3 "Other Systems Implemented" indicates 49 additional systems being used, with information on developers and solutions applied.

- Section 2.4 "Related Applications" indicates 8 intelligent systems being used in other sectors (plus those in the cross-cutting chapter) which may have application in the iron and steel industry.

2.2. Selected Application Targets

Title: **Hot Stove Optimization - a fuzzy logic system for automatic control of hot stove combustion**

User: Kawasaki Steel Corporation
Chiba Works, Japan

Developer/Vendor: Kawasaki Steel Corporation
Equipment Technology Department
Chiba, Japan

Description: This fuzzy logic expert system automatically sets the flow rate of combustion gases for optimized hot stove operations. It was implemented to reduce the consumption of fuel gas and to lower the silica brick temperature. The system analyzes information on stove heat level, heat level change, dome and silica brick temperatures and adjusts the heat input and gas calorific value (a mixture of blast furnace gas and coke oven gas). The fuzzy logic expert control model is based on the qualitative judgments and experience of hot stove operators.

Cost to Implement: $70,000 to $90,000

Other Requirements:
- on-line process control software
- mathematical models describing relationships between heat input, stove heat level and level change index, brick and dome temperatures, etc.

Hardware Requirements:
- workstation for the expert system
- process control computer with on-line data acquisition for:
  - calorific value of blast furnace gas and coke oven gas
  - dome and silica brick boundary temperatures
  - blast temperature

Reported Benefits:
a) thermal efficiency increased by 3 percent from 83.2 to 86.2 percent
b) silica brick boundary temperature was reduced by 20 to 30 degrees to a temperature range of 360 to 370°C

Reference: Maki, Y. et al., *Proceedings of the IFAC Workshop on Automation in Mining, Mineral and Metal Processing*, Buenos Aires, Argentina, pp. 247-253, 1989.

Title: **Blast Furnace Operation - an expert system for control of blast furnace operations at Nippon Steel**

User: Nippon Steel Corp.
Kimitsu Works, Japan

Developer/Vendor: Nippon Steel Corp.
Electronics & Information Systems Div.
Tokyo, Japan

Description: This expert system supports control of the blast furnace to ensure stable operation and the quality of the hot metal. It eliminates typical problems encountered with conventional control while ensuring stable and optimized furnace operations. It provides the blast furnace operators with information about furnace conditions and recommends actions for optimal control. The system contains the knowledge of experienced operators about the control of daily operations, measures to be taken in contingency situations, shut-down procedures and troubleshooting of the equipment. It signals and corrects any departures from the optimal operation.

Cost to Implement: $400,000 to $500,000

Other Requirements:
- models for heat level prediction, cohesive zone profile, etc.
- data links to plant control system

Hardware Requirements:
- workstation and printer for the expert system
- blast furnace process control system
- additional sensors for hot metal iron temperature, burden permeability, belly brick temperature, etc.

Reported Benefits:
a) improved stability in 93 percent of operating situations
b) reduced variances on most operating variables resulting in improved hot metal quality and energy savings
c) improved flexibility to implement changes to operating conditions

Reference: Amano, S. et al., *ISIJ International*, vol. 30, no. 20, pp. 105-110, 1990.

Title: **BAISYS - an expert system for real-time control of blast furnace**

User: NKK Corporation
Fukuyama Works, Japan

Developer/Vendor: NKK Corporation
Process Control Department
Hiroshima, Japan

Description: This expert system is a part of the furnace control system and the total computerization of the steel works. It predicts and controls abnormal furnace conditions, furnace thermal conditions, and furnace burden distribution. It uses certainty factors and fuzzy rules to make inferences from imprecise and ambiguous data. It collects real-time information on the status of the furnace, extracts important facts and data, makes inferences about the current and future operating conditions of the furnace, and implements the required control actions to achieve stable and optimized operating conditions.

Cost to Implement: $400,000 to $500,000

Other Requirements:
- mathematical models of shaft differential pressure, burden descent velocity, etc.
- process control software including noise filtering, etc.
- self-learning fuzzy membership functions

Hardware Requirements:
- workstation for the expert system
- sensors and instrumentation for the blast furnace
- blast furnace process control system

Reported Benefits:
a) more stable and efficient furnace operations even with inexperienced operators
b) accurate trend forecasts for operations
c) reduced hot metal temperature and heat loss from the hearth
d) reduced hot metal temperature standard deviation to ±10°C
e) reduced silicon content standard deviation to ±0.05 percent

Reference: Niwa, Y. et al., *ISIJ International*, vol. 30, no. 2, pp. 111-117, 1990.

Title: **Blast Furnace Heat Control - an expert system to predict/control blast furnace heat level**

User: Kobe Steel Co.
Kobe Works, Japan

Developer/Vendor: Kobe Steel Company
Electronics Research Laboratory
Japan

Description: This expert system predicts and controls blast furnace heat level. It uses two models for prediction of heat level: a rule-based model for short-term predictions and a statistical model for forecasting long-term heat variations. The rule-based model incorporates fuzzy membership functions for parameters required for estimation of carbon loss and heat level. Comparing the results obtained using the expert system to the action of experienced operators, the system matched or outperformed the operators 98 percent of the time.

Cost to Implement: $200,000 to $300,000

Other Requirements:
- models relating heat level indices to heat level variations
- statistical model for prediction of long-term hot metal temperature variations
- communication links for process data

Hardware Requirements:
- workstation for the expert system
- blast furnace process control system with instrumentation, sensors, control actuators

Reported Benefits:
a) ability to predict short- and long-term heat level variation
b) automatic determination of control actions and their values
c) improved consistency of heat-level control

Reference: *Kobelco Technology Review*, March, 1991.

Title: **Operation of Blast Furnace - an expert system to aid in control of blast furnace**

User: POSCO
Pohang, Korea

Developer/Vendor: RIST
Pohang, Korea

Description: This expert system supports control of blast furnace operations. It assists the operators in interpreting process measurements and recommends control actions required for optimal furnace operation. The system is interfaced with a plant process computer which collects operational data and then transfers the data to the expert system for analysis. The analysis consists of two steps: 1) diagnosis of initial phenomena of inactive zone formation to prevent the fluctuation of temperature and pressure profiles; and 2) diagnosis of the extent of inactive zone formation to prevent long-term unstable conditions.

Cost to Implement: $120,000 to $150,000

Other Requirements:
- communication links to the process computer
- process database
- models describing relationships among different transition indices

Hardware Requirements:
- workstation for the expert system
- blast furnace process control system
- additional sensors on blast furnace

Reported Benefits:
a) improved diagnosis/prediction of abnormal process behavior
b) improved stability of the blast furnace operation

Reference: Choi, T.H. et al., *Processing of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 45-49, 1991.

Title: **Expert System for Heat Balance Control of an Iron Blast Furnace**

User: BHP Steel
Newcastle Steelworks, Australia

Developer/Vendor: BHP Research
Newcastle, Australia

Description: This system provides guidance to the operators for heat balance control of an iron blast furnace. It replaced a set of manuals containing procedures for operating the blast furnace. The expert system eliminates many shortcomings of the manuals such as ambiguous, incomplete or insufficient knowledge, and procedures that previously led to incorrect interpretation of procedures and to inconsistency of control actions. It does not perform control changes but just recommends them to the operators for their final decision.

Cost to Implement: $40,000 to $60,000

Other Requirements:
- Standard Operating Manuals (SOM)
- data communication links to the plant computer

Hardware Requirements:
- PC-AT computer
- process monitoring computer

Reported Benefits:
a) increased compliance with standard operating (SOP) procedures from 38 to 75 percent
b) reduction of unnecessary heat changes from 20 to 0 percent.
c) elimination of heat changes not covered by the SOP

Reference: Panjkovic, V. et al., *Proceedings of the 5th Australian Joint Conference on Artificial Intelligence*, Singapore, pp. 19-24, 1992.

Title: **ESWGR - an Expert System for Waste Gas Recovery During Steelmaking**

User: British Steel Corp.
Scunthorpe Works, UK

Developer/Vendor: Data Sciences Ltd.
Farnsborough, UK

Description: This system improves the operation of programmable logic controllers (PLCs) governing the collection of gas exiting the steelmaking vessels. The original process control and monitoring system aborted gas collection whenever any problem arose in the gas recovery system. The expert system interprets the output of the PLCs and waste gas analysis instrumentation. It then diagnoses the gas recovery system so that unnecessary flaring of gas can be prevented.

Cost to Implement: $70,000 to $90,000

Other Requirements:
- data communication software
- process database

Hardware Requirements:
- workstation for the expert system
- process monitoring computer
- PLCs controlling the waste gas recovery
- gas analyzers

Reported Benefits:
a) improved, more robust, process monitoring system
b) increased collection of gas from steelmaking vessels, lowering the need to purchase energy

Reference: Moore, R.B., *Proceedings of the 1992 IEEE International Symposium on Intelligent Control*, Glasgow, Scotland, pp. 584-585, 1992.

Title: **BOF Process Control - a hybrid expert system for optimization of blowing control of the basic oxygen furnace**

User: Nippon Steel Corporation
Sakai Works, Sakai, Japan

Developer/Vendor: Nippon Steel Corporation
Technical Division, Sakai, Japan

Description: This hybrid system is for optimization and blowing control of the BOF. It consists of two parts: 1) a rule-based reasoning, static expert system to correct for the error factors in controlled parameters; and 2) the fuzzy reasoning, dynamic expert system to correct for in-furnace slag formation reactions. The system was implemented to improve the capabilities of the existing conventional blowing control system that uses mathematical models to determine the amount of oxygen, flux and coolant required. It determines the setting of blowing-control end-points and compensates for reaction of slag formation.

Cost to Implement: $80,000 to $120,000

Other Requirements:
- empirical mathematical models determining the amount of oxygen, flux and coolant
- software for communication between the expert system computer and the process computer

Hardware Requirements:
- workstation for the expert system
- data collection hardware for:
  - bottom blowing gas rate
  - BOF off-gas flow rate
  - BOF off-gas analysis
  - oxygen flow rate
  - flux coolant charging

Reported Benefits: End of blow results (average of over 50 heats)
a) variance of temperature decreased from ±11.6°C to ±8.2°C
b) variance of carbon decreased from 0.032 percent to 0.027 percent
c) variance of phosphorous decreased from 0.0056 percent to 0.0050 percent
d) variance of manganese decreased from 0.075 percent to 0.058 percent

Reference: Yoshida, T. et al., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 51-56, 1991.

Title: **Blowing Control System for Basic Oxygen Furnace**

User: NKK Corporation
Fukuyama Works, Japan

Developer/Vendor: NKK Corporation
Department of Process Control
Fukuyama, Japan

Description: This expert system evaluates and predicts the outcome of the blowing conditions such as the quality of slag formation and the possibility of slopping in the BOF. It designs and adjusts the blowing control pattern by using experienced operators' heuristics and calculated slag formation and slopping parameters. It recommends adjustments to the blowing pattern indices and indicates whether tapping is possible at the time of sub-lance measurement after blowing. NKK reports significantly improved blowing control with the new system.

Cost to Implement: $200,000 to $300,000

Other Requirements:
- a mathematical model of desiliconization, decarbonization and low-carbon stages
- communication links for accessing process data

Hardware Requirements:
- workstation for the expert system
- process computer with instrumentation, sensors and control actuators (about 500 I/O points)

Reported Benefits:
a) reduced staff for blowing control to one operator
b) reduced blowing time
c) improved blowing control and efficiency (e.g., phosphorous content closer to specifications and with reduced deviation)
d) reduced consumption of flux

Reference: Furukawa, T., *American Metal Market*, p. 4, 1991.

Title: **Continuous Caster Control - A real-time expert system applied to control the mold bath level of a continuous caster**

User: Sumitomo Metal Industries
Wakayama Steel Works, Japan

Developer/Vendor: Sumitomo Metal Industries
System Engineering Division, Kashima, Japan

Description: This expert system controls the bath level of a round billet continuous caster. It reduces the fluctuations of the mold bath level which negatively affect the surface quality of cast billets. The system performs the following functions: 1) optimization of bath control parameters; 2) identification of the causes of control malfunctions; and 3) diagnosis of operating conditions. It is a hybrid system consisting of an expert system added to a conventional control system. This system is also applicable to slabs and bloom casting.

Cost to Implement: $150,000 to $180,000

Other Requirements:
- data links between the process database and the expert system

Hardware Requirements:
- workstation for the expert system
- on-line process computer with sensors/information on:
  - mold bath level
  - temperature of the molten steel in the tundish
  - casting speed
  - mold oscillator stroke signal, etc.

Reported Benefits:
a) improved control of the continuous caster
b) frequency of excessive fluctuation ($\geq$5 mm width) was decreased by 40 percent
c) maximum fluctuation width decreased by over 30 percent

Reference: Kubota, S. et al., *Sumitomo Search*, no. 50, pp. 51-58, 1992.

Title: **VASE - Voest-Alpine Scheduling Expert for a Steel Plant**

User: Voest-Alpine mbH
Linz, Austria

Developer/Vendor: Voest-Alpine
Linz, Austria

Description: VASE assists the scheduling dispatcher to maximize the length of casting sequences and minimize the tundish changes, the waiting time of the converters and the variations in the widths of the slabs in a sequence. It consists of five components: 1) order preprocessing, to translate a set of orders into a set of heats; 2) knowledge base, to identify successful planning strategies; 3) heat scheduling, to establish the correct sequence of heats and to minimize the differences between slabs; and 4) schedule optimization, to optimize the production time schedules.

Cost to Implement: $500,000 to $800,000

Other Requirements:
- metallurgical knowledge base
- similarity algorithms for classifying orders
- process database
- data communication links

Hardware Requirements:
- workstation for the expert system
- process computer with sensors and instrumentation

Reported Benefits:
a) generation of consistent, optimized production schedules
b) improved quality control in the plant
c) reduced production cost
d) improved energy efficiency

Reference: Stohl, K. et al., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 39-44, 1991.

Title: **A Neural Networks Based Breakout Forecasting System for Continuous Casting of Steel**

User: Nippon Steel Corp.
Yawata Works, Japan

Developer/Vendor: Fujitsu Ltd.
Kawasaki, Japan

Description: This system is based on multiple neural networks and uses a signature of abnormal and subtle changes in temperature at the wall of the caster mold to diagnose and predict possible breakouts. It contains two neural networks for identifying the temperature patterns: one for time-series temperature changes and the other for spatial distribution of temperature. The neural network system forecasts breakouts more accurately and sooner than the conventional system so that action can be taken to avoid them.

Cost to Implement: $70,000 to $90,000

Other Requirements:
- historical breakout data including the spatial and time distribution of temperature in the mold
- data acquisition system
- data communication links

Hardware Requirements:
- workstation for the neural networks
- thermocouple sensors in the mold
- process monitoring computer

Reported Benefits:
a) improved breakout detection, about 6.5 seconds earlier than conventional systems
b) significant reduction of errors in underforecast and overforecast of breakouts
c) reduction in production shutdowns and losses due to breakouts

Reference: Hatanaka, K. et al., *Fujitsu Scientific and Technical Journal*, vol. 29, no. 3, pp. 265-270, 1993.

Title: **A Neural Networks Based System for the Recognition of Stenciled Characters on Slabs**

User: Kawasaki Steel Corp
Chiba Works, Japan

Developer/Vendor: Kawasaki Steel Corp
Technical Research Division
Chiba, Japan

Description: This neural networks-based system recognizes stenciled codes on the surface of slabs. The characters are extracted from the image taken by MOS cameras by means of pattern matching. The images of read characters are analyzed by the neural networks to evaluate the similarity between the characters and the standard patterns. The neural networks function both as a non-linear discriminant function and as an evaluation function for the quality of the characters. The system has two trained networks, one for the alphabetic characters and one for the numeric characters.

Cost to Implement: $50,000 to $70,000

Other Requirements:
- image synthesizer
- database of stenciled images
- signal processing software

Hardware Requirements:
- two MOS cameras
- monitor
- workstation for the expert system
- halogen light source

Reported Benefits:
a) correct classification of stenciled characters increased to 99 percent or better
b) the rate of underreported blurred characters reduced to 0 percent
c) the rate of the excess alarms reduced to 3 percent

Reference: Asano, K. et al., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 147-153, 1991.

Title: Expert System for the Control of Cold Coil Transportation

User: Kawasaki Steel Corp.
Mizushima Works, Japan

Developer/Vendor: Kawasaki Steel Corp.
Mizushima, Japan

Description: This expert system was developed for real-time control of cold coil transportation in the finishing line. It generates and implements optimum schedules for transferring slit coils; it also controls the transfer of coils by monorail-type carriers. The system works cooperatively with the process computer which supervises the operation of all facilities on the production lines. It decides on the transportation carrier and timing in real-time., It then sends, via the process computer, the carrier movement order to direct digital controllers positioned on the route to the terminal.

Cost to Implement: $180,000 to $250,000

Other Requirements:
- finishing line simulator
- data communication software

Hardware Requirements:
- process computer for real-time transportation control
- on-line computer for product information
- direct digital controllers

Reported Benefits:

a) real-time control of finishing line actions of less than 3 seconds in 97 percent of cases
b) reduced cost of control system development by half compared to conventional programming
c) improved software quality and maintainability
d) control of transportation in finishing line at maximum efficiency

Reference: Anabuki, Y., Kawasaki Steel Corp., Mizushima, Japan.

Title: **Expert System for Shape Control in Rolling Mills**

User: Kawasaki Steel Corp.
Sendzimir Mill, Japan

Developer/Vendor: Hitachi Ltd
Hitachi Research Laboratory
Tokyo, Japan

Description: This expert system was developed to fully automate shape control in rolling mills. It recognizes and controls spatially distributed waveform patterns and reduces the degree of steepness of strip shape. It uses a combination of fuzzy rules and neural networks for recognition of waveforms and fuzzy rules for control of the actuators. The control is executed according to the extracted waveform composition.

Cost to Implement: $120,000 to $150,000

Other Requirements:
- statistical model of steepness input and output data patterns
- data acquisition software
- process database

Hardware Requirements:
- shape steepness monitoring instrumentation
- workstation for the expert system

Reported Benefits:

a) average degree of steepness in the shape of rolled coil decreased from 1.8 to 1.4 percent

Reference: Hattori, S., *Hitachi Review*, vol. 42, no. 4, pp. 165-170, 1993.

Title: **Expert System to Schedule Seamless Steel Pipe Production**

User: Kawasaki Steel Corp.
Chiba, Japan

Developer/Vendor: Kawasaki Steel Corp
Systems Laboratory
Tokyo, Japan

Description: This expert system determines the manufacturing order in the production of seamless steel pipe. It generates a plan of rolling sequences for three rolling days including 200 to 500 lots to be sequenced in one rolling. The system determines the starting lot and sequences of lots from thin to thick product. It optimizes the productivity under about 50 production constraints.

Cost to Implement: $200,000 to $300,000

Other Requirements:
- process scheduler
- process database
- communication link to DCS

Hardware Requirements:
- work station for the expert system
- process monitoring computer
- distributed control system

Benefits Reported:
a) generation of a rolling sequence composition in 2 to 3 hours vs 11 hours required for human expert
b) system's schedules are as good as those of human experts
c) prompt rescheduling in response to a change in rolling sequence composition requirements

Reference: Fujimoto, H., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 71-77, 1991.

Title: Expert System to Control Coil Transfer and Storage in Hot Strip Mill

User: Sumitomo Metal Industries
Kashima Works, Japan

Developer/Vendor: Sumitomo Metal industries
System Engineering Division
Osaka, Japan

Description: This expert system provides real-time control of coil transfer and storage tasks. It automatically creates transfer plans for the finishing line for each selected coil. It considers current information on rolling processes, positions of cranes and lifting devices, conveyer location and operation, and the location and loading state of each coil car. The system's objective is to keep transport equipment operating at the highest efficiency.

Cost to Implement: $150,000 to $200,000

Other Requirements:
- communication network between the main computer and DCS stations
- process databases

Hardware Requirements:
- workstation for the expert system
- distributed control system for coil transfer in finishing line
- main plant computer with scheduling plans

Reported Benefits:
a) reduction of materials handling staff by over 50 people
b) reduction of lead time by 2.8 days
c) increased overall efficiency of materials flow

Reference: Kuribayashi, T. et al., *Sumitomo Search*, no. 50, pp. 59-67, 1992.

Title: **Expert System for Scheduling of Plate Mill Operations**

User: Rautaruukki Oy
Raahe Steel Works, Finland

Developer/Vendor: Rautaruukki Oy
Raahe, Finland

Description: This expert system schedules slab processing in the reheating furnace, on the cooling bed, and through the plate rolling mill. The system's task is to plan slab processing using different routes and to produce plates which conform to the specifications in the customer's order. The expert scheduler functions as part of a hierarchical distributed scheduling system for the whole steel works.

Cost to Implement: $200,000 to $300,000

Other Requirements:
- communication software to exchange information with other parts of the distributed system
- process database
- plate mill scheduler
- master scheduler for the steel works (optional)

Hardware Requirements:
- workstation for the expert system
- plate mill computer

Reported Benefits:
a) improved rolling schedules based on several criteria rather than on particular technological preferences as is the case in human-made schedules
b) smaller time buffers between processing of slabs with different thickness
c) reduced overheating of slabs, etc.

Reference: Lassila, O. et al., *Proceedings of the IFAC Workshop on Expert Systems and Metal Processing*, Espoo, Finland, pp. 103-108, 1991.

Title: **Scheplan - A Scheduling Expert for Steelmaking Processes**

User: NKK Corp.
Ohgishima Plant, Japan

Developer/Vendor: IBM Japan
Tokyo, Japan

Description: This expert system schedules the operations of three converters, one refining device, and five continuous casters. The system handles such scheduling issues as fixed sequences of production stages, machine conflicts among products, waiting times, continuous casting and maintenance. It uses cooperative scheduling, i.e., it generates possible schedules which are then checked by the operators. The operators can also interact with the scheduling process to further refine the schedule.

Cost to Implement: $600,000 to $900,000

Other Requirements:
- process database
- data communication links to the main computer

Hardware Requirements:
- high-end workstation for the expert system
- steelmaking and casting computer control

Reported Benefits:
a) reduction of the daily scheduling time from four hours to less than 30 minutes
b) improved schedule quality, e.g. the average machine waiting time was reduced from 16 to 8 minutes
c) reduction in production cost (about 1 million dollars a year)

Reference: Numao, M. et al., *International Workshop on Artificial Intelligence for Industrial Applications*, IEEE 88CH2529, pp. 467-472, 1988.

Title: **Expert System for Steel Plate Production Design**

User: Rautaruukki Oy
Raahe Steel Works, Finland

Developer/Vendor: Rautaruukki Oy
Raahe, Finland

Description: This expert system assists plant engineers in selecting production parameters in order to achieve target steel plate properties. It searches and modifies historical production data to the given target plate properties. It provides the upper and lower limits on production parameters which the user can fine tune further to achieve optimal operation.

Cost to Implement: $60,000 to $90,000

Other Requirements:
- statistical model relating steel properties to operating parameters
- a database of production runs
- process monitoring information

Hardware Requirements:
- workstation for the expert system
- process monitoring computer

Reported Benefits:
a) improved quality of the steel plates produced
b) better designed, more optimal operations

Reference: Veijola, E. et al., *Proceedings of the International Iron & Steel Institute*, pp. 59-62, 1989.

Title: **Expert System for Control of Electrical Energy Consumption in a Steel Plant**

User: Outokumpu Oy
Torino, Finland

Developer/Vendor: Technical Research Center of Finland
Espoo, Finland

Description: The objective of this expert system is to minimize peak power usage by arc furnaces and rolling mills. Previously, peak power demand was controlled by imposing temporary power restrictions on short notice. The new expert system allows the plant to meet peak load demands more effectively by predicting power load a few hours ahead. The optimization of electrical power demand and reduction of peak electricity demand are implemented by forecasting load demand and adjusting plant production schedules accordingly.

Cost to Implement: $300,000 to $500,000 (off-line system)

Other Requirements:
- models of power consumption by arc furnaces, rolling mills and other processes
- process database
- data communication links to process scheduler
- process scheduler

Hardware Requirements:
- workstation for the expert system

Reported Benefits:
a) improvement in the existing peak load control (neither qualitative nor quantitative data given)

Reference: Koponen, P. et al., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 31-317, 1991.

Title: **Expert System for Steam Pressure Control at the Steelworks**

User: Kawasaki Steel Corporation
Mizushima Works, Japan

Developer/Vendor: Fujifacom Corporation
Tokyo, Japan

Description: Kawasaki Steel Corporation developed a system for plant-wide control of total energy use and electricity production at the Mizushima Steel Works. The system's objective is to prevent any energy shortages or surpluses, and to maintain enough flexibility in the operation to respond to unforeseen changes in plant operating conditions. The expert system component handles the steam production and utilization in the Works. The plant-wide system controls and optimizes the supply and demand of steam for the operations.

Cost to Implement: $50,000 to $80,000

Other Requirements:
- process monitoring information (on-line) on steam consumption at various points within the Works
- data links to the plant-wide control system

Hardware Requirements:
- PC-AT (if stand alone)
- process computer and instrumentation for monitoring plant-wide energy consumption

Reported Benefits:
a) improved energy savings
b) improved control of steam line pressure and supply/demand of steam

Reference: Akimoto, K. et al., *Proceedings of the IFAC Workshop on Automation in Mining, Mineral and Metal Processing*, Buenos Aires, Argentina, pp. 281-286, 1989.

Title: **Expert System for Diagnosis of Equipment Faults in Steel Manufacturing**

User: Nippon Steel Corp.
Oita Works, Japan

Developer/Vendor: Nippon Steel Corp.
Computer Systems
Japan

Description: This expert system handles preventive maintenance problems at three Nippon Steel manufacturing plants. It was developed to reduce the occurrences of major problems due to equipment breakdown: 1) the loss of large amounts of energy due to terminating and resuming operations; and 2) the necessity for frequent rescheduling of planned production due to prolonged work disruptions. It diagnoses over 500 pieces of electrical and mechanical equipment. With the installation of the expert system, the plant operators can diagnose and fix breakdowns with the shift maintenance staff.

Cost to Implement: $800,000 to $1,200,000

Other Requirements:
- comprehensive data acquisition system
- process databases
- data communication software

Hardware Requirements:
- workstation for the expert system
- intelligent data loggers
- variety of sensors, instruments, etc.

Reported Benefits:
a) reduced maintenance personnel by 35 people
b) reduced duration of work disruptions (and energy losses)

Reference: Hirata, T. et al., *Operational Expert System Applications in the Far East*, Pergamon Press, 1991.

Title: **Boiler and Furnace Control - an expert system for optimization of boilers at British Steel**

User: British Steel plc
Ebbw Vale, UK

Developer/Vendor: British Steel plc
Bristol, UK

Description: This expert system optimizes operations of multiburner installations in boilers and furnaces. The common problem with multiburner installations is that the exit gas analysis reflects only the overall air-to-fuel ratio. Also, measurement of air-to-fuel ratio on individual burners is not accurate and is very expensive. The solution implemented was to use a small number of sensors to monitor the air-to-fuel ratio of selected burners and to control the burners with the aid of the expert system.

Cost to Implement: $40,000 to $50,000

Other Requirements:
- data links to analogue channels
- data acquisition software

Hardware Requirements:
- PC-AT for the expert system
- sensors and instrumentation for:
  - flue gas analysis
  - level of firing
  - temperature, pressure and humidity of combustion air
  - fuel pressure and temperature

Reported Benefits:
a) energy savings of 1.5 percent for Ebbw Vale plant
b) energy savings at other plants:
  - 2 to 5 percent for boilers
  - 5 to 20 percent for furnaces

Reference: Partington, D., *Proceedings of the International Iron and Steel Institute*, pp. 15-30, 1989.

2.3. Other Systems Implemented

Ironmaking

1. **Blast Furnace Operations** - a prototype intelligent system developed by Seoul University to support blast furnace operations in integrated iron and steelmaking works. The system uses neural networks to identify potential operational problems of the blast furnace and recommend corrective actions to the operators. Source: *Hwahak Konghak*, vol. 29, no. 3, pp. 270-283, June 1991.

2. **Coke Plant Operation** - an expert system which plans and optimizes the operation of the coke plant at Yawata Works, Nippon Steel. It automates the operators' functions by capturing their expertise and experience. Nippon Steel reports large manpower savings achieved through its implementation. Source: Nippon Steel, Japan.

3. **Blast Furnace Conditions** - a prototype system developed by Abo Akademy, Finland, for real-time diagnosis of blast furnace conditions. It analyzes data to detect invalid measurement values, trends and changes in the blast furnace, and to identify important control patterns in the operations. The control patterns are used to suggest possible control changes in the operation of the furnace. Source: *Proceedings of the IASTED International Symposium*, AINN, pp. 263-266, 1990.

4. **Blast Furnace Operations** - an expert system to control blast furnace operations at Kashima No. 1 Furnace, Sumitomo Metal Industries. It determines the causes of furnace operation abnormalities and selects the necessary actions for long-term control of the blast furnace. The system is a hybrid system including knowledge-based diagnostic rules and numerical models of blast furnace processes. Source: Sumitomo Metal Industries, Kashima Works, Japan.

5. **Prototype-0** - a prototype expert system for control of the sintering process in an iron and steel company in Egypt. The system covers knowledge of sintering, including its mechanisms and control processes. Source: *First International Conference on Expert Systems and Development Proceedings*, Cairo, Egypt, pp. 53-70, 1992.

6. **Real-Time Control** - an expert system for real-time control of a blast furnace at China Steel, Taiwan. It integrates mathematical models of the furnace's reactions with a knowledge base of control procedures acquired from the operators. The system judges furnace conditions from the on-line data and previous records, and designs control strategies for the blast furnace operation. Source: *International Journal of Systems Science*, vol. 23, no. 1, pp. 17-35, 1992.

7. **Blast Furnace Fuzzy Model** - a prototype fuzzy logic expert system for modeling blast furnace smelting processes. It was developed by the Tianjin Institute of Industrial Automation and Instrumentation, China. It uses a simple fuzzy logic semantic model describing the control actions of the furnace operators. Source: *Industrial Applications of Fuzzy Control*, Elsevier Science Publishers, 1985.

8. **Scheduling Heat Zones** - an expert system for optimizing daily production scheduling from the blast furnace through the hot rolling mills at Thyssen Stahl AG, Germany. The system develops production sequences within the constraints of production orders' specifications. It also maximizes throughput and improves product quality. Source: International Iron and Steel Institute, 1989.

Steelmaking

9. **Steel Production** - an expert system to assist in operating the basic oxygen furnace in the steelmaking plant at BSC's Ravenscraig Works, Motherwell, Scotland. The system continuously monitors the BOF processes and provides diagnostic reports about potential process problems. It also provides maintenance schedules to reduce breakdown and production losses. Source: *I&CS*, vol. 63, no. 6, pp. 111-112, 1990

10. **Intelligent Arc Furnace** - a neural network-based electrode position optimization system for electric arc furnace operation at North Star Steel Co., USA. The system learns and recognizes complex relationships of closed-loop furnace electrode controls and predicts future responses in order to solve for unwanted trends, correct for time constants of the electrode drive, etc. It also corrects for any flicker problems when the furnace is at the border of instability. Source: *Iron Age*, vol. 8, no. 8, pp. 14-17, August 1992.

Continuous Casting

11. **Continuous Caster Steel Mill Scheduling** - a fuzzy logic-based expert system developed by Pyromet Automation Services, PA, for on-line monitoring and reactive scheduling of a continuous caster in a steel mill. The system first creates an "area schedule" based on the steel orders and time constraints, and then develops an operational plan. The plan can be modified for any required adjustments as the expert system monitors the manufacturing process. Source: *IEEE Control Systems*, vol. 12, no. 3, pp. 78-86, June 1992.

12. **A Caster Scheduling Expert** - an expert system to assist in production scheduling at Wheeling-Pittsburgh Steel Corp., USA. The system considers a number of constraints including steel grades and chemistries, quality codes, rush and hold priorities, past, present and future needs, number of heats, scheduled width changes, and a number of caster-related constraints. It helps the scheduler to analyze order information and to build a product schedule. It can be linked with a separate works simulation program to perform "what-if" scenario analysis. Source: *Controls and Systems*, Vol. 39, no. 9, pp. 30-31, Sept. 1992.

13. **Equipment Fault Diagnosis** - a prototype neural network expert system for diagnosis of mechanical equipment faults in integrated steel plants. The system has been developed in the FOXBASE language on an IBM PC-AT and has been tested in several field applications. Source: *Computers in Industry*, Vol. 16, no. 2, pp. 169-177, Jun 1991.

14. **Fuzzy Expert** - an expert system to predict equipment life expectancy for scheduling maintenance intervals in a continuous caster plant. The system answers questions about how long equipment will be usable and when it will have to be maintained. It outperforms operators in predicting life-expectancy by considering a larger amount of input data and more up-to-date information about equipment operation. Source: *Computers & Chemical Engineering*, vol. 18, pp. 155-159, 1994.

15. **Electric Furnace Optimization** - a prototype expert system, developed by Hiroshima University, to perform optimal operation planning of a steelmaking electric furnace. The system uses fuzzy logic modeling methods to optimize electric furnace operations. Source: *Japanese Journal of Fuzzy Theory and Systems*, vol. 5, no. 1, pp. 83-91, 1993.

16. **Continuous Casting of Steel Billets** - a prototype system developed by the University of British Columbia to assist in troubleshooting quality problems in the continuous casting of steel billets. The system can guide operators in analyzing quality-related problems and provides a source of fundamental knowledge related to caster operation. It can diagnose a combination of defects in billet casting based on interpretation of the casting data. Source: *Proceedings of the IFAC Workshop*, Pergamon, Oxford, UK, pp. 95-102, 1992.

17. **Continuous Steel Casting** - a prototype neural network based expert system for control of a continuous caster in Finland. The system models and forecasts potential technical or quality-related problems in casting, based on operational experience and information about the incoming ladle of steel. It predicts possible occurrences of problems at the beginning or at the end of casting. Source: *IFAC Expert Systems in Mineral and Metal Processing*, Espoo, Finland, 1991.

18. **Fuzzy Controllers for Continuous Casting** - a prototype fuzzy logic controller developed by Esacontrol S.P.A., Italy. The system has an adaptive or learning capability to modify the fuzzy membership functions for the selected input and output variables. It has shown performance superior to that of conventional PID controllers and comparable to controllers with adaptive algorithms. Source: *Industrial Applications of Fuzzy Control*, Elsevier Sciences Publishers, 1985.

19. **Breakout Detection** - an expert system for early potential breakout detection in the continuous caster at Mannesmannrohren-Werke AG, Germany. The system is used for training operators and for detecting and diagnosing potential breakouts during the night shift. It is a part of a plant-wide distributed control system. Source: International Iron and Steel Institute, 1989.

Rolling

20. **Plate Mill Rolling Sequence Scheduling** - this expert system schedules the rolling sequence for the plate mill at Kobe Steel Ltd., Japan. It generates an optimum solution for scheduling slabs within a large number of process constraints. The expert system's schedules significantly improved the product quality and productivity of the mill. Source: Kobe Steel Ltd., Japan

21. **Steel Forging Process Planning** - a prototype expert system developed by Imperial College, UK for the process planning of cold steel forging. It identifies relevant

operations and their sequences from the required shape of forging. The forging specifications and tools are displayed in computer drawings together with the information essential for equipment design and selection. Source: *IEEE Conference Publication No. 322* pp. 141-146, June 27-29, 1990.

22. **ICLX** - this expert system diagnoses equipment faults in the steel rolling mill at British Steel. It monitors equipment throughout the plant, identifies equipment faults and recommends corrective procedures and/or additional tests to the operating staff. It also advises the maintenance staff about costs/benefits of the prescribed tests. Source: British Steel, UK.

23. **Rolling Mill Diagnostics** - a prototype expert system developed by Carnegie Mellon to address process problems in the multi-stand hot strip finishing mills. The system assists mill operators in diagnosing causes of production problems such as incorrect width or thickness of the finished products, etc. It runs on a PC AT using Personal Consultant Plus expert shell from Texas Instruments. Source: *1987 IEEE Industry Applications Society Annual Meeting*, Part II, Pittsburgh, PA., pp. 1081-1086, Oct. 18-23, 1987.

24. **Fault Localization** - this expert system monitors and diagnoses faults for the hydraulic screw-down of the tandem cold mill at Sumitomo's Kashima Steel Works. It also recommends corrective actions for equipment faults. It allows the operators, with no knowledge of maintenance procedures, to diagnose problems of the hydraulic screwdown even under abnormal operating conditions. Source: Sumitomo Metals, Kashima Works, Japan.

25. **QES** - a prototype expert system developed by Northwestern University for use in the hot strip mill. The system monitors the process and recommends control actions that the user must take to improve the product quality. Source: *IEEE Expert*, vol. 7, no. 5, pp. 36-42, 1992.

26. **Flatness Control** - an expert system for automatic flatness control (AFC) at Kobe Steel. The system adjusts the target shape pattern in the AFC system based on the material characteristics and operating conditions. It was shown to improve the operation of the rolling process. Source: *1991 International Conference on Industrial Electronics, Control and Instrumentation*, IEEE, New York, vol. 1, pp. 54-59, 1991.

27. **Fast Detection of Metal Surface Defects** - a neural networks-based prototype, developed by Fraunhofer-Institute, for detection and classification of defects on treated metal surfaces. The system is applied to surface inspection of rolling bearing metal rings. The defects are classified by textural segmentation using trained neural networks. Source: *IEEE International Joint Conference on Neural Networks*, IEEE, New York, vol. 2, pp. 1148-1153, 1991.

28. **SMARTVIS** - an expert system, developed at Rautaruukki, Finland, for automatic surface inspection of flat steel products. It has been used for surface defect detection at a carbon steel pickling line and at an anneal/pickle stainless steel line. It classifies defects accurately and reliably based on fuzzy and expert knowledge rules acquired from the operators. The machine learning component of the system allows operators to automatically regenerate classification rules from historical examples. Source: Rautaruukki New Technology, Oulu, Finland.

29. **Stainless Steel Rolling** - an expert system to assist in scheduling cold rolling of stainless steel strip at BHP Steel, Australia. It combines operators' knowledge with physical models of rolling and the metallurgy of the operations. It provides initial mill set-up schedules, reactive reschedules and subsequent on-line control. Source: BHP Steel Coated Products, Port Kembla, Australia.

30. **Rod and Bar Rolling** - a fuzzy inference-based control system for control of rod and bar rolling at Muroran Works of Nippon Steel Corporation. The system detects the tension from the load parameters and modifies roll revolution speeds, using fuzzy inference rules, to reduce the tension to zero. Source: Nippon Steel Corp., Hokkaido, Japan.

31. **TANDEM** - a prototype expert system for troubleshooting electrical faults on a tandem cold rolling mill at SAIC, Argentina. It focuses on providing direct operational diagnosis without the need for explanations or listing of many fault possibilities. Source: *IFAC Automation in Mining, Mineral and Metal Processing*, Buenos Aires, Argentina, 1989.

Other

32. **ISPA** - Intelligent Statistical Process Analysis automatically generates process control models for steel operations at USS/Kobe Steel Company. This expert system retrieves the process data and builds statistical models of the process without the need for an expert engineer. It reduces the time and cost needed for building statistical models and allows for frequent updating of the models as processes change. Source: Artificial Intelligence Technologies, Hanthorne, NY, USA.

33. **Stainless Steel Grading** - an expert system to assist with the grading of stainless steel slabs at British Steel's, Sheffield plant. It uses quality grading rules to alert plant operators about any potential quality problems so as to permit them to take corrective action. Source: British Steel, Sheffield, UK.

34. **Steel Plant Operation Scheduling** - an expert system developed for allocating production resources in steel plants. It was implemented using Knowledge Tool shell and is available from IBM, San Jose, US. Source: *Proceedings of the Sixth Conference on Artificial Intelligence Applications*, IEEE Computer Society, pp. 108-113, March 5-9, 1990.

35. **DIADEM** - an expert system to assist in pressure die casting. It identifies defects due to casting, determines the probable causes of the defects and recommends corrective action to eliminate future defects. Source: *Proceedings of the 16th International Die Casting Congress and Exposition*, Detroit, pp. 137-142, 1991.

36. **FsESS** - this expert system schedules manufacturing operations in steel forging at City Forge of Ellwood City, PA. It uses information on each order, steel grades, special alloys, molds, etc. and generates a schedule to meet the production order at the minimum cost. The system was developed by Carnegie Group, Pittsburgh, PA. Source: *AI Expert*, vol. 5, no. 5, pp. 72, May 1990.

37. **Planning Expert System** - an expert system developed to plan daily vehicle assignment tasks for the product shipments at Kawasaki Steel Corp. The system improves plant planning functions, production control and time of response to

meet customers' orders. Source: *Fourth International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems,* IEA/AIE-1991.

38. **ExTran** - an expert system developed for scheduling the movement of raw materials in steel mills. The system examines data from the on-line process control database and generates a set of possible raw material transfer schedules for the next eight-hour period. The schedules can be queried, modified or accepted by the operators. Source: *Intelligent Control,* IEEE New York, pp. 128-131, 1992.

39. **QDES** - quality design case-based reasoning expert system for steel products at Sakai Works, Nippon Steel. The system assists plant engineers in the design of production conditions for the manufacturing of steel products. It starts the design with a search for similar past orders, modifies the previous designs to the current order requirements and recommends the design of production conditions to plant engineers for further modification or improvement. QDES reduces the design cycle time by over 85 percent and improves design accuracy by over 30 percent. Source: Nippon Steel Corp., Sakai, Japan.

40. **DESPLATE** - a prototype expert system developed by Hong Kong University for diagnosing faulty shapes of steel plates. It contains knowledge rules from several electrical and mechanical engineering experts about the rolling mill's technology and operations. Each knowledge area and discipline constitutes its own knowledge base. Source: *Proceedings of the International Conference on Manufacturing Automation,* Publ. Univ. of Hong Kong, pp. 389-94, 1992.

41. **Large-Diameter Steel Pipes** - an expert system developed to generate optimal production specifications for the material design of large-diameter steel pipes. It produces optimal production specifications such as chemical composition, rolling and heat treatment conditions, etc., based on customer requirements and with the objective of minimizing the production cost and maximizing product quality. Source: Sumitomo Metal Industries, Kashima Works, Japan.

42. **Automatic Knowledge Acquisition** - a knowledge acquisition system for automating steel processes at Kawasaki Steel Corp. Its objective is to reduce the time involved in developing and implementing expert systems. The system was applied in developing an expert system for controlling material flow at a cooling bed of the plate mill. Source: Kawasaki Steel, Okayama, Japan.

43. **Air Separation** - an expert system for automatic control of the air separation plant at Yawata Iron Works, Nippon Steel Corp. The system improves on the control and energy efficiency of the existing model-based control of the separation plant. It can meet the changing demands for the product gases with improved flexibility and response time. Source: Nippon Steel Corp., Kitakyusyu, Japan.

44. **Case-Based Learning** - prototype expert systems for application of case-based reasoning in sheet metal manufacturing in Germany. The systems were implemented in metal forming, sheet metal manufacturing and classification of sheet metal parts. Source: *Computers in Industry,* vol. 17. no. 2-3, pp. 195-206, 1991.

45. **Maintenance Management** - an expert system to assist in maintenance planning and troubleshooting at Tata Iron & Steel, India. It was developed in C-language and encodes operators' judgments and reasoning used in developing maintenance schedules at the plant. Source: *The Second International Conference on Industrial*

and Engineering Applications of Artificial Intelligence and Expert Systems, ACM, New York, vol. 2, pp. 112-118, 1989.

46. **Continuous Annealing** - an expert system for controlling operation of the continuous annealing line at Hoesche Stahl AG, Germany. It diagnoses strip pass-line problems and assists operators during the start-up and shut-down procedures. Source: International Iron and Steel Institute, 1989.

47. **Smelting Prescription** - an expert system to assist in specifying metallurgical procedures in the electric steelmaking plant of Krupp Stahl AG, Germany. It also assists in developing specifications for altered and new steel grades. Source: International Iron and Steel Institute, 1989.

48. **Production Order** - an expert system for scheduling and allocating production in a cold mill of Krupp AG, Germany. It also allocates the rolled products to the existing customer orders. Source: International Iron and Steel Institute, 1989.

49. **Benzol Recovery Plant** - an expert system for on-line supervision of the benzol recovery plant at NKK's Keihin Works, Japan. It provides guidelines for optimizing and troubleshooting the distillation and absorption processes. Source: NKK Corporation, Kawasaki, Japan.

2.4. Related Applications

The following are intelligent systems used in other sectors which apply methods or solutions that might be of interest to the iron and steel industry:

1. TOP EXPERT, **Cement**, p. 74
2. ABB LINKman, **Cement**, p. 75
3. BATEXPERT, **Cement**, p. 76
4. PROGNOS, **Mining and Metallurgy**, p. 88
5. OpAS, **Oil and Gas**, p. 107
6. Groundwood Mill, **Pulp and Paper**, p. 118
7. Paper Production Scheduling, **Pulp and Paper**, p. 120
8. Steam and Power Toolkit, **Pulp and Paper**, p. 122
9. Cross-Cutting, all

3. CEMENT

3.1. Summary

The study identified fifteen different AI systems implemented in the cement sector. This number, however, does not count the application of LINKman, BATEXPERT and FLS systems at multiple sites. Including the multiple sites, the number of intelligent systems implemented by the cement sector is over 80 worldwide.

The majority of the identified applications address control and optimization of kiln operations. Considering that kiln processes are energy intensive and that kiln operations determine the productivity, cost and quality of the final product, this focus on the kiln section is understandable.

Kiln control is difficult because the materials and operations used are complex and relationships are not well understood. First, it is virtually impossible to develop detailed control models of the operations. Second, kiln processes often become unstable at lower operating temperatures so operators tend to run kilns at temperatures higher than required. This wastes energy and burns the clinker. Kiln control is further complicated by changes in feed composition and by process disturbances such as thermal cycles, or clinker building up on and falling away from the kiln refractory. Application of intelligent control systems alleviates many of these problems and provides improved process stability, product quality and energy efficiency.

Figure 3.1 is a schematic of cement-making process steps with the number of implemented AI systems identified for each area. Note that for the rotary kiln area seven systems are identified. However, if multiple site installations are counted, the total number of applications is 65 systems worldwide. As expected, the largest number of intelligent systems has been implemented for kiln control. Other areas have far fewer AI applications.

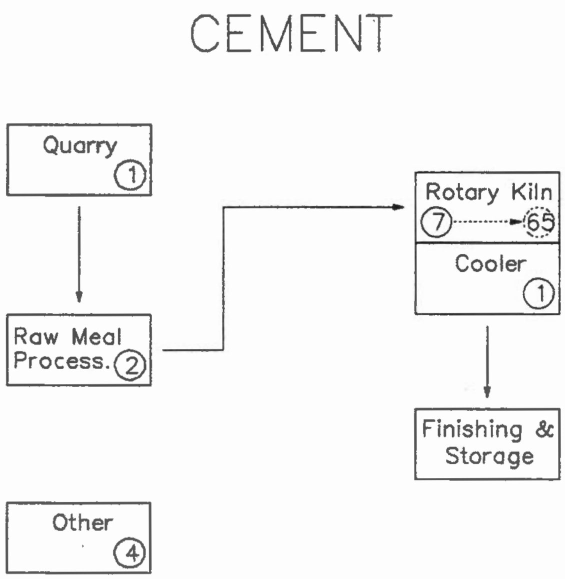

Figure 3.1. SCHEMATICS OF CEMENT-MAKING PROCESS

Figures 3.2 to 3.4 show the distribution of the implemented systems by application type, geographic region and technology used. The key conclusions from these figures are:

- Control constitutes 60 percent of all applications (90 if multiple site installations are included). The distant second and third are planning and monitoring, respectively.

- Europe accounts for most of the application sites (over 65 percent). North America is a distant second (20 percent). This is not surprising since most of the systems were developed and are commercially offered by European companies.

- The cement sector is unique in its heavy use of fuzzy logic. The application of fuzzy logic outnumbers the use of expert systems by two to one (ten to one if multiple site installations are included).

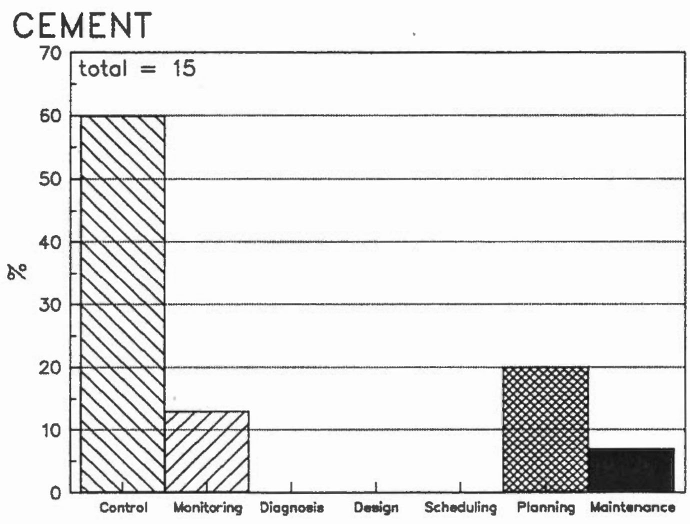

Figure 3.2. AI USE IN CEMENT PRODUCTION BY APPLICATION

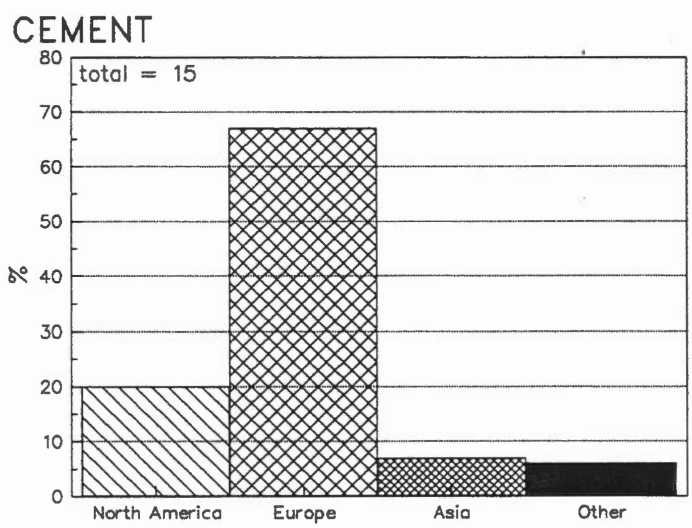

Figure 3.3. AI USE IN CEMENT PRODUCTION BY CONTINENT

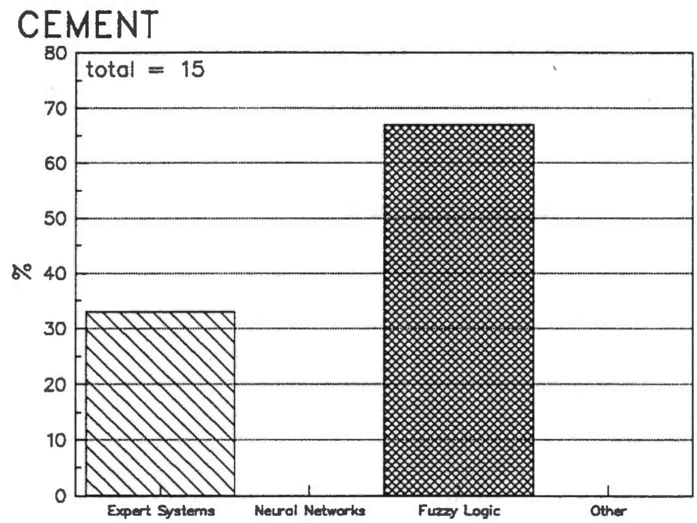

Figure 3.4. AI USE IN CEMENT PRODUCTION BY TECHNOLOGY

The following three sections provide examples of intelligent systems being applied in the cement sector. These sections are provided, not as a comprehensive review, but to show the types of problems being solved by the industry through AI technologies.

- Section 3.2 "Selected Application Targets" gives detailed information on developers, principles, cost and benefits of 5 systems.
- Section 3.3 "Other Systems Implemented", indicates 10 additional systems being used, with information on developers and solutions applied.
- Section 3.4 "Related Applications", indicates 12 intelligent systems being used in other sectors (plus those in the cross-cutting chapter) which may have application in the cement industry.

3.2. Selected Application Targets

Title: **TOP EXPERT - a kiln optimization expert system**

User: Cementos Cruz Azul
Lagunas Plant
Mexico

Developer/Vendor: Cementos Cruz Azul
Lagunas Plant
Mexico

Description: This expert system assists in optimization of operations at THE Lagunas cement plant facilities. The plant had a history of high energy and refractory usage prior to THE installation of the expert system. TOP EXPERT helped to increase the plant's efficiency and productivity. It consists of three modules: 1) fact-based module containing process data, process measurements and control points; 2) rule-based module with knowledge rules, constants, mathematical functions and data archiving; and 3) inference engine for evaluating THE fact base and the rule base. TOP EXPERT uses 10 input variables describing the operating status of the kiln and 5 output variables controlling the operations.

Cost to Implement: $120,000 to $150,000

Other Requirements:
- mathematical models and fuzzy logic membership functions
- process database
- data communication software

Hardware Requirements: workstation for the expert system

Reported Benefits:
a) increased plant productivity by 1.7 percent
b) reduced energy use per unit production by 8.2 percent
c) reduced electricity consumption per unit production by 7.6 percent

Reference: Gil, C.G.L., *Proceedings of the IEEE Cement Industry Technical Conference*, Dallas, Texas, U.S.A., pp. 244-252, 1992.

Title: **ABB LINKman - an expert system for control of cement manufacturing plants**

User: 55 cement plants worldwide

Developer/Vendor: ABB LINKman
Beckenham, UK

Description: ABB-LINKman offers comprehensive monitoring, control and optimization for cement kilns. It comes in two versions: LINKman Classic including a fuzzy expert system and LINKman Graphic incorporating object-oriented technology and enhanced visual and expert system capabilities. Both systems operate on Micro VAX platforms and offer extensive control screens to aid operators in tuning and optimizing the control loops. LINKman Graphic offers multicolored graphics and Windows-based options.

LINKman technology combines state-of-the-art computer process control with experience in development of expert systems for cement kilns since 1981. The strength of ABB-LINKman lies in its knowledge base which includes a comprehensive set of process supervisory rules from kiln operators.

Cost to Implement: $300,000 to $500,000

Other Requirements: data bridge codes

Hardware Requirements: plant interface system to DCS, PLC, etc.

Reported Benefits:

a) fuel consumption reduced by 2.5 to 5 percent (10 percent best achieved)
b) clinker grindability improved by 2.5 to 5 percent (10 percent best)
c) milling cost reduced by 7.5 to 15 percent (30 percent best)
d) peak and average refractory temperatures reduced by 50°C to 100°C (200°C best)
e) refractory life increased by 30 percent
f) NO_x levels decreased by 25 percent (50 percent best)
g) kiln availability improved to 80 percent (90 percent best)

Reference: Haspel, D.W., ABB Linkman Systems Ltd., Beckenham, Kent, United Kingdom.

Title: **BATEXPERT - an expert system for improved heat economics**

User: Ciments Francais Group
Couvrot, Beffes, Bussac Plants

Developer/Vendor: BATEXPERT
Ciments Francais
France

Description: This fuzzy logic expert system controls kiln operations at several Ciments Francais plants. It is marketed by Ciments Francais subsidiary, BATEXPERT Ltee. BATEXPERT addresses several operational and diagnostic problems encountered in kiln operations. These include the need for: 1) consistency in operation of the kilns; 2) frequent adjustment of control variables in response to changes in operating conditions; 3) continuous monitoring and interpretation of sensor data; 4) good diagnostics of the kiln to reduce unscheduled shutdowns; and 5) optimization of the entire plant including pre-calciner, kiln and cooler in order to achieve optimized energy use and productivity.

Cost to Implement: $300,000 to $400,000

Other Requirements: data links to plant computer

Hardware Requirements: interface to plant control system

Reported Benefits:
a) improved kiln availability by 10 percent
b) reduced heat consumption per unit product by 3 percent
c) increased kiln throughput by 5 percent
d) reduced use of electricity per unit produced by 8 percent

Reference: Levine, P., *World Cement,* pp. 133-135, April, 1990.

Title: Cement Production Control - an expert system for supervisory control in cement manufacturing

User: General Cement Co.
Heracles II Plant
Greece

Developer/Vendor: Amper SA
Information Systems
Greece

Description: This expert system provides supervisory control at Heracles II plant in Greece. It consists of nine smaller expert subsystems arranged in groups. They include distributed experts for kiln, raw materials mill, finishing product mill and coal mill control. Each subsystem has fewer than 125 rules and 40 to 50 rules are usually sufficient to describe knowledge in most subsystems. The subsystems optimize operations and energy usage in each plant area. Use of distributed expert subsystems has allowed General Cement Co. to carry out the expert system development in phases, over several years, while benefiting from each installation.

Cost to Implement: $200,000 to $300,000

Other Requirements: a network for distributed computing

Hardware Requirements: PC AT for expert system

Reported Benefits:
a) increased plant productivity by 4 to 5 percent
b) increased energy efficiency per unit production by 4 percent
c) improved plant availability to 92 percent

Reference: King, R.E., *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 5, no. 2, pp. 167-176, 1992.

Title: **FLS Automation - an expert system for plant-wide control of cement manufacturing**

User: Over 100 control installations worldwide

Developer/Vendor: FLS Automation
Hunt Valley, MD, US

Description: FLS Automation offers a comprehensive plant-wide automation system called Summit Series. It controls quarry utilization, grinding and milling operations, kiln operations, production scheduling, laboratory management and product quality. The system is a modular, vertically integrated, open system with the ability to interface with a variety of hardware systems. Summit Series includes ECS (Expert Control and Supervisory) system for control and optimization of the cement manufacturing processes. It has unlimited input/output points, graphics displays and software modules including: Opstation, CEMScanner, Fuzzy Logic, PowerGuide, Refractory Management, Reporting Module and Intelligent Alarm Module. The Fuzzy Logic module provides high level control and optimization for the plant kiln including control setpoints for the Distributed Control System, data for visual displays and status reports.

Cost to Implement: $200,000 up

Other Requirements: data communication codes

Hardware Requirements:
- plant interface to DCS, PLCs, etc.
- host computer for multi-tasking, communication links, new displays, etc.

Reported Benefits:

a) benefits are similar to those reported by other plants: productivity increased by 2 to 5 percent, energy use reduced by 4 to 8 percent, plant availability improved by 5 to 10 percent
b) other benefits include: improved work practices, consistent approach to control, better knowledge about process dynamics and process control

Reference: Jurko, B., FLS Automation, Hunt Valley, Maryland, U.S.A.

3.3. Other Systems Implemented

1. **Cement Kiln Control** - an expert system prototype provides process control in cement manufacturing in UK. It includes programs that generate control strategies based on current operating data and control rules. The prototype also has a plant dynamic simulator for diagnosis of process faults. Source: *IEEE Colloquium of Real-time Expert Systems in Process Control*, no. 107, London: IEEE, pp. 71-79, 1985.

2. **Cement Manufacturing Preventive Maintenance** - an expert system for cost effective maintenance at Dundee Cement Co, Clarksville, MO, USA. It oversees equipment utilization and availability, preventive maintenance, lubrication scheduling, spare parts inventory, and expandable parts inventory. The program is also coupled with the corporate payroll and general ledger system for cost accounting and control. Source: *IEEE Transactions on Industry Applications*, vol. IA-20, No. 3, pp. 528-531, May/June 1984.

3. **QSO (Quarry Scheduling Optimization) Expert** - a prototype system for optimization of raw material extraction at quarries. It provides interactive, graphic-oriented programs for short-term quarry scheduling and production control. Source: *World Cement*, p. 207, May 1990.

4. **A Hybrid Control System** - an expert system for automated management and control of a cement kiln at Onada's plant, Japan. The kiln control system consists of three parts: steady-state control, nonsteady-state control and emergency control. The expert system uses theoretical optimization algorithms and operating rules acquired from operators. Source: 1992 *IEEE Cement Industry Technical Conference XXXIV*, New York, Cat. No. 92CH3165-8, pp. 253-267, 1992.

5. **Raw Material Blending** - a prototype expert system for blending raw materials in cement manufacturing in Giza, Egypt. It handles variations in the chemical composition of the raw materials by adjusting the blending scheme. It also maintains the quality of the raw meal while minimizing the variance in its composition. Source: *Proceedings of the Second IASTED Intern. Conf. Computer Applications in Industry*, ACTA Press, Zurich, vol. 1, pp. 266-269, 1992.

6. **The Cement Kiln** - a prototype system for multivariate nonlinear control of a cement kiln in Spain. It facilitates periodic tuning of the control program to compensate for the process behavior and production requirements. The tuning tasks can be performed by the operators without any experience in software programming or control design. Source: *Advance Control of Chemical Processes*, Pergamon, Oxford, pp. 291-294, 1992.

7. **Intelligent Tuning** - an expert system to maintain the quality of raw materials blending at Lafarge Coppee, France. It provides two levels of control strategies for ensuring the robustness of the blending control at cement plants. It maintains the quality of the blend at the reference values and minimizes the variations of the chemical composition of the raw meal blend. Source: *Intelligent Tuning and Adaptive Control*, Pergamon Press, Oxford, pp. 301-306, 1991.

8. **Cement Klinker** - an expert system to automatically control kilns and operations at 25 plants of Lafarge Coppee. It controls precalciner temperature setpoints, exhaust fan speed, meal rate, coal rate and kiln speed. The system's input variables include

gas analysis, kiln amperes, kiln temperatures, and free lime analysis. Lafarge reports increased production by 5 percent and decreased energy consumption by 5 percent for an average plant. Source: *World Cement*, p. 20, July 1991.

9. **CIM-EXPERT** - an expert system to prevent overburning of lime in limestone calcining plants in Italy. It controls a two-shaft rectangular kiln for producing quicklime. Source: *World Cement*, vol. 21, no. 8, p. 336, Aug. 1990.

10. **ITECA** - an intelligent system for controlling cement plant operation. It includes special instrumentation for control and optimization of plant operations such as carbonate strength analyzer for controlling the uniformity of the raw meal, a fire loss analyzer to measure the decarbonization rate at the precalciner, a free lime content analyzer to control the firing process, and a fineness analyzer to control the size distribution at the crusher outlet. Source: *World Cement*, p. 128, Apr. 1990.

3.4. Related Applications

The following are intelligent systems used in other sectors which apply methods or solutions that may be of interest to the cement industry.

1. Hot Stove Optimization, **Iron and Steel**, p. 38
2. Heat Balance Control, **Iron and Steel**, p. 43
3. ESWGR, **Iron and Steel**, p. 44
4. Scheplan, **Iron and Steel**, p. 56
5. Control of Electrical Energy Consumption, **Iron and Steel**, p. 58
6. Diagnosis of Equipment Faults, **Iron and Steel**, p. 60
7. Boiler and Furnace Control, **Iron and Steel**, p. 61
8. HelpSAG, **Mining and Metallurgy**, p. 91
9. SAG Circuits, **Mining and Metallurgy**, p. 93
10. Process Control, **Mining and Metallurgy**, p. 94
11. OpAS, **Oil and Gas**, p. 107
12. Groundwood Mill, **Pulp and Paper**, p. 118
13. Cross-Cutting, all

4. MINING AND METALLURGY

4.1. Summary

Review of the mining and metallurgical sector uncovered over 50 intelligent system applications in the industry including field tested prototypes. This sample is a representative cross section of AI systems in the sector.

Figure 4.1 is a schematic representation of operations in the mining and metallurgical sector with the number of AI systems identified in each area (numbers in circles). The systems applied are as follows:

- exploration (3 systems)
- surface mining (8 systems)
- underground mining
  - machines (10 systems)
  - ventilation/transportation (7 systems)
- mineral processing
  - grinding (5 systems)
  - flotation (8 systems)
  - other (10 systems)

Figures 4.2 to 4.4 show the distribution of systems identified by the type of application, geographic region and technology. The key conclusions from these figures are:

- The largest application domains are control (39 percent), monitoring (18 percent) and planning (16 percent). Most of the control, monitoring and diagnosis applications are in the metallurgical sector, while planning and scheduling applications are found in mining.
- More than one-half of all applications identified are in North America with Europe accounting for about one-fourth of applications. Australia, Africa and South America combined have about 11 percent of the applications.
- Most applications use expert system technology. There are, however, several neural networks applications in mineral processing.

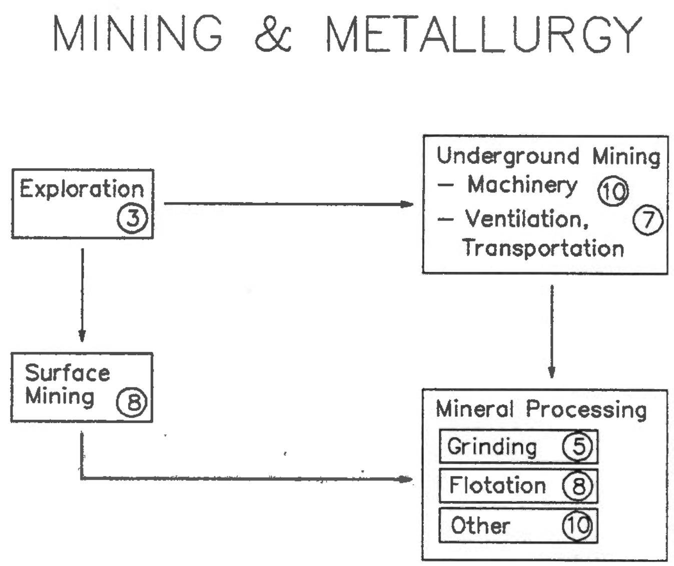

Figure 4.1. SCHEMATICS OF MINING AND METALLURGICAL OPERATIONS

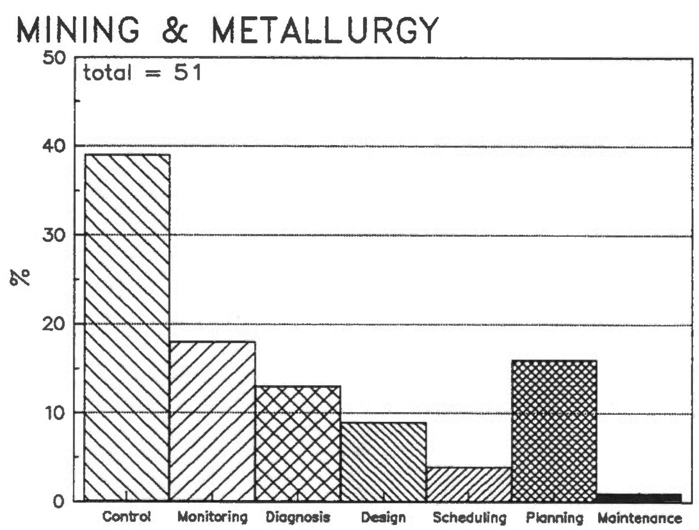

Figure 4.2. AI USE IN MINING AND METALLURGY OPERATIONS BY APPLICATION

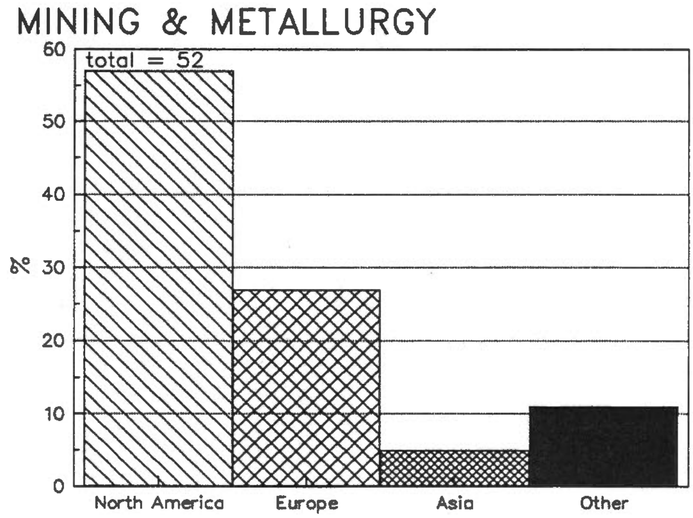

Figure 4.3. AI USE IN MINING AND METALLURGY OPERATIONS BY CONTINENT

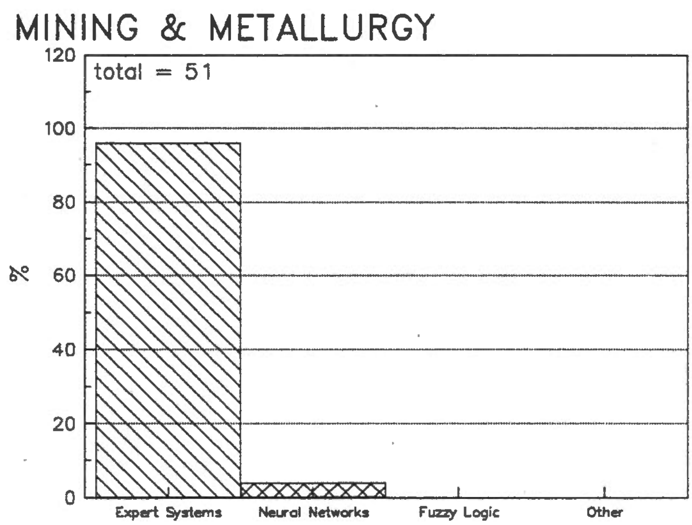

Figure 4.4. AI USE IN MINING AND METALLURGY OPERATIONS BY TECHNOLOGY

AI applications in the metallurgical industry share many common characteristics with those in the iron and steel industry. They are small to mid-size applications developed by large companies with a focus on productivity and product quality. The expert systems are often part of the overall control system.

The following three sections provide examples of intelligent systems being applied in the mining and metallurgy sector. These sections are provided, not as a comprehensive review, but to show the types of problems being solved by the industry through AI technologies.

- Section 4.2 "Selected Application Targets" gives detailed information on developers, principles, cost and benefits of 9 systems.
- Section 4.3 "Other Systems Implemented", indicates 43 additional systems being used, with information on developers and solutions applied.
- Section 4.4 "Related Applications", indicates 12 intelligent systems being used in other sectors (plus those in the cross-cutting chapter) which may have application in the mining and metallurgy industry.

4.2. Selected Application Targets

Title: **CHOOZ - an expert system for staffing planning in underground mines**

User: Tanoma Coal Co.
Indiana, PA, US

Developer/Vendor: Tanoma Coal Co.
Indiana, PA, US

Description: The purpose of CHOOZ is to aid mine managers in staff selection for different shifts. The system uses information about the experience and union seniority of available workers and assigns work crews to different jobs and shifts. CHOOZ incorporates information about workers, jobs, tools, skills, makeup of mining crews, distances, times and facts describing relationships among these parameters. The facts and rules define the problem within which crews have to be scheduled. The system is helpful in assisting mine supervisors in making crew scheduling changes necessitated by unforeseen circumstances. CHOOZ runs on an IBM PC and has been used since 1987.

Cost to Implement: $60,000 to $90,000

Other Requirements: process database

Hardware Requirements: PC AT for the expert system

Reported Benefits:

a) improved quality of crew schedules
b) elimination of late shift start-ups due to unforeseen changes in worker assignments

Reference: Britton, S., *Coal Age*, pp. 69-70, January, 1987.

Title: **Flotation Expert Display - an expert system to aid process operators in making better decisions**

User: Outokumpu Oy
Enoukoski Mine
Finland

Developer/Vendor: Outokumpu Electronics Oy
Riihiontunie
Finland

Description: Outukumpu Oy has implemented the FX-Flotation Expert system at its Enoukoski copper mine. The system assists plant engineers and the mill superintendent to select supervisory control and standardize the operating procedures for each shift. The system provides operators with the following information: 1) the most suitable setpoint adjustment to achieve specific operating targets; 2) the success ratio of control actions; 3) a review of operating experience. FX-Flotation Expert classifies the data according to preselected criteria and presents the data in appropriate form for the operators.

Cost to Implement: $120,000 - $150,000

Other Requirements: communication links for process data

Hardware Requirements: plant-wide process control system

Reported Benefits:
a) improved product recovery
b) standardized operating procedures among shifts
c) improved troubleshooting of on-stream analyzers

Reference: Karhu, L., *Powder Technology*, vol. 69, pp. 61-64, 1992.

Title: **PROGNOS- a prototype expert system for maintenance of mining machinery**

User: LKAB Company
Kiruna Mine
Sweden

Developer/Vendor: LKAB Company
Kiruna Mine
Sweden

Description: PROGNOS assists in fault diagnosis of transmission systems of Load-Haul-Dump (LHD) vehicles at LKAB's Kiruna mine, Sweden. It also proposes repair actions for the faults. It was developed using 1st-Class expert system shell and includes six classes of knowledge: 1) description knowledge outlining the hierarchical design of the transmission system; 2) behavioral knowledge identifying normal and abnormal functioning of the equipment; 3) operational knowledge describing principles of equipment operations; 4) heuristic knowledge defining associations between faults and their symptoms; 5) diagnostic knowledge outlining methods for diagnosing faults; and 6) maintenance knowledge providing information relevant to the maintenance of the equipment. LKAB reports satisfactory operations of PROGNOS at the mine and acceptance of the system by the mine repair personnel.

Cost to Implement: $60,000 to $90,000

Other Requirements:
- historical fault reports for the transmission system
- vehicle maintenance manuals

Hardware Requirements: PC AT for the expert system

Reported Benefits: a) reduction in repair time of LHD vehicles

Reference: Vagenas, N., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 173-178, 1991.

Title: **Phosphate Flotation - an expert system for control of the phosphate flotation process**

User: Kemira Oy
Siilinjarvi Plant
Finland

Developer/Vendor: Kemira Oy
Porkkalankatu
Finland

Description: This system aims at maximization of flotation cell recovery while maintaining the concentrate grade at a given level. The grinding system includes two different control strategies: a multivariate control system and a combination of single-loop controllers to handle large variations in ore composition. It also includes analysis of process alarms and optimization of process conditions. The flotation expert system includes three main modules: 1) steady-state modules with mass and water balance calculations; 2) dynamic calculations module with flotation process dynamic simulator; and 3) control strategies module which is able to simulate different single input/single output controllers. The aim of the software is not to provide automated supervisory control but to support, train and guide the process operator to more efficient control actions.

Cost to Implement: $80,000 to $120,000

Other Requirements:
- models of flotation processes
- ONSPEC control software

Hardware Requirements: PC AT for the expert system

Reported Benefits:

a) improved concentrate recovery (1.5 percent P_2O_5) while maintaining the concentrate grade
b) improved control of disturbances in the flotation process caused by lag time delays, non-linear responses and the varying composition of the ore

Reference: Jamsa-Jounela, S.L. et al., *Proceedings of the IFAC Workshop on Automation in Mining, Mineral and Metal Processing*, Buenos Aires, Argentina, pp. 45-52, 1989.

Title: **Proscon - an expert system to aid operators in control of ore concentrators**

User: Outokumpu Oy
Pyhasalmi Mine
Finland

Developer/Vendor: Outokumpu Oy
Pyhakumpu, Finland

Description: Proscon provides comprehensive process monitoring and control for the grinding and flotation circuits. The system has the capability to: 1) announce process disturbances through a speech synthesizer; 2) provide reporting and cost optimization for each circuit; 3) identify control setup for grinding and flotation operation; 4) monitor and replay set point changes; and 5) rank the shifts according to the optimization of the system. The system provides a display of the latest values of the most important process measurements, i.e., metal analyses, forecast of the operating profit and actual results, reagent cost for each circuit, etc. Proscon also automatically maintains a history of the averages of all variables to provide production comparison between the shifts.

Cost to Implement: $120,000 to $180,000

Other Requirements:
- speech synthesizer
- relational databases
- data communication software including noise filtering

Hardware Requirements: plant-wide computer control

Reported Benefits:
a) reduction in variation in throughput capacity
b) increased throughput
c) decreased energy consumption
d) reduction in generation of overfine material

Reference: Miettunen, J., *Proceedings of the IFAC Workshop on Automation in Mining, Mineral and Metal Processing*, Buenos Aires, Argentina, pp. 109-114, 1989.

Title: **HelpSAG - an expert system for control of SAG/Ball Mill Circuits**

User: Dominion Mining Ltd.
Paddy's Flat Gold Plant
Western Australia

Developer/Vendor: Orway Mineral Consultants
and Mennetech, Australia

Description: HelpSAG provides a quick reference manual and on-line advisory help for the plant shift operators. The on-line help includes troubleshooting procedures and mill power optimization. HelpSAG was developed using an expert system shell EMB which allows the plant expert to build relationships between reference manual pages and type of troubleshooting procedures. The system runs on a PC AT and has been well accepted by the plant operators. Since HelpSAG's installation, several other systems have been implemented including HelpCIL for running CIL circuits and HelpLeach for solving problems with leaching circuits.

Cost to Implement: $120,000 to $150,000

Other Requirements:
- training manuals
- modelling program for optimizing plant throughput
- historical data on circuit troubleshooting
- data communication link between the plant computer and the expert system

Hardware Requirements: PC AT for the expert system

Reported Benefits:
a) minimized effects of the loss of trained and experienced staff
b) reduced number of calls on professional staff for training and for solving routine circuit problems
c) improved milling strategies for plant optimization

Reference: Bradford, S.H., *Proceedings of the IFAC Workshop on Expert Systems in Mineral and Metal Processing*, Espoo, Finland, pp. 1-6, 1991.

Title: **Autoflote - an expert system for control of a coal fines circuit**

User: Kembla Coal and Coke
Parkside Colliery, UK

Developer/Vendor: Century Oils
Australia

Description: Autoflote is a tailor-made flotation control system for optimization of coal fines circuits. It consists of turbidity probes for monitoring changes in plant conditions, a sampling sub-system for circuit monitoring, a process computer to interpret the plant inputs and control plant equipment, and a host computer to provide management reporting and an operator interface to the system. It uses readings from the turbidity probes in the flotation feed, product and tailings to adjust the flotation reagent in order to accommodate changes in feed solids content and size distribution. The feedback strategy involves changes in the reagent dosage to produce the optimum yield and ash in the product. At Parkside Colliery, Autoflote controls flotation reagent dosage, flotation cell level and thickener flocculant dosage, Baum washer solids concentration and thickener performance. The system was tailor-made to minimize the need for plant modifications.

Cost to Implement: $250,000 to $350,000

Other Requirements: included in Autoflote

Hardware Requirements: included in Autoflote

Reported Benefits:

a) for the thickener operation: reduced flocculant consumption, greater quantity and guaranteed quality of available clarified water, ability to run thickener with a high bed level, reduced operator actions
b) for the baum circuit: jig yield increased by 4.1 percent, combustible recovery increased by 5.3 percent
c) for overall plant: increased throughput by 25 percent without loss of product quality

Reference: Rouse, B. et al., *Mine Quarry*, vol. 21, no. 3, pp. 8-16, 1992.

Title: **SAG Circuits - an expert system for control of semi-autogenous grinding circuits**

User: Copper Mine, Mexico
Copper Mine, Chile

Developer/Vendor: Control International
Salt Lake City, US

Description: Control International reports application of expert systems for supervisory control of semi-autogeneous mill circuits in copper ore plants in Mexico and Chile. Both systems were designed for supervisory control and optimization of mill circuits using existing control plant I/O networks. The systems perform dynamic optimization of the mill using simple mill models relating mill throughput to mill holdup, ore grindability and mill power. The system strategy is to raise the feedrate whenever possible and to change other variables before cutting feedrate.

Cost to Implement: $120,000 to $150,000

Other Requirements:
- data links to plant control system
- SAG mill mathematical models of grinding

Hardware Requirements: high end workstation for the expert system

Reported Benefits:
a) increase in circuit throughput by 5 to 8 percent
b) decrease in energy consumption by 4 to 5 percent
c) improvements in productivity of 6 to 15 percent in difficult to control circuits
d) solution to problems caused by a high turnover rate of plant personnel

Reference: Broussard, A., *World Mining Equipment*, vol. 16, no. 4, pp. 34-37, 1992.

Title: **Process Control - an expert system for supervisory control of a zinc plant**

User: Outokumpu Oy
Kakkola Zinc Plant
Finland

Developer/Vendor: Outokumpu Electronics Oy
Riihiontunie
Finland

Description: This expert system provides quick information on the overall status of the plant operations. Process areas and operations controlled by the expert system include thickening, production rate, analytical assays, evaluation of the solution volume, and specific gravity and equipment monitoring. The system provides background supervisory-type information on important operating factors which may have been overlooked and not remedied by the plant operators. It provides specific instructions about plant areas that require immediate attention and recommends how abnormal process conditions should be corrected. The system also ensures uniform operating procedures among shifts.

Cost to Implement: $80,000 to $140,000

Other Requirements: communication software between the expert system workstation and plant computer

Hardware Requirements: high-end workstation for the expert system

Reported Benefits:
a) more stable operations
b) improved plant economics

Reference: Karhu, L. et al., *Powder Technology*, vol. 69, pp. 64-66, 1992.

4.3. Other Systems Implemented

Exploration

1. **Prospector** - an expert system developed by SRI International to identify the probability of finding particular ore deposits in a specific geological region. The system uses information about geology coupled with information obtained from geological surveys of the region. The latest version includes descriptive mineral deposit models and graphs. Source: *Proceedings of the Annual AI Systems in Government Conference*, Washington, DC, IEEE Computer Society Press, pp. 89-92, March 1992.

2. **Geotechnical Risk** - a prototype expert system for assessment of geological risk at surface coal mines. It determines slope stability by linking expert rules to geological models and specialized mining software. Source: *Second International Symposium on Mine Planning and Equipment Selection*, Calgary, Nov. 7, 1990.

3. **Mining Method** - a decision-support system for selecting mining methods for ore deposits. It helps to select the correct mining method and ensures that all important issues have been considered in the evaluation. The key parameters used are the characteristics of the ore body and ground stability. Source: *SME Annual Meeting*, Salt Lake City, Feb. 26, 1990.

Surface Mining

4. **EXPATEC** - this expert system assists in diagnosis of the automatic transmission controller used on heavy-payload mining and earth-moving equipment at Bharat, India. It improves the identification and troubleshooting of faults in large rear dumpers. Source: *Computers in Industry*, vol. 17, no. 4, pp. 375-384, Dec. 1991.

5. **Acid Mine Drainage** - a prototype expert system for modeling water quality for acid mine drainage at Ontario mine sites. The system (RAISON, Regional Analysis by Intelligent System on Micro Computer) is based on steady-state and time-dependent models for concentration of pollutants in rivers and lakes. Source: *Second International Conference on the Abatement of Acidic Drainage*, Montreal, Sept. 16, 1991.

6. **MINDER** - an expert system for selecting surface mining methods and equipment at UK surface mines. It ranks equipment using fuzzy logic and presents the choices to the design engineer for further evaluation. *Second International Symposium on Mine Planning and Equipment Selection*, Calgary, Nov. 7, 1990.

7. **Equipment Selection** - a prototype expert system for the design and planning of surface mining operations. It selects mine equipment such as hydraulic excavators and draglines based on the mine operating data provided by the user. Source: *Mineral Science and Technology*, no. 10, p. 323, 1990, UK.

8. **Storage of Coal** - a prototype expert system for recommending procedures for handling stockpiles of coal in a safe manner. It assesses the spontaneous combustion

risk of a coal stockpile design, identifies the design faults and recommends corrective actions as required. *Mineral Science and Technology*, vol. 12, p. 253, 1991.

9. **Dragline Efficiency** - this expert system is for on-line monitoring and optimization of a Marion 8200 dragline at a New Brunswick coal mine. The system monitors strain in the tristructure, lubrication status, production and safety parameters, etc. It can also be used for training novice operators. Source: *22nd APCOM 90 Symposium*, Berlin, September 17, 1990.

10. **Walking Dragline** - a prototype expert system for diagnosing faults in 18 different components of a dragline. It diagnoses dragline faults from the user's input data describing the problem. Source: *Mineral Science and Technology*, vol. 11, p. 71, 1990, USA.

11. **Spontaneous Combustion** - a prototype expert system for assessing spontaneous combustion risk in longwall mining. It identifies risk factors and evaluates self-heating risk in a longwall face. The users can assess the effect of alternative mining methods on the spontaneous combustion risk. Source: *Mining Science and Technology*, vol. 11, p. 45, 1990.

Underground Mining

12. **DUSTPRO** - a prototype developed at US Bureau of Mines for the control of the mine ventilation system to minimize miners' exposure to respirable dust. The system uses information about the available ventilation equipment and control procedures, and mine ventilation regulations. It provides recommendations for reducing dust levels in the mine to safe environmental working levels. Source: *ESD/SMI Second Annual Expert System Conference*, Detroit, MI, pp. 377-385, April 12-14, 1998.

13. **Mine Ventilation Control** - a prototype developed at Kentucky University for controlling operations of a mine ventilation network. The system uses simulation programs of mine ventilation to arrive at best ventilation control. Source: *Proceedings of the 5th US Mine Ventilation Symposium*, West Virginia University, pp. 566-572, May 3-5, 1991.

14. **FANPRO** - an expert system to aid in diagnosis of mine ventilation. It diagnoses mechanical and electrical problems with fans, fan drives, and mine-induced turbulence at the fan outlet. The system requires the user to answer questions and enter data, determines the causes of the problem and recommends solutions. Source: *5th US Mine Ventilation Symposium*, Morgantown, June 3, 1991.

15. **SCAR** - a prototype developed at Alabama University to diagnose electrical faults in shuttle cars. The program traces the possible faults from the initial symptoms of the failed equipment and from answers to questions posed by the system. Source: *IEEE Transactions of the Industry Applications Society*, vol. 25, no. 4, pp. 691-698, July-Aug 1989.

16. **SHEARER** - an expert system to recognize faults in coal cutting equipment at British Coal, Berton-Trent, England. Source: *The Sixth Annual Technical Conference of the British Computer Society Specialists Group on Expert Systems*, Cambridge, England, pp. 231-241, Dec. 1986.

17. **Optimal Blast Design** - a prototype expert system for determining the best suitable blast design. It determines costs of drilling, blasting, loading, hauling, and trouble-free blast, and optimizes the blast design using specific blast parameters. Source: *Second International Symposium on Mine Planning and Equipment Selection*, Calgary, Nov. 7, 1990.

18. **Hoist Safety and Productivity** - a prototype expert system for improving hoist safety and productivity. The system's knowledge base includes information on optimizing hoist operations, selecting the hoist, checking for safe operation, and hoist regulations. An example of the system's use is modification of a hoist braking system. Source: CANMET, Ottawa, Canada.

19. **Continuous Mining Machines** - an expert system for on-line diagnostic maintenance of continuous mining machines. It provides hydraulic and electric motor diagnostics for Joy 16CM miner and electric diagnostics for Joy 14CM machines. Source: US Bureau of Mines, Pittsburgh, USA.

20. **Ground Control** - an intelligent system to assist ground personnel to operate complex mine models at Falconbridge. It makes all the choices required for modelling of mine stability based on user selected rock properties, joint patterns, and rock bolt types. Source: *92nd Annual General Meeting of the CIM*, Ottawa, May 6, 1990.

21. **Shaft Hoisting Systems** - the expert system to assist in selecting drum hoists and the associated wire and motors. It makes recommendations on the number of hoists required, the rope needed, the drum dimensions, and the horsepower rating of the motor. Source: *92nd Annual General Meeting of the CIM*, Ottawa, May 6, 1990.

22. **Mine Operations Decision Support** - a prototype expert system developed at CANMET and NRC for scheduling, dispatching and reconciling production data at Denison Mines. Source: *CANMET Report MRL 90-093*, August 1990.

23. **Hydraulic Maintenance** - a prototype expert system for diagnosis of hydraulic maintenance of a continuous mining machine. It monitors the machine's hydraulic system and diagnoses the system failures. Source: *SME Annual Meeting*, Salt Lake City, Feb. 26, 1990.

24. **MMSS** - a mine management support system for scheduling, time reporting, personnel training, etc. in underground coal mines. It handles information on workforce data, operating plans, mining laws, work rules and schedules, inventories, mine performance, and administrative procedures. Source: *SME Annual Meeting*, Salt Lake City, Feb. 26, 1990.

25. **Blast Design** - a prototype expert system for design and evaluation of blasts. It predicts blast fragmentation patterns and select blasting detonator delays. Source: *International Journal of Surface Mine Reclamation*, no. 4, p. 7, 1990.

26. **On-Board Diagnostics** - an expert system developed for diagnostics of mining machines for the South African mining industry. The system's diagnosis is based on a series of questions to be answered by the operators. Source: *Journal of South African Institute of Mining and Metallurgy*, vol. 90, no. 1, p. 11, 1990.

27. **ECAS** - a prototype expert system (Emergency Control Advisory System) developed by Australian Coal Industry Research Laboratories to assist mine rescue teams

during a coal mine disaster. The system ensures that the recovery crew investigates all appropriate alternatives, and does not undertake any activities which might increase the danger. The system is also used for training recovery crews. Source: *NEURON DATA*, Palo Alto, US.

Mineral Processing

28. **Aluminum Extrusion** - expert system developed to assist in quality and process design in aluminum extrusion at Kobe Steel. Source: Kobe Steel, Japan.

29. **Aluminum Processing** - this expert system supports the planning of processes for smelting and rolling of aluminum, copper and other metals at Kobe Steel. It can generate job schedule and production plans for processing various materials to the specifications of individual clients. Source: Kobe Steel, Japan.

30. **Grinding Circuit** - an expert system for supervisory control of the grinding circuit at Les Mines d'Or Kiena. It optimizes the grinding circuit operation while a supervisory program performs the regulatory and supervisory control. Source: *25th Annual Meeting of Canadian Mineral Processors*, Ottawa, Jan. 1993.

31. **Froth Identification** - an expert system to assist operators to use froth conditions to control the flotation circuit at Highland Valley Copper Plant. The system uses froth type description as an indicator of the operating conditions. Source: *25th Annual Meeting of Canadian Mineral Processors*, Ottawa, January 1993.

32. **Fertilizer Granulation** - a prototype expert system developed to aid in controlling fertilizer granulation at Intevep S.A. in Venezuela. It addresses the production, quality control, and environmental impact of the fertilizer production. Source: *Phosphorus & Potassium*, No. 183, p. 30 1993.

33. **Lead and Zinc Operations** - a prototype expert system to monitor organic additives in electrolyte at Cominco B.C. lead/zinc refinery. It is designed to assist plant operators in relating the overpotential measurements with other operating parameters such as electrolyte composition, temperature, stability of electrofining anodes, etc. The derived correlations are used for control of electrodeposition. Source: *International Symposium on Electrometallurgical Plant Practice*. Montreal, Oct. 21, 1990.

34. **Intelligent Control for Electrolytes** - an expert system to control and maintain the electrolytic tankhouse at Montreal's CCR copper refinery. Source: *International Symposium on Electrometallurgical Plant Practice*, Montreal, Oct. 21, 1990.

35. **Flotation Circuit** - a prototype expert system for on-line control of a copper flotation circuit. The system runs in cooperation with regulatory controllers. It adjusts regulatory loop setpoints in real time based on the assays data received from on-stream analysis. Source: *23rd Annual Meeting of the Canadian Mineral Processors*, Ottawa, Jan. 1991.

36. **Iron Mine** - an expert system developed for monitoring and controlling an autogenous mill and spiral circuit at Wabush iron ore mine. It monitors operating parameters such as mill power draw and feed rate and improves the control, recovery and productivity of the mill. Source: *24th Annual Operators' Conference of the Canadian Mineral Processors*, Ottawa, Jan. 21, 1992.

37. **Operation Advisor** - an expert system to monitor key process variables and provide on-line advice to the sulphur well operators at a Frasch sulphur mine. It includes qualitative process modelling, statistical process control, and a process management database. The system resulted in more efficient use of heat, an extended well life and cost savings. Source: *Control '90 - Mineral and Metallurgical Processing*, Salt Lake City, Nov. 1, 1990.

38. **Potash Flotation** - a prototype learning expert system for control of flotation parameters. It includes control rule generation from historical data and implementation of the rules for automatic supervisory process control. Source: *Aufbereit Tech*, vol. 32, no. 5, p. 215, 1991.

39. **SIS** - a prototype expert system (Separator Identification System) for generation of near-optimal separation sequences for multi-component mixtures. It recommends separation sequences and operations based on the physical properties of the mixture. It uses fuzzy logic for uncertainty management. Source: *Canadian Journal of Chemical Engineering*, vol. 69, no. 1, p. 67, Feb. 1991.

40. **Flotation Pilot Plant** - a prototype expert system for control of flotation columns at Minnovex pilot plant. The system helps to characterize the operations of individual columns. It is incorporated in an overall supervisory system including training, on-line help and decision-making for columns control. Source: *22nd Annual Meeting of the Canadian Mineral Processors*, Ottawa, Jan. 16, 1990.

41. **Modelling control in mineral plants using neural networks** - a neural network-based prototype for generation of the control transfer function for a grinding circuit. The output of the plant (the percent passing 200 mesh in cyclone overflow) is predicted from the current and two past values of the output, values of water addition to the sump box and the values of the circulating load. The network model had to be supplemented with an adaptation routine in order to provide an efficient controller. Source: *IFAC Expert Systems in Mineral and Metal Processing*, Espoo, Finland, 1991.

42. **Control of mineral processing plants using neural networks** - a prototype system to control a hydrocyclone classifier. Its objective is to control the sump level and the product size specification in the cyclone product streams in the presence of significant fluctuations in the circuit feed. The neural net model allowed users to compensate for the interactions of circuit variables and to build more robust control models. Source: *IFAC Expert Systems in Mineral and Metal Processing*, Espoo, Finland, 1991.

4.4. Related Applications

The following are intelligent systems used in other sectors which apply methods or solutions that may be of interest to the mining and metallurgy industry:

1. Hot Stove Optimization, **Iron and Steel**, p. 38
2. Control of Electrical Energy Consumption, **Iron and Steel**, p. 58
3. Steam Pressure Control, **Iron and Steel**, p. 59
4. Diagnosis of Equipment Faults, **Iron and Steel**, p. 60
5. Boiler and Furnace Control, **Iron and Steel**, p. 61
6. TOP EXPERT, **Cement**, p. 74
7. ABB LINKman, **Cement**, p. 75
8. BATEXPERT, **Cement**, p. 76
9. Cement Production Control, **Cement**, p. 77
10. OpAS, **Oil and Gas**, p. 107
11. Pitch Expert, **Pulp and Paper**, p. 117
12. Groundwood Mill, **Pulp and Paper**, p. 118
13. Crosscutting, all

5. OIL AND GAS

5.1. Summary

The oil and gas sector has the smallest number of intelligent systems identified in this study. Two reasons may account for this: 1) activities in the oil and gas sector such as exploration, production and upgrading require multidisciplinary knowledge and are not easily amenable to development of intelligent systems; and 2) the oil and gas industry has relatively few cooperative R&D projects. Since the development and demonstration of new technologies requires large resources and often a joint industry effort, the absence of such joint programs could explain the small number of intelligent systems developed. Another reason could be that the industry is publicity shy about the proprietary systems developed.

Figure 5.1. shows a simplified schematic of crude oil processing, including process areas and the number of intelligent systems identified. A number of applications offer operational support in remote locations. This choice of applications is logical since one of the key benefits of intelligent systems is to provide expertise where it is not readily available.

The application areas and the number of identified intelligent systems are as follows:

- exploration (2)
- drilling and production (2)
- separation and dehydration (2)
- upgrading and processing (2)
- other (1)

OIL & GAS

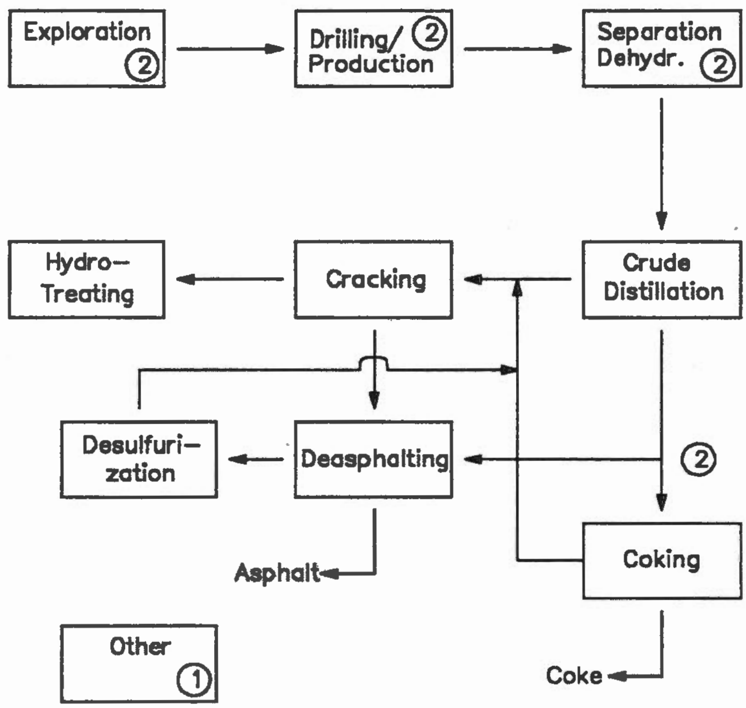

Figure 5.1. SIMPLIFIED SCHEMATIC OF CRUDE OIL PROCESSING

Figures 5.2. to 5.4 show the distribution of the intelligent systems by the type of application, geographic location and technology. The key conclusions from these figures are:

- the most frequent application domains are maintenance (23 percent), planning (22 percent) and design (22 percent). This, however, could be due to the low number of reported systems for refinery processing.

- the majority of systems have been applied in North America with a much smaller number in Europe and Asia. This pattern correlates well with the number of major international oil companies in those locations.

- most of the applications use expert system technology (about 90 percent) while the remaining use fuzzy logic. There are, however, a number of academic publications (not counted here) which report on the use of neural networks in crude oil processing. Possibly these applications will be implemented in the near future.

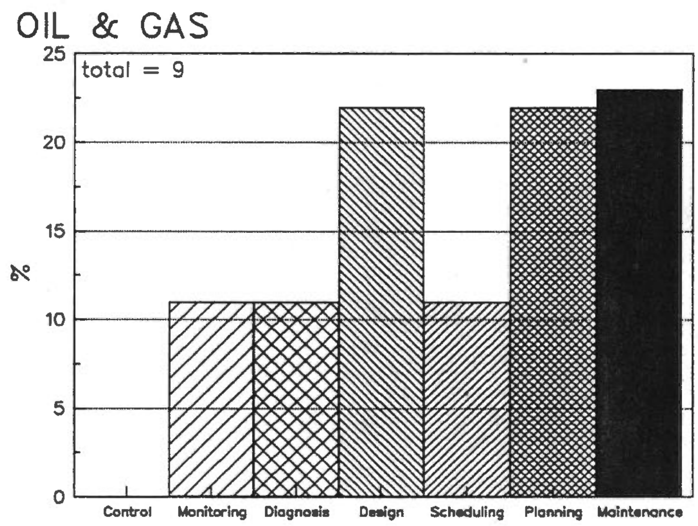

Figure 5.2. AI USE IN THE OIL & GAS INDUSTRY BY APPLICATION

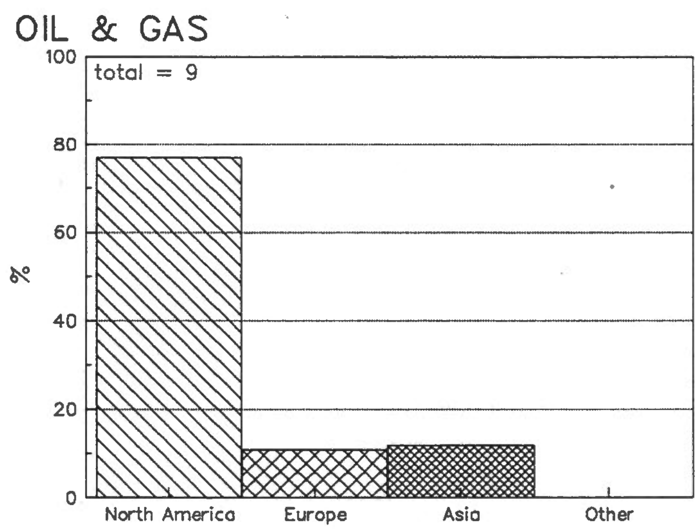

Figure 5.3 AI USE IN THE OIL & GAS INDUSTRY BY CONTINENT

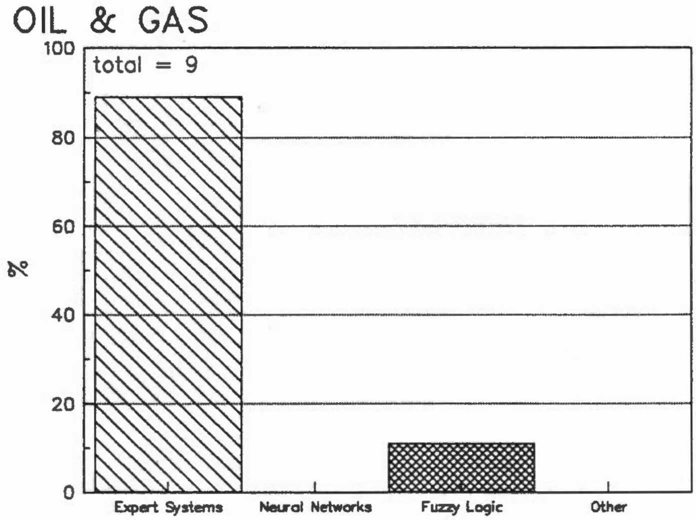

Figure 5.4. AI USE IN THE OIL & GAS INDUSTRY BY TECHNOLOGY

As indicated, the information about the oil and gas sector has to be considered with caution because only a few intelligent systems are identified and reported. However, some of the observed trends, such as using expert systems in remote locations and the large number of applications in North America, seem to reflect true industry trends.

The following three sections provide examples of intelligent systems being applied in the oil and gas sector. These sections are provided, not as a comprehensive review, but to show the types of problems being solved by the industry through AI technologies.

- Section 5.2 "Selected Application Targets" gives detailed information on developers, principles, cost and benefits of 3 systems.
- Section 5.3 "Other Systems Implemented", indicates 6 additional systems being used, with information on developers and solutions applied.
- Section 5.4 "Related Applications", indicates 13 intelligent systems being used in other sectors (plus those in the cross-cutting chapter) which may have application in the oil and gas industry.

5.2. Selected Application Targets

<u>Title</u>: **UNIK-CPS - an expert system for scheduling crude oil delivery to refineries**

<u>User</u>: Yukong Ltd.
Seoul, Korea

<u>Developer/Vendor</u>: Yukong Ltd.
Seoul, Korea

<u>Description</u>: UNIK CPS's objective is to minimize major cost factors such as purchase prices, quality loss, delivery cost and inventory cost. The crude oil differs in origin and composition and its suitability depends on refinery production capabilities. UNIK-CPS performs the scheduling with three key components: a fact database, a generated schedule and a rule base. The fact database, schedule base and the crude consumption model are represented as frames while the rule base is represented as production rules. The fact database contains the descriptions (prices, purchase and delivery data, vessels, etc.) and constraints (refinery capacity, min-max inventory, crude assays, etc.). The generated schedule is represented in tree structure whose nodes are frames. The production rules are divided into four groups: selection of crude oil, determination of vessel, adjustment of crude oil and blending of crudes.

<u>Cost to Implement</u>: $300,000 to $400,000

<u>Other Requirements</u>: none

<u>Hardware Requirements</u>: workstation for the expert system

<u>Reported Benefits</u>:
a) improved, more comprehensive, crude oil delivery scheduling
b) possibility of timely testing of alternative schedules

<u>Reference</u>: Lee, J.K. et al., in *Operational Expert Systems in the Far East*, Pergamon Press, pp. 109-121, 1991.

Title: **SlurryMINDER - an expert system for design of cement slurry for the well casing**

User: Dowell Schlumberger
155 locations, 55 countries

Developer/Vendor: Dowell Schlumberger
Houston, US

Description: This system assists engineers and laboratory technicians in slurry formulation for cementing of oil well casing. It specifies the chemical additives to be used in slurry design depending on the location and other design data for the oil well. The system ranks the recommended additives for further selection by the user. The user can specify a number of alternative slurry formulations for the system to generate. Once the additives are selected, the system can then generate information on the additive concentration, pricing, etc. SlurryMINDER is used at over 150 field locations in 55 countries.

Cost to Implement: $500,000 to $800,000

Other Requirements: information on slurry formulation, etc.

Hardware Requirements: PC AT

Reported Benefits:
a) improved design consistency and quality
b) slurry design savings of 6,000 to 18,000 hours per year
c) analysis savings of $ 120,000 per year

Reference: Kelly, E.B. et al. in *Innovative Applications of Artificial Intelligence 4*, The AAAI Press, pp. 193-215, 1991.

Title: **OpAS - an Operator Advisor System for training operators**

User: Chevron
Richmond, USA

Developer/Vendor: Chevron Research and Technology Co.
Richmond, CA, USA

Description: This system assists operators in applying control strategy which is consistent from shift to shift so that variability of product quality and operating cost of the refinery can be optimized. It operates on-line with access to plant data through the plant monitoring computer. It monitors key supervisory information about the plant. The system interfaces are event driven, i.e., they focus on the current operating status of the plant and on decision-making required by the operator. OpAS is not a real-time control system but an advisory system that has access to on-line data. Its objective is not to control the refinery plant but to provide on-line operator coaching which is appropriate to the situation. OpAS can also be used as a simulator for off-line training.

Cost to Implement: $50,000 to $80,000

Other Requirements:
- real-time data network.
- process database

Hardware Requirements:
- PC AT for the expert system

Reported Benefits:
a) improved management of process expertise (results similar to quality improvement teams)
b) improved performance of inexperienced operators (lower product variability and improved quality from shift to shift).

Reference: Touchstone, T. et al., *Oil and Gas Journal*, vol. 88, no. 7, pp. 41-44, 1990.

5.3. Other Systems Implemented

Exploration/Drilling/Production Areas

1. **SEPDESIGN** - an expert system developed by Shell Oil for design of separator vessels for use in surface production facilities and gas plants. The system includes Shell's experience in the design of separators and automates calculations involved in vessel selection. SEPDESIGN's recommendations include economic and production considerations such as process-related data (flow rates, pressures, fluid composition, etc.) and project-related data (project life, space limitations, environmental, etc.). Source: Shell Oil, Houston, US.

2. **EXPLORE** - an expert system developed by BP America to assist engineers and geologists in evaluation of candidate sites for oil exploration. It evaluates a proposed exploration site based on information such as geological formations, proximity to transportation systems, and environmental issues. EXPLORE makes a recommendation on the basis of the cost of facility and drilling, and on the environmental impact on the site. Source: BP America, Cleveland, US.

3. **ACIDMAN** - an expert system developed by ARCO to assist in the acid treatment of damaged or clogged wells. It specifies the formulation and volume of acid brew for each well depending on the geological formation, well structure, environment, etc. It generates a report which lists the required acid mixture composition, quantity, and methods of implementation for safe and effective acid treatment. ARCO also developed an expert system for cathodic protection of pipelines, well casting, cleanup of spills, etc. Source: Atlantic Richfield Company, US.

4. **Gas Dehydration** - a real-time expert system developed by Elf Aquitaine for dehydration of three offshore platform wells. Source: *SPE Petroleum Computer Conference*, Dallas, June, 1991, pp. 167-79.

5. **Integrated Oil Exploration** - a prototype fuzzy sets system for analysis of oil exploration data. The objective of the system is to aid in geological interpretation of seismic data. To do this, the system includes fuzzy rules describing the texture and segmentation of seismic sections and Dempster-Shaper theory to deal with incomplete and inexact information. It combines the knowledge from geophysical, geological and geochemical data using evidential reasoning. Source: Unical Corporation, Upgrading and Refining Areas.

6. **Flare** - an expert system for forecasting and diagnosis of flaring at Texaco refineries. Texaco Information Technology Department used Gensym G2 shell to develop a productivity shell which can be easily customized by a plant's computer staff for specific plant needs and situations. One of the reported applications of the productivity shell was to monitor flaring occurrences at Texaco refineries. When the system detects a potential flaring situation it provides appropriate advice to the operator. The operator can then ensure that the relief valves do not stay open. Source: Texaco, Houston, US.

5.4. Related Applications

The following are intelligent systems used in other sectors which apply methods or solutions that may be of interest to the oil and gas industry:

1. Hot Stove Optimization, **Iron and Steel**, p. 38
2. BAISYS, **Iron and Steel**, p. 40
3. ESWGR, **Iron and Steel**, p. 44
4. BOF Process Control, **Iron and Steel**, p. 45
5. Continuous Caster Control, **Iron and Steel**, p. 47
6. Scheplan, **Iron and Steel**, p. 56
7. Control of Electrical Energy Consumption, **Iron and Steel**, p. 58
8. Steam Pressure Control, **Iron and Steel**, p. 59
9. Diagnosis of Equipment Faults, **Iron and Steel**, p. 60
10. Boiler and Furnace Control, **Iron and Steel**, p. 61
11. TOP EXPERT, **Cement**, p. 74
12. Flotation Expert Display, **Mining and Metallurgy**, p. 87
13. Process Control, **Mining and Metallurgy**, p. 94
14. Crosscutting, all

6. PULP AND PAPER

6.1. Summary

The study identified 23 different intelligent systems implemented in the pulp and paper sector worldwide. If multiple sites for the same or shared systems (e.g., Pitch Expert) are counted, the number of intelligent systems implemented by the sector is over 50 systems. Including university prototypes, the total number of intelligent systems/applications in support of the pulp and paper sector is estimated to be about 70.

Figure 6.1 shows the distribution of AI systems by the major process areas. The number of identified intelligent systems are:

- chipping and grinding (1)
- pulp plant area (9)
- paper plant area (13)

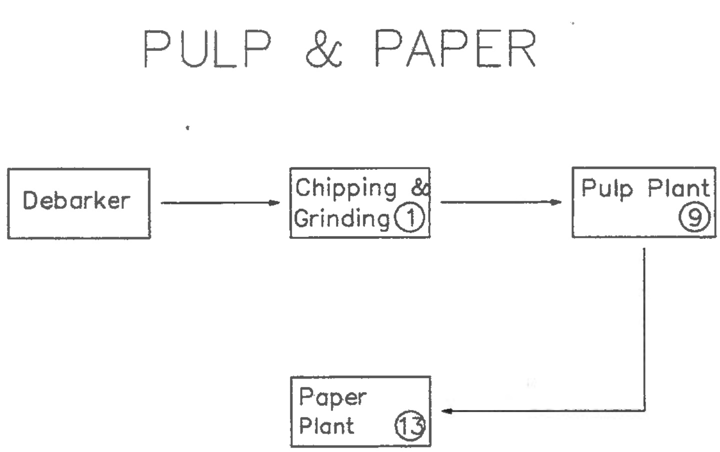

Figure 6.1. SIMPLIFIED SCHEMATICS OF PULP AND PAPER PROCESSING

Figures 6.2 to 6.4 show the distribution of pulp and paper applications by type of use, geographic region and technology. The key conclusions from these figures are:

- The majority of applications in this sector are in monitoring (optimization, quality control, etc.) and diagnosis (faults, unscheduled stops, etc.). Together they constitute almost 80 percent of all applications.

- Both North America and Europe share the leadership in implementation of AI systems. Asia and other locations are a distant third and fourth, respectively.

- Expert systems are the major AI technology used in the sector; however, neural networks have been implemented in several prototypes in diagnosis and control applications.

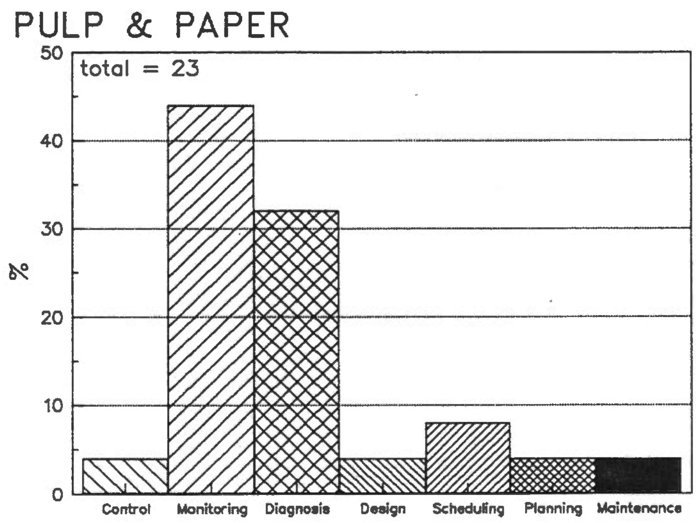

Figure 6.2. AI USE IN PULP AND PAPER PRODUCTION BY APPLICATION

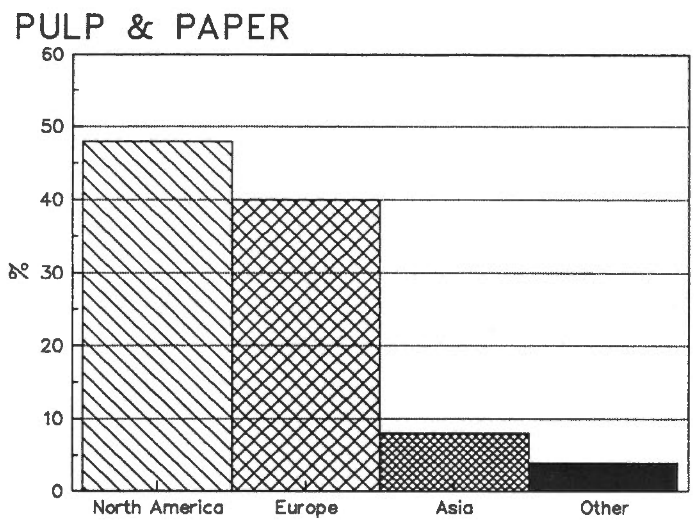

Figure 6.3. AI USE IN PULP AND PAPER PRODUCTION BY CONTINENT

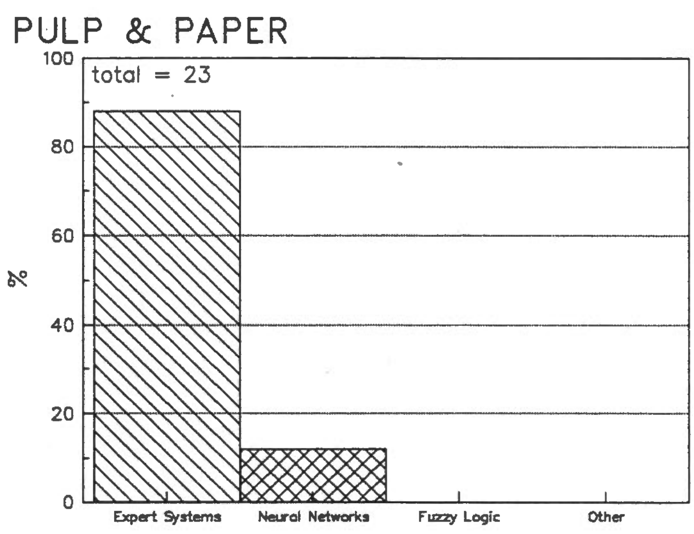

Figure 6.4. AI USE IN PULP AND PAPER PRODUCTION BY TECHNOLOGY

An interesting characteristic of this sector is that many applications are relatively large in terms of their scope and labour effort (several person-years and hundreds of thousands of dollars). Most of the large systems were developed by industry funded institutes (e.g., PAPRICAN, Canada; C.T.P., France) and have been used by a number of companies. The majority of smaller systems were developed by American engineering consulting companies like Rust International, Anderson Consulting, AND Automation International.

Intelligent systems have been applied in all major areas of pulp and paper plants. The most promising applications are:

Chipping and Grinding Area: energy management; condition monitoring and equipment fault diagnostics.

Pulp Plant Area: control of continuous digesters, refiners and recovery boilers; various fault diagnostics and predictive maintenance; energy management.

Paper Plant Area: quality and productivity management; equipment diagnostics, predictive maintenance and vibration control; production scheduling.

The following three sections provide examples of intelligent systems being applied in the pulp and paper sector. These sections are provided, not as a comprehensive review, but to show the types of problems being solved by the industry through AI technologies.

- Section 6.2 "Selected Application Targets" gives detailed information on developers, vendors, applications, cost and benefits of 10 systems.
- Section 6.3 "Other Systems Implemented", indicates 13 additional systems being used, with information on developers and solutions applied.
- Section 6.4 "Related Applications", indicates 14 intelligent systems being used in other sectors (plus those in the cross-cutting chapter) which may have application in the pulp and paper industry.

6.2. Selected Application Targets

Title: **Level Expert - an expert system to diagnose level problems**

User: Wiggins Teape Appleton
Dover Mill, UK

Developer/Vendor: Wiggins Teape R&D
Beaconsfield, UK

Description: This expert system diagnoses paper machine faults at Dover Mill, UK. It can identify "level" problems (lack of flat appearance) in papermaking. It provides the users with a ranked list of likely causes of "level" problems which they can investigate further. Level Expert makes level control expertise available at all times. After requiring the operator to answer 15 questions, it typically identifies 20 possible fault causes in less than 20 seconds. Level Expert was built using Crystal shell within the budget of 40 person-days. The system can be exported to other paper plants with very little additional development.

Cost to Implement: $25,000 to $35,000

Other Requirements: none

Hardware Requirements: PC AT

Reported Benefits:

a) saved $ 15,000 to $ 40,000 annually
b) productivity was improved by 2 percent and reliability was improved by 1 percent
c) maintenance requirements were reduced by 3 percent
d) quality was improved

Reference: *Manufacturing Intelligence, Award 1990, UK*, Department of Trade and Industry, London, UK.

Title: **BQES - an expert system for solving boxboard quality problems**

User: Fraser Inc
Edmundston, NB
Canada

Developer/Vendor: PAPRICAN
Montreal, Canada

Description: BQES makes the knowledge of engineering staff and expert operators available for training novices and less skilled operators in troubleshooting boxboard quality problems. BQES's approach to training requires operators to go through a series of interactive steps until the problem is considered solved. These steps include identifying and selecting the problem, providing information on the problem, selecting one or more recommended actions, and providing corrected (new) measurement values. The user has a choice of three interaction modes during training: 1) simulation mode providing impressions of real-time runs; 2) playback mode with a fixed sequence of interactions; 3) exercise mode with step-by-step instructions. BQES has a number of innovative training features such as simulating new problem development before the current problem is solved, context-sensitive priorities which allow the system to address the most important quality problems first, and playback of earlier runs to develop training exercises.

Cost to Implement: $250,000 to $350,000

Other Requirements: database of playback runs

Hardware Requirements: workstation for the expert system

Reported Benefits:
a) a comprehensive model of quality troubleshooting
b) a training system for the operators
c) improved diagnoses of quality problems and troubleshooting procedures

Reference: Bouchard, D.C., PAPRICAN, Montreal, Canada.

Title: **Felt Advisor - an expert system for design of felt in paper manufacturing**

User: Nippon Felt Co. Ltd
Tokyo, Japan

Developer/Vendor: Chiyoda Corporation
Yokohama, Japan

Description: Felt Advisor solves operational problems at paper mills caused by, or related to, felt design. It identifies possible papermaking troubles in the design stage. The system contains over 1000 rules on characteristics of felts, possible mechanisms causing felt-related troubles, performance records, design and manufacturing of wet felts, etc. Felt Advisor can also rate the performance of felts and predict possible troubles during paper making.

Cost to Implement: $300,000 to $500,000

Other Requirements:
- process database
- information on the design, manufacturing and performance of wet felts

Hardware Requirements: workstation for the expert system

Reported Benefits:
a) ability to predict the possibility of trouble for each felt in its design stage
b) improved diagnosis of problems with existing designs
c) quantitative evaluation and ranking of felt designs

Reference: Kawata, H. et al., *1990 Engineering Conference*, Seattle, WA, pp. 367-372, Sept. 24-27, 1990.

Title: **Pitch Expert - an expert system to diagnose/solve pitch problems in kraft pulp mills**

User: Members of Canadian Pulp and Paper Association
Canada

Developer/Vendor: PAPRICAN
Montreal, Canada

Description: Pitch Expert was developed to diagnose and solve pitch problems in kraft pulp mills. The system incorporates procedural knowledge for analysis and diagnosis of pitch problems, a method of requesting information on specific pitch formation, a report generator with prioritized conclusions and recommendations, and a query facility to explain the system's conclusions. Pitch Expert was implemented using the ART shell on a SPARC workstation. The users access the system via a modem. The users represent over 30 mills and 20 companies in Canada.

Cost to Implement: free to the PAPRICAN members

Other Requirements: modem software

Hardware Requirements:
- PC AT computer
- modem

Reported Benefits:

a) potential for over $500,000 savings in chemical additives per mill per year
b) 90 percent accuracy in diagnosing pitch problems
c) improved training in pitch control for mill engineers and operators
d) improved knowledge of pitch and other operational problems in pulp mills

Reference: Kowalski, A. et al., *Computers in Industry*, vol. 23, no. 1-2, pp. 109-116, 1993.

Title: **Groundwood Mill - an expert system for electricity demand optimization**

User: CPP Netherlands
Weesp, Netherlands

Developer/Vendor: Foxboro Netherlands
Soest, Netherlands

Description: This expert system was developed to optimize plant electricity production and demand, and to reduce the plant's peak electricity demand. It is based on the KES shell and is installed on a PC computer. It evaluates the operational constraints on the groundwood mill and determines which machine can be selected for load shedding purposes without interrupting production. The types of operational constraints considered by the system include: 1) operator time required to implement control procedures; 2) technical limitations such as difficulty in restarting or the possibility of damage to grinders; 3) the need not to interrupt production; 4) the maintenance requirements of machines; 5) the work environment; and 6) time constraints such as weekends and holidays.

This system monitors the operational conditions of the plant including status of each grinder and levels in the buffer vessels. It provides a summary of conditions plus suggested actions for load shedding to the operator, and explains the advice when queried.

Cost to Implement: $200,000 to $350,000

Other Requirements:
- data communication software
- process databases

Hardware Requirements:
- high-end workstation for the expert system
- process monitoring computer and instrumentation

Reported Benefits:
a) clear explanations for the recommended load shedding including why the specific advice is given, and on what bases
b) detailed information on the possibility of changing the load of individual machines

Reference: Beij'derwellen, P.R. et al., *Journal A*, vol. 29, no. 1, pp. 27-32, 1988.

Title: **EPAQ - a real-time expert system for paper quality control**

User: Norske Skogindustrier Oy
Skog, Finland

Developer/Vendor: ABB Stromberg Drives Oy
Helsinki, Finland

Description: Norske Skogindustrier developed an expert system, EPAQ, to optimize the quality of the newsprint produced at its Skog Mill, Norway. The system presents advice to the quality control specialists who then make changes to the operating conditions of the mill. Based on customer requirements, EPAQ presents the quality engineer with current quality forecasts and process target data for composition of pulp, amount of color additives, amount of bleaching chemical, degree of refining of chemical pulp, and calender pressure on the paper machine.

Cost to Implement: $300,000 to $500,000

Other Requirements: quality control software (e.g., ABB Afora Auto Quality)

Hardware Requirements:
- workstation for the expert system
- distributed control system
- plant-wide process control computer

Reported Benefits:

a) better and faster decision-making resulting in less out-of-specification paper production
b) reduced use of expensive chemical additives
c) staff can be trained faster using the system's simulation capabilities
d) quality decisions are consistent throughout the shifts and are of "expert quality" resulting in a decrease in quality variation of the product
e) system can be used for more complex optimization analysis of operations

Reference: Ahman, T. et al., *1991 Engineering Conference*, Nashville, Tennessee, U.S.A., pp. 123-131, Sept. 30 - Oct. 3, 1991.

Title: **Paper Production Scheduling - an expert system to schedule/control paper production machines**

User: Oji Paper Co. Ltd
Tomakami Mill, Japan

Developer/Vendor: Toshiba Corporation
Tokyo, Japan

Description: This expert system is part of a plant-wide scheduling and controlling system but it schedules only paper production machines. It consists of three subsystems: 1) product group scheduling to make a rough schedule; 2) individual scheduling to detail results of the rough schedule; and 3) balanced scheduling to optimize the results of the individual schedules. The scheduling system was implemented using the ASIREX shell and it consists of about 150 production rules and a few hundred constraint conditions. The system contains three types of knowledge: 1) knowledge with a fixed format and a fixed number of arguments, implemented using frames and rules for interpreting; 2) knowledge with a fixed format and a variable number of arguments, implemented with fixed format rules; and 3) knowledge which needs global comparison with a unique criteria, implemented with rules and procedural evaluation functions.

Cost to Implement: $300,000 to $400,000

Other Requirements:
- plant-wide production management system
- paper production scheduling database
- network software

Hardware Requirements:
- workstation for the expert system
- plant management computer

Reported Benefits:
a) time needed to prepare a monthly schedule was reduced from 3 days to 2 hours
b) improved schedule quality, i.e., more consistent, optimized production schedules
c) ability to reschedule production for new urgent orders

Reference: Kojima, S. et al., in *Operational Expert Systems Applications in the Far East*, Pergamon Press, pp. 122-132, 1991.

Title: **COATEX - an expert system with knowledge of paper coating**

User: Wiggins Teape
Ely Mill, UK

Developer/Vendor: Wiggins Teape R&D
Beaconsfield, UK

Description: COATEX is part of a continuous process monitoring and control system for paper coaters. It was developed on a PC AT but its run-time versions are embedded in the plant control system. It is used 24 hours a day as an advisor to production and maintenance supervisors, production engineers, quality inspectors and coating experts. Wiggins reports a number of benefits of the system including reduced plant downtime, improved quality and consistency of decisions, and improved training of the coater operators.

Cost to Implement: $70,000 to $90,000

Other Requirements:
- communication links
- process database
- data acquisition software

Hardware Requirements: PC AT

Reported Benefits:
a) reduced downtime due to grade change or 2 percent increase in plant uptime
b) improved product quality and improved consistency in decision-making
c) better understanding of coating technology

Reference: Grigoriu, M.M., *Paper Technology*, vol. 31, no. 12, pp. 18-24, 1990.

Title: **Steam and Power Toolkit (SPT) - a modeling tool for assessing choices in boiler and turbine operation**

User: Chesapeake Corporation of Virginia
West Point, Virginia, USA

Developer/Vendor: Rust International Corp.
Birmingham, Alabama, USA

Description: SPT is a modeling tool for performing "what-if" analysis of steam and power loads in boilers and turbines. It is based on G2 expert shell with generic rules provided for initial plant applications. SPT includes predefined icons such as deaerator tanks, pumps, valves, boilers, headers, and turbines. In steam balance monitoring, the user can monitor screen readouts on boiler information, and on steam generated and/or makeup water. For power generation and load shedding, the system calculates the power generated by the turbines and determines the power to be bought by, or sold to, the utility.

Rust has implemented a simplified SPT system for energy monitoring at the Chesapeake facilities. The plant consists of six power boilers and seven turbines producing 1.4 million pounds per hour of steam and 95 MW of power. The system monitors boiler steam generation and firing rates, turbine generator power produced, current loadings and purchased power. It calculates steam costs, turbine generator efficiency, cost of cogenerated power and predictable billable demand. This information is used to avoid on-peak demand charges.

Cost to Implement: $50,000 up

Other Requirements: a data highway or LAN to enter real-time process data values.

Hardware Requirements:
- workstation for G2-based system
- PC AT for energy monitoring system only

Reported Benefits:
a) reduced on-peak demand charges
b) better tuning of boiler and turbine generator operation

Reference: Price, B., RUST Engineering Company, Birmingham, AL, U.S.A.

Title: **A Neural Networks-based System for Brownstock Washer Control**

User: Ashdown Mill
Georgia Pacific Corp.
Arkansas, USA

Developer/Vendor: Automation Technology Inc.
Mobile, AL, USA

Description: This neural networks-based system was developed to assist in operating a brownstock washer. It predicts real-time values for soda loss, washer mat consistency and washer mat unit density. The development and periodic tuning of the neural network controller consisted of two steps: 1) training the network based on historical process data including all process variables around the bleach washer; and 2) implementing the trained network using rule-based pre-processing and post-processing elements interfaced with a process control computer. The trained neural network is used to simulate sensor process variables such as washer mat consistency, washer mat density and soda loss. These values, along with historical parameters, are used for controlling washing operations.

Cost to Implement: $40,000 to $60,000

Other Requirements:
- neural network software for developing the control models
- compilers for embedding the trained network in the control software

Hardware Requirements: PC AT for training network models

Reported Benefits:

a) better predictive capabilities than the statistical models which were previously used
b) mat consistency error was reduced from 22.0 to 6.5 percent
c) generation of empirical models for variables that are difficult to measure and obtain
d) easier to develop models and more robust process control models

Reference: Beaverstock, M. et al., *Pulp & Paper*, vol. 66, no. 9, pp. 134-136, 1992.

6.3. Other Systems Implemented

Pulp Plant Area

1. **RECOVERY BOILER ADVISOR** - this expert system developed by Stone and Webster assists in detecting leaks in recovery-boiler tubes. The system, Recovery Boiler Advisor (RBA), helps boiler operators to distinguish between a major tube rupture and other less critical events that upset the boiler operation. RBA can detect concurrent tube ruptures in several sections of the boiler; it can also diagnose situations which operators may misinterpret as a tube rupture.

   RBA architecture uses blackboards which contain raw process data, interpreted process data, history of the raw data and advice associated with the conclusions. Blackboard implementation is based on the Montrex shell and runs on a DEC VAX computer. Access to the mill data can be through either DCS links or a software link to a mill-wide system. The data analysis module serves as a data collection and interpretation module including data reconciliation and noise filtering. The rule base of RBA uses NEXPERT OBJECT shell. It has about 150 rules and is linked directly to Montrex blackboards. The rules validate data from the sensors, compare the suspect values with values obtained from on-line computer models and compare the interpretation of the suspect upset for compatibility with other data trends and changes. Source: *Stone & Webster*, Boston, US.

2. **Thermomechanical Pulping Control** - an expert system prototype to assist in control and operation of a thermochemical pulping refiner. It provides operators with real-time control advice. It was implemented using NEXPERT Object shell. Source: *77th Annual Meeting, Canadian Pulp and Paper Association*, Montreal, Canada, Jan. 31 - Feb. 1, 1991.

3. **Fired Heater Advisor** - this expert system was developed by Stone and Webster for operation of fired heaters. The system can be linked to on-line data from a distributed control system or process computer. It monitors (real-time) the burners, air preheater, fuel supply , heating coils, fans and control valves. The expert system is implemented on a PC AT. Source: *The International Journal of Knowledge Engineering*, vol. 7, no. 4, p. 250, November 1990.

4. **Pulp Blending** - an expert system to assist in stock blending at OUNO's Thorold Mill, Ontario. It is based on G2 expert system shell linked to Fisher Provox Distributed Control System. The system runs on a VAX computer with real-time VMS operating system. It uses information on production plans and current inventory to determine the required amounts of additives and deinked pulp for different target blend compositions. The objective of the system is to keep inventory of deinked pulp at an optimum level in relation to the deinking mill and paper machine operation. Source: *Pulp & Paper*, vol. 67, no. 4, pp. 88-99, Apr. 1993.

5. **EVAP** - an expert system to assist in fault diagnosis and operator training in the evaporator section of the chemical recovery process at Associated Pulp and Paper Mills' pulp mill at Burnie, Australia. Its purpose is to optimize the maintenance and reduce downtimes of the evaporator process. It is being used as a fault diagnosis assistant and for training. Source: *Proceedings of the 5th Australian Joint Conference on Artificial Intelligence '92*, World Scientific, Singapore, pp. 7-12, 1992.

6. **IOSS (Intelligent Operation Support System)** - an intelligent operation support system for a batch chemical pulping process operated by Fraser Inc. of New Brunswick. The system uses both knowledge rules and quantitative models to provide estimated "cooking time" and kappa numbers, as well as other information in support of process control. It is also used for training novice engineers and operators. Source: *3rd IFAC Symposium*, Pergamon Press, Oxford, pp. 315-319, 1993.

Paper Plant Area

7. **Paper Mill Maintenance Management** - an expert system to assist in analysis and planning of equipment maintenance at Barrow Paper Mill, UK. The system includes management of downtime/maintenance, backlog/worklisting, plant inventory, variation surveys and engineering stores. It facilitates the flow of data used for planning maintenance, improves on maintenance practices, and reduces time needed to generate maintenance reports. Source: *The 10th National Maintenance Engineering Conference*, April 1984.

8. **SENSODEC-10** - a prototype expert system developed to assist in control and condition monitoring of paper machines. It performs several levels of condition monitoring including analysis of the machine parts and machine groups. The system diagnoses abnormal operating conditions such as pressure and vibration, or product thickness, and moisture content and identifies the probable causes of the process faults. Source: *Paper* (Germany), vol. 44, no. 10A, pp. V173-V195, October 1990.

9. **CHROMA** - an on-line expert system developed by Anderson Consulting to assist paper manufacturers with product quality management. It monitors real-time process data such as process speed and pulp mix and advises operators whenever deterioration of product quality occurs. It has a self-learning capability that can include new operating knowledge. Source: *AI in Business and Management, PC AI*, pp. 31-34, Mar/Apr. 1992.

10. **WEDGE (Wet End Diagnostic GEnius)** - a prototype expert system developed by Finnish Pulp and Paper Research to assist in controlling product quality as well as to improve machine efficiency in paper production. Its rule base was derived from quantitative modelling of the process using statistical process control, multichannel autoregressive modelling and spectral analysis of the quality of the product. Source: *24th EUCEPA Conference 1990: Control Maintenance Environment*, Stockholm, Sweden, pp. 45-63, May 8-11, 1990.

11. **BREAKEXPERT** - a prototype expert system developed by French Pulp and Paper Research to diagnose causes of paper breaks on the paper machine. It diagnoses different types of breaks (e.g., simple or unitary breaks or repetitive breaks) and the break location (e.g., in machine direction or in cross direction). BREAKEXPERT also runs two break-recording databases. The first database contains data on the diagnostic sessions including the diagnosis, the second database contains all the data associated with the breaks. In its advice to the operators, the system first provides information on how to restore correct operating conditions, then tries to diagnose the underlying causes by posing a series of questions and by recommending remedial actions for the future. The diagnosis is considered successful when a paper machine is operating correctly. Source: *Pulp & Paper*, vol. 67, no. 4, pp. 88-99, April 1993.

12. **Web Breaks** - a prototype neural network-based intelligent system for control and diagnosis of paper breaks. It adjusts the absolute value of the retention aid flowrate based on the production rate and on the paper grade produced. Source: *IECON '91*, vol 9, pp. 1413-1417, 1991.

13. **AESOP** - a prototype expert system developed by Texas A&M for identification and diagnosis of visual paper defects at Temple-Inland, US plants. Source: *Pulp & Paper*, vol. 66, no. 9, pp. 129-130, September 1992.

6.4. Related Applications

The following are intelligent systems used in other sectors which apply methods or solutions that may be of interest to the pulp and paper industry:

1. Hot Stove Optimization, **Iron and Steel,** p. 38
2. Heat Balance Control, **Iron and Steel,** p. 43
3. VASE - Voest Alpine Scheduling Expert, **Iron and Steel,** p. 48
4. Scheplan, **Iron and Steel,** p. 56
5. Control of Electrical Energy Consumption, **Iron and Steel,** p. 58
6. Steam Pressure Control, **Iron and Steel,** p. 59
7. Diagnosis of Equipment Faults, **Iron and Steel,** p. 60
8. Boiler and Furnace Control, **Iron and Steel,** p. 61
9. TOP EXPERT, **Cement,** p. 74
10. ABB LINKman, **Cement,** p. 75
11. PROGNOS, **Mining and Metallurgy,** p. 88
12. HelpSAG, **Mining and Metallurgy,** p. 91
13. Process Control, **Mining and Metallurgy,** p. 94
14. OpAs, **Oil and Gas,** p. 107
15. Cross-Cutting, all

7. CROSS-CUTTING

Cross-cutting identifies intelligent system applications that can be applied in all heavy industry sectors. Only selected application targets are listed in this chapter.

Title: Diesel Engine - a fuzzy logic system for control of diesel engines.

User: across industry

Developer/Vendor: Ship Research Institute
Mitaka, Tokyo, Japan

Description: This system addresses control of diesel engines at different operating conditions, e.g., frequent changes of load. It uses a fuzzy logic optimizing controller with embedded control rules for searching optimum operating points. The fuzzy rules allow the system to deal with noisy operating data based on the knowledge of the designer or an experienced operator. The system reduces the risk of fatal control actions during the search for optimum conditions.

Cost to Implement: $80,000 to $120,000

Other Requirements: software for development of fuzzy control systems

Hardware Requirements: none (embedded in the control systems)

Reported Benefits:

a) fuel consumption rate decreased by 3 and 5 percent at 1/2 and 1/4 load, respectively
b) the time to reach the optimum operation was shortened to about 1/30 over ordinary optimization, without reducing control precision

Reference: Murayama, Y., *Industrial Applications of Fuzzy Control*, Elsevier Science Publishers, North-Holland, pp. 63-71, 1985.

Title: **AMETHYST - an expert system for automatic diagnosis of rotating machinery faults.**

User: across industry

Developer/Vendor: Intelligent Applications Ltd.
Livinston Village, Scotland, UK

Description: AMETHYST diagnoses machinery faults such as bearing, gear or blade problems; misalignments between drive motors and the prime units; cavitation in pumps; and problems caused by resonances. Typical fixed or variable-speed machines diagnosed include fans and blowers, motors, generators, pumps, compressors, various drives, and turbines. The system's objective is to allow non-experts to perform vibration-based condition monitoring of rotating machinery. AMETHYST is packaged as a complete product which requires no special training or programming by the end user. It can be customized to address special needs of the user.

AMETHYST consists of two software packages integrated with the IRD Mechanalysis, USA, condition monitoring software which is used as the main database. The expert system modules include the diagnostic rules and smart links to the IRD database. The rules have tree-like structures so that the systems do not have to search through a large number of rules to identify the next rule. The system has special features for searching through the spectrum for specific symptoms, harmonics, etc.

Cost to Implement: $200,000 to $300,000

Other Requirements: IRD Michroanalysis condition monitoring software

Hardware Requirements: vibration monitoring probes, sensors

Reported Benefits:
a) reduction of time required to diagnose machine faults from 4-8 hours to a few minutes
b) an industry average staffing reduction of one half person-year per plant

Reference: Milne, R., *Operational Expert Systems in Europe*, Pergamon Press, pp. 244-258, 1991.

Title: SECAL - an expert system for diagnosing boiler operation.

User: CYDSA Corporation
RYSEL Plant
Guadalajara, Mexico

Developer/Vendor: ITESM
Monterrey, Mexico

Description: SECAL was developed to assist in operating steam boilers in a synthetic textile fiber plant producing CRYSEL. The process is highly energy consuming and requires careful balance of the steam demand and supply. The development of the system was prompted by the retirement of an expert boiler operator, inefficient boiler plant performance and difficulties in training novice operators. The system addresses diagnosis and operation of combustion sections, water supply, steam supply and boiler water quality control. It was developed and installed over two years, by being carefully phased into operations.

Cost to Implement: $120,000 to $150,000

Other Requirements: communication links to process data

Hardware Requirements:
- workstation for the expert system
- boiler control computer network

Reported Benefits:

a) measurable benefits:
   - operation within specification increased from 86.5 to 95.6 percent
   - unscheduled boiler shut-downs decreased from 4.2 to 0.8 percent
   - unscheduled shut-downs of air preheaters decreased from 12 to 3 percent
   - total combustion related efficiency improvements estimated at $85,000 US per year

b) able to keep the knowledge of retired experts, improved training of novice operators

Reference: Cantu-Oritz, F.J. et al., *Operational Expert System Applications in Mexico*, Pergamon Press, pp. 7-26, 1991.

Title: **ESCORT - a prototype expert system for supervision of complex operations in real time.**

User: across industry

Developer/Vendor: PA Computers
London, UK

Description: ESCORT provides an environment for building real-time expert systems to help in dealing with information overload in the plant environment. It is configured to aid process operators in control rooms, remote control stations, etc. It addresses the limitations of the current process control computers which display large quantities of plant information, making operator decisions complex and difficult under abnormal operating conditions. ESCORT was designed to relieve pressure on operators by applying expert knowledge about the incoming data and advising on the best actions to take. It is capable, with customization, to recognize plant problems or operator errors, prioritize abnormal events, analyze abnormal events, present problem diagnosis to the operator and explain the reasoning to the operator.

Cost to Implement: $100,000 plus, depending on the complexity of the process.

Other Requirements: data communication networks

Hardware Requirements: plant control system

Reported Benefits:
a) reduces number of people necessary to staff control rooms
b) prevents unnecessary equipment shutdown
c) focuses operator attention on critical plant data
d) effective way to deal with information overload

Reference: Sachs, P.A. et al., *Expert Systems*, vol. 3, no. 1, pp. 22-29, 1986.

Title: **Startup Scheduling - an expert system for plant startup.**

User: Tokyo Electric Power Co.
Tokyo, Japan

Developer/Vendor: Hitachi Ltd.
Ibaraki-ken, Japan

Description: This expert system's objective is to optimize the start-up time of turbines without shortening the lifetime of turbine rotors due to thermal stress. The system uses a plant dynamic model of boiler and turbine heat transfer to improve precision and stability of stress control. The system functions consist of two parts: start-up scheduling and operation support. The initial schedule is created by modifying the standard schedule through the use of fuzzy inferencing techniques and the initial plant state data. The initial schedule is then optimized, taking into consideration likely turbine stresses resulting from the schedule. The operation support part of scheduling is based on the comparison of predicted and actual stress dynamics of turbine rotors. The generated schedule is modified as required, to minimize the stress.

Cost to Implement: $300,000 to $400,000

Other Requirements: plant dynamics model including boiler model and a turbine heat transfer model

Hardware Requirements: data links to the plant supervisory computer

Reported Benefits:

a) plants are started quickly and on time
b) optimum start-up schedule is derived even in time constrained situations
c) operators' work was lessened
d) operators can be trained in start-up procedures using the expert system

Reference: Aoyagi, A., *International Workshop on Artificial Intelligence for Industrial Applications*, IEEE, pp. 167-172, 1988.

Title: **Continuous Emission Monitoring (CEM) - an intelligent system for monitoring emissions from boilers**

User: Arkansas Eastman
Arkansas

Developer/Vendor: Pavilion Technologies
Austin, US

Description: This intelligent system was developed to meet regulatory requirements for continuous monitoring or estimating of boiler emissions. The system is based on Pavilion's adaptive modelling software Process Insights and Software CEM. The software uses neural networks, fuzzy logic and chaos theory to develop process models from historical boiler operating data. The process models can be used for predicting boiler emissions from current boiler operating data. The system monitors 21 key process variables simultaneously and predicts the boiler emissions within the required ±20 percent of EPA's CEM regulations. The system can also provide estimated values (simulated signal) for failed sensors to the boiler DCS system to ensure continuous optimized boiler control. The sensor validation capability of the system allows up to 5 sensors to be in error without compromising the model's predictive capability.

Cost to Implement: $50,000 up (depends on the level of effort required to develop models)

Other Requirements:
- data communication software
- neural network models

Hardware Requirements: plant DCS system

Reported Benefits:
a) replacement of expensive emission monitoring equipment ($200,000 up), with less costly Software CEM
b) ability to handle failed sensors by simulating the sensors' signals
c) improved process operation and optimization through better understanding of the effects of process operating variables

Reference: Pavillion Technologies Ltd., 3500 West Balcones Center Drive, Austin, TX, 78720, USA.

APPENDIX A

AI Primer

A.1. Historical Review

The term Artificial Intelligence (AI) was introduced in the mid-1950's to define a branch of computer science that was researching development of intelligent machines. Intelligent machines meant machines that could modify their behavior in order to achieve specific goals. The research included activities such as use of symbolic, non-algorithmic methods for problem solving, use of computer reasoning instead of just calculating numeric outcomes, and acquiring and manipulating knowledge.

The early AI work was strongly influenced by the techniques and methodologies of computational linguistics, cognitive science, computational modeling, operational research and psychology. However, as the AI field matured, several principal subfields emerged reflecting the variety of goals and methodologies of AI research. The major subfields established in the 1990's are:

- robotics
- computer vision
- speech synthesis and recognition
- natural language processing
- automated learning and reasoning
- neural networks
- expert systems

Table A.1. presents major milestones in the development of AI and its subfields. We review these milestones here in terms of four critical periods in AI development. These are:

- early research
- fall and disillusionment
- early applications
- entering mainstream markets

Table A.1. SIGNIFICANT MILESTONES IN AI FIELD

1956	A small group of computer scientists attend an IBM-sponsored AI workshop at Dartmouth College
1960	General Problem Solver program demonstrates the need for separating problem-solving algorithms from problem-knowledge algorithms
1971	Sir James Lighthill critically reviews AI accomplishments and negatively affects the funding in Europe and US
1978	Development of DENDRAL marks the start of expert systems era
1975-80	Nestor, Inference Corp., Symbolics, IntelliCorp begin to market AI technologies developed at MIT, Brown University, Control Data, etc.
1983	Carnegie Group founded by four Carnegie-Mellon professors, Syntelligence formed by Schlumberger, IntelliCorp introduces first expert system shell KEE and goes public.
1984-86	Fortune 500 companies like General Motors, Texas Instruments and Wang acquire equity position in AI start-ups and provide the necessary capital for growth (first buy-in)
1985-90	US government contracts are awarded to developed AI systems for DOD, ERDC, RADC, DARPA (first round)
1985	*Byte* and *PC Magazine* feature AI as their cover stories. First voice recognition and natural language query systems are introduced.
1985	BBN laboratory announces a breakthrough in parallel processing by linking 128 Motorola 6800 processors. First knowledge expert systems implemented in C language.

Table A.1. SIGNIFICANT MILESTONES IN AI FIELD (cont'd)	
1986	Gensym Corporation founded by exiting Lisp machine executives starts AI vertical markets. General Motors funds installation of vision-guided robots, Nestor introduces neural network, handwriting recognition systems.
1987	Gensym introduces G2 expert system application for real-time environments. Neuron Data introduces NEXPERT on VAX in addition to PC and MAC platforms.
1988	AICorp introduces KBMS into the IBM mainframe and OS/2 environments; DEC introduces VAX Grammar Checker; Inference introduces C-version of its ART expert system tools; IntelliCorp introduces main-frame version of KEE.
1989	Neuron Data introduces NEXPERT for DOS and OS/2 environment. C-language versions of major expert shells KBMS, ART-ADA etc. are introduced. Togai InfraLogic is formed to offer fuzzy logic technology. Sun Microsystem introduces RISC-based SPARCstation.
1990	Babcock-Hitachi introduce a commercial fuzzy logic air conditioning controller. PC-based neural network systems are introduced by HNC, Nestor, NeuralWare, Ward Systems, California Scientific.
1991	Large intelligent systems (MarketExpert, StockExpert) are introduced in banking and finance. Nestor NN technology is introduced in GO Corp.'s PenPoint operating system; major AI vendors open consulting decisions, Inference introduces CBR Express a case-based reasoning tool for business and industry and Neuron Data introduces open interface in its multiplatform development environment.
1991-92	Today's major neural networks, PC expert system shells and database mining tools are introduced.
1993	Aion & AiCorp merge to form Trinzic with a focus on providing advanced development tools and services for business process automation. Gensym, Talarian, etc. signed partnership agreements with a number of process industry and manufacturing companies.

The current trends in AI are discussed in Section A.2 while emerging and future technologies are discussed in Section A.3.

A.1.1. Early Research

Early AI research was based at AI groups established at prestigious American and European universities such as MIT, Carnegie-Mellon and Oxford. The research groups were small and focused on work in areas such as automatic theorem proving, and new programming languages (LISP). The computer programs developed in this early period addressed problems in decision and game theory, and computational logic. The programs could solve chess or checkers problems or simple, general, question-answering problems in the sciences. The most historically important program developed at that time was the General Problem Solver (GPS) which could solve a variety of problems requiring symbolic reasoning. GPS underscored the importance of separating knowledge about problems from the problem-solving methodology. Developers of GPS approached this by defining: 1) stages of problem solving and; 2) operations that can be applied to each stage. The program's goal was to find a series of states and associated operators. This approach was, however, seriously limited by the complexity of finding appropriate operators and the time and memory requirements to perform such computationally intensive procedures.

At the end of the 1960's, it became apparent that major reorientation of AI research was required in order to make AI methods more practical. Thus in the 1970's we saw the demise of academic AI research and the gradual emergence of new thinking in AI.

A.1.2. Fall and Disillusionment

In 1971, the British Science Research Council undertook an in-depth review of the funding and accomplishments of AI groups at British universities. The review prepared by Sir James Lighthill was highly critical of the ongoing research and the results achieved. The report stressed the fact that despite the promises and expenditures made throughout the 1960's, no single practical AI solution or technology was developed by the funded programs. Most damaging, however, was Lighthill's recommendation that there was no need for a separate AI field because automation and computer science fields would deliver the technologies and solutions studied by AI researchers. After the report was published, most of the government funding in the UK and USA was cut and a number of AI research programs were eliminated at universities.

A.1.3. Early Applications

Despite the strong negative impact of Lighthill's report, several universities continued research programs in AI. In retrospect, it is clear that AI researchers overpromised the immediate benefits in the 1960's but Lighthill's report also understated the long-term benefits of AI. This type of misinformation and deficiency in evaluating new technologies is not unique to the AI field but is common to all new technologies.

The upturn in AI research came, therefore, with two research projects underscoring the need for practical solutions. These projects, DENRAL and MYCIN, opened new areas of knowledge-based systems (KBS) or expert systems. They led to a major shift in development of intelligent systems. We review both systems briefly below.

DENDRAL

DENDRAL development began at Stanford University in 1965 as part of the NASA program to send unstaffed spacecraft to Mars. The objective of the DENDRAL project was to develop a computer program that could perform chemical analysis of Martian soil. The technical challenge was to analyze and identify unknown chemical compounds among hundreds of thousands of possible chemical structures.

In their research, the Stanford team discovered that an expert chemist uses rules-of-thumb to identify and ignore structures that are unlikely to conform to analyzed data. The team elicited these rules from expert chemists and incorporated the rules in the NASA program. As a result, the program could recognize molecular structures of unknown compounds as well as an expert chemist.

The work on DENDRAL made the AI researchers realize that the success of intelligent systems depends not only on search techniques but also on information about the problem. Thus an intelligent behavior depends as much on the knowledge available as on the method of reasoning. This realization led to the key concept and methodology of today's expert systems where the knowledge base and inferencing techniques are separate and are considered equally important.

MYCIN

MYCIN is a bench mark for today's rule-based expert systems. Many of the features that we see in today's expert systems were first tested and implemented in MYCIN. MYCIN was developed in the mid-1970's at Stanford University to aid physicians in diagnosis and treatment of infectious blood diseases. It took about twenty person-years to develop the system in Lisp programming language.

The MYCIN team developed programming and design techniques that formed the basis for understanding and developing future expert systems. The most important of those techniques were:

- backward-chaining techniques for testing hypothesis
- knowledge separate from program control

- incorporation of meta-rules to redirect search to more promising sets of rules
- use of inexact reasoning such as rule certainty factors or acceptance of a physician's answer as "don't know"
- retaining memory of previous sessions for a given patient
- use of natural language interface
- provision of explanations for recommendations
- provision of alternative recommendations if requested

These technical features and the fact the system addressed practical needs in the medical community resulted in large success and the acceptance of MYCIN by physicians. The success reignited interest in development and commercialization of AI systems. In the 1980's we see, therefore, a number of programs, companies and applications being introduced (Table A.1).

In the early 1980's, new applications came primarily from university research but by mid-decade, significant funding was being allocated to AI development by government and large private corporations. In the late 1980's, the AI industry became more mature with major players, directions and products already in place. By 1990, the combined sales of AI systems and related products including professional services reached into hundreds of million dollars.

A.1.4. Entering the Mainstream

During the 1990's AI is entering the mainstream of business and information technologies. Two trends are dominant in the AI industry:

1. Restructuring - with mergers of the major players and fall-out of weak companies.
2. Shift from general to more specialized markets.

Both restructuring and the shift to vertical markets are the results of increased market influence on the AI industry. To secure growth, the industry turned to commercial markets rather than government, venture capital and large corporations. Mergers of firms like Aion and AICorp and establishment of a number of joint development partnerships between AI firms and major computer and software vendors further improved the financial health of this research-intensive industry and addressed the market and product weaknesses of AI firms. Emergence and emphasis on new computer technologies such as object-oriented programming (OOP) and graphical user interfaces (GUI) had positioned many AI companies well in those emerging markets and technologies.

In the 1990's, the AI industry has become stronger and more integrated into the mainstream of computing while emphasizing specific vertical applications and solutions. What this means to the current trends is discussed in the next section.

A.2. Current Trends

In addition to restructuring and shifting to more specialized markets, the AI industry is targeting technologies that are close to AI, to embed and submerge AI in mainstream applications, and looking for smaller, well defined problems and solutions. The trends also show significant reduction in pricing of AI tools and geographic decentralization of capabilities and skills.

In what follows we discuss current markets, strategies and infrastructure of the AI industry. A detailed description of the technologies, tools and vendors is given in Appendix A "Intelligent Tools".

A.2.1. Markets

The 1993 market for AI tools is estimated at about 200 million dollars U.S. (Figure A.1). Including services, custom applications and consulting, the market ranged between 250 and 350 million dollars U.S. The important shifts in various tools are summarized below.

Expert Systems

- PC and Mac tools: In the 1990's this market saw a significant decline in sales of small tools from 11 million dollars in 1988 to 1.4 million dollars U.S. in 1990. The reasons for this decline are not clear except that the decline was paralleled by an increase in sales of workstation tools as the prices for workstations decreased. There is visible, however, a gradual comeback in the market for small tools with the 1993 sales reaching

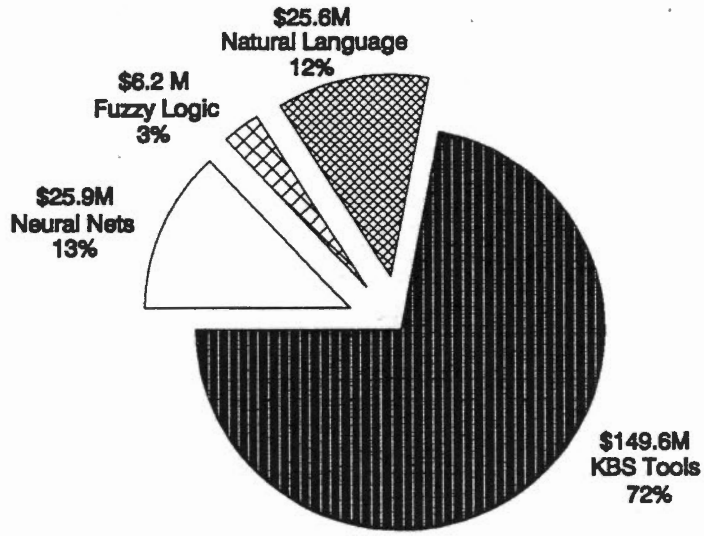

Figure A.1. MARKETS FOR AI TOOLS (1993)

2.9 million dollars U.S. The average cost per unit also increased from about $200 in 1990 to $390 U.S. in 1993. This price increase reflects the increased sophistication and complexity of small tools, which makes them more suitable for serious applications. The newer tools are often priced at several thousands dollars and offer capabilities equivalent to those of mainframe systems just a few years ago. Another reason for the increase in sales of PC and Mac software small tools is the interest in object-oriented programming (OOP) tools which several vendors offer embedded in small tools.

- Workstations: There was a significant increase in the sales of workstation tools in the late 1980's from about 24 million dollars in 1998 to over 50 million dollars U.S. in 1993. The price per unit, however, remained almost unchanged with an average price of 6 to 7 thousand dollars per unit. The growth of workstation applications seems to come at the expense of small and mainframe applications.

- Mainframe Tools: The market for mainframe tools stabilized in the early 1990's after an unusual peak in 1990. The market remains at a flat level of about 30 million dollars U.S. per year as most of the growth is taking place in other platforms, and it is increasingly difficult to find new market applications for large tools.

- Lisp Tools: The current market for Lisp programs has stabilized at about 10 million dollars U.S. a year which is less than half of its peak sales in 1990. The main reason for the decline is the increased use of other languages in AI applications such as OOP and C language in custom systems.

- Problem Specific Tools: Domain-specific tools experienced the highest growth of any type of tools in the early 1990's and they continue to do so. In 1989, their sales were about 6 million dollars U.S, while in 1993 sales increased to over $50 million. As discussed, this increase reflects the industry shift to more specific, vertical market applications.

Neural Networks (NN)

The current market for neural network applications is estimated at over 60 million dollars U.S.. The major segments of the market are shown in Figure A.2. The large market for NN commercial applications also reflects the vendors' shift to offering total solutions for business and industry. Examples of such applications are credit card fraud detection and intelligent character recognition. These applications of NN are embedded in the business systems.

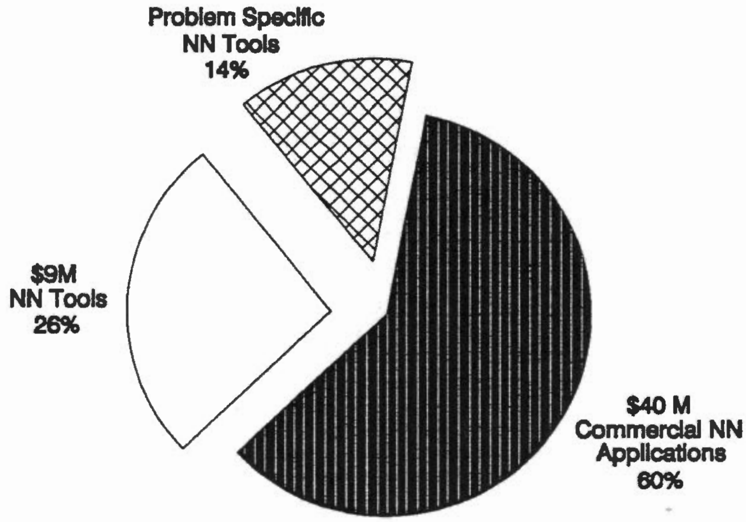

Figure A.2. MARKETS FOR NEURAL NETWORK TOOLS (1993)

Problem-specific tools are the second largest market for NN technologies. Examples are process control applications, vision and imaging systems in food packaging and just-in-time inventory systems.

The market for neural network building tools remains small. The majority of growth in the NN industry is taking place in problem- and application-specific areas rather than generic tools which are often difficult to apply.

Fuzzy Logic

The North American market for fuzzy logic tools is still small (about 6 million dollars U.S., Figure A.1). Most of these tools are sold for process control application. There is, however, some growth in the application of fuzzy logic in business in hybrid expert systems. In 1994, there are five vendors of fuzzy logic software, but many manufacturing companies offer fuzzy controls embedded in products like cameras, home appliances, and elevator and train control systems.

Natural Language Development Tools

This market subsegment includes intelligent database interfaces, text retrieval and voice recognition. The 1993 market for natural language development tools is estimated at 25 million dollars U.S. (Figure A.1). The major market for natural language technology is in commercial applications which is estimated at 60 million dollars in 1993. This category includes products like spelling and grammar checkers, machine translation systems and voice activated products. It is expected that this market will increase steadily in the coming years.

Summary

The market figures indicate that expert systems are the most commercially accepted AI application technologies. There is no reason that the market for expert systems will significantly increase in the coming years but its specific domain or embedded applications will continue to grow.

The markets for NN and fuzzy logic tools are much smaller, but again we will see an increase in domain specific use of these technologies as more industrial applications are developed.

The market for natural language tools and technologies is expected to increase as commercial applications of these technologies increase in business, industry and households - most are embedded in mainstream products and uses. The growth may be very gradual, however.

A.2.2. Strategies

Major strategies implemented by the AI industry in the 1990's included:

- targeting high technology markets that are close to AI, e.g. object-oriented programming, graphical development environments, re-engineering
- development of embedded and submerged applications
- development of problem-specific applications

All these strategies are a significant departure in how AI is employed - not as thinking machines but as a part of more traditional applications.

Targeting technology markets that are close to AI could be considered an attempt to ride on the latest fashion. However, in practice, the reception of AI products by customers is often more favorable when they don't feel intimidated by the AI connotation as a technology for "rocket scientists". Many AI vendors thus repositioned their products closer to the mainstream with the emphasis on the software engineering benefits accrued from AI tools. This strategy, in general, met with good success but it also backfired in a few cases where the vendor was unable to develop new market positioning while losing old markets. Examples of success are portable, graphical interface development tools or marketing CASE tools.

The strategy of embedding AI means to market AI not as a stand-alone technology but as part of more traditional applications where AI is only a component of the overall solution. An important part of an embedded AI application is that AI is invisible and does not require the user to understand any AI technology. Examples of such applications are financial management systems, customer service systems and schedulers. By adding intelligence to these applications and products, AI vendors increase their value and attractiveness.

Development of specific, often small, applications also constitutes a significant shift in AI vendor strategy. Applications that previously were considered uninteresting now are being discovered as excellent target applications. Examples include process control and help desk applications. Thinking small and practical became the buzzword in the AI industry. Most important, these applications turned out to be very profitable to many vendors.

Another interesting trend has been a shift from large (>$500,000) projects to smaller, well defined projects addressing smaller solutions and requiring fewer resources. This paralleled the trend in mainstream computing where a major shift took place from mainframes to minicomputers, workstations and PC networks.

The focus on specific applications has been paralleled by the adoption of new computing technologies such as object-oriented programming, graphical user interfaces, open systems, and multiplatform software. These have had strong impact on productivity, not only in program development (OOP), but also in making it easier to understand what AI programs do for the user. Graphical user interfaces became an integral part of process related programs that aid the operators in understanding what is happening. Another computing trend is the shift from complete proprietary systems to open systems where equipment and software from different vendors can be integrated. Users also demand that programs be portable to different computers because of the variety of computers in the corporate environment and the increased use of networking. This forced AI vendors to offer more compatibility and more platform choices.

AI applications also became more focused on specific vertical markets with vendors specializing in industry specific solutions. In the 1990's we see a significant increase in the sales of domain-specific application expert systems (Figure A.3). The number of units (applications) sold increased from about 200 in 1989 to 2,200 in 1994 while revenues increased from 6 to 49 million dollars U.S. These numbers do not include the services offered with the software sales. Entering specific markets for information processing technologies also meant that AI vendors had to offer total solutions rather than AI technologies only. However, their competitive advantage would be still be based on advanced technologies when competing against IBM, ABB, Bailey and other process automation vendors.

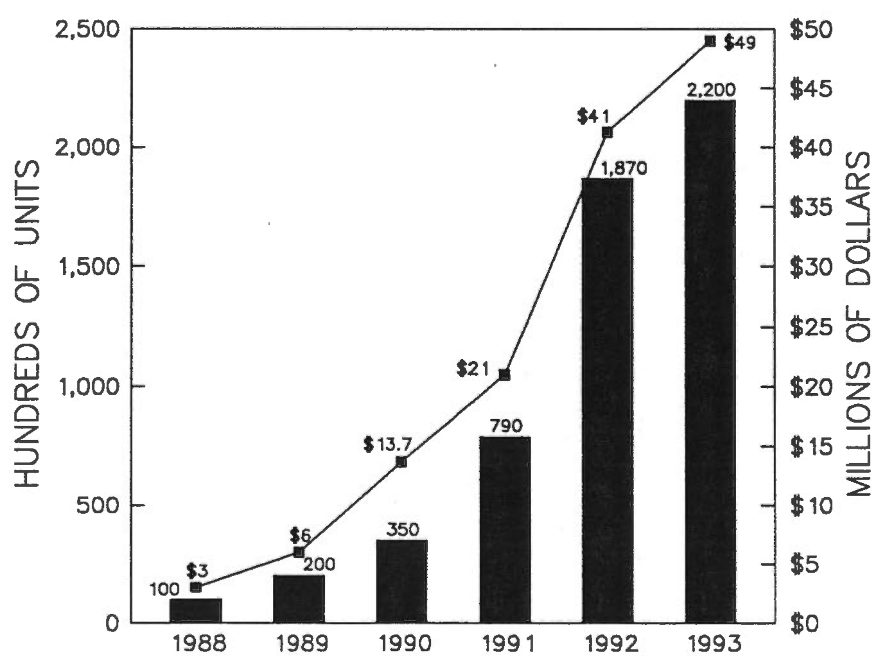

Figure A.3. MARKET TRENDS OF DOMAIN-SPECIFIC APPLICATIONS

An important part in offering industry-specific solutions has also been played by consulting companies and equipment vendors that have had a long presence in business and industry. Established equipment vendors are developing area-specific computing solutions with a significant content of AI technologies.

A.2.3. Infrastructure

It is estimated that in 1994 over 100 companies are active in development, marketing and application of AI technologies in North America. The majority of them (about 90 percent) have fewer than 10 employees and are one product companies. There are an additional 50 to 100 companies which provide consulting and value-added programming with some AI content. Many of these are small companies focused on specific areas of AI applications. They also use AI in support of other consulting in business, industry or government. A few, large Fortune 1000 companies like IBM, ABB and Schlumberger have active AI groups, although many of these groups were dismantled in the late 1980's. These groups would now be active as part of other units such as advanced technology applications groups.

The AI business infrastructure is supported by a large number of researchers in academia and independent institutes working with some aspects of AI. The 1993 *AI Directory of the American Association for Artificial Intelligence* lists over 140 educational institutes with AI research groups in the US and nine Canadian institutions. The Canadian groups listed are at universities - Queen's, McGill, Toronto, Calgary, Waterloo and British Columbia. This list does not include research groups at other Canadian universities like University of Alberta, Regina, Nova Scotia, and Manitoba.

The 1993 AAAI Directory also lists over 16,000 members, most of whom are from North America. The membership of the Canadian Artificial Intelligence Association is over five hundred.

The North American infrastructure is also supported by a number of academic and business publications. The major ones are *AI Expert* (circulation over 28,000), *PC AI* (over 20,000) and *AI Magazine* (12,000).

In Canada, there are 10 to 15 independent AI companies that sell AI tools or services. Interestingly enough, Canadian companies are recognized as leaders in predictive modeling, classification and database "mining" tools in North America. Most of the Canadian companies offer application development services while also selling add-on specialty tools.

The 1990 *B.O.S.S. Directory of Research and Development Laboratories/Facilities in Canada* lists over 130 companies involved in AI research including consultants, industry and business. A random sampling of the lists showed that less than one quarter of these companies are currently active in developing AI applications.

The total North American AI infrastructure is quite large and includes an estimated 15 to 20 thousand people working in the field. In addition, another 5 to 10 thousand people are active, at some point, in area-specific AI developments.

The major infrastructure shift in the 1990's has been significant decentralization of the AI community from the original hubs in the Boston-Cambridge and Palo Alto-San Jose areas to strong groups in Pennsylvania, Arizona, Oregon, and Canada. This decentralization increases the diversity of interest and applications, and improves dissemination of AI technologies.

A.3. Emerging Technologies

The previous sections discussed current trends in AI markets and applications. The major technology areas identified were expert systems, natural languages, neural networks and fuzzy logic. These technologies and their applications are discussed in more detail in Appendix B. Several new technologies emerged in the 1990's and, although their markets are small, they add unique and significant applications to the AI industry. They are case-based reasoning, genetic algorithms and machine learning. We discuss briefly their markets and applications below.

A.3.1. Case-Based Reasoning (CBR)

CBR is a technology that allows the user to represent knowledge in terms of historical cases or events. CBR compares new situations to historical records in a database and retrieves the most relevant records for comparison. The user can therefore inspect how the past problems were solved and select a similar procedure for solving the new case at hand.

CBR in some sense represents a higher reasoning approach than expert systems or neural networks. The idea is that people very seldom reason in terms of rules or dependencies but rather in terms of similar experiences that they encountered in the past. The technology offers a new way of working with records and data.

In the 10 years of CBR research, several techniques have been developed but since the technology is just entering into commercial applications, it is still unclear which technique is best suited for different applications. The early implementations of CBR were found to be very successful in classification and diagnosis problems. Applications having a natural fit for CBR are help desk and customer support. Benefits of using CBR in problems like design and scheduling are still not clear.

Five major vendors are offering CBR tools with total sales of about 6 million dollars U.S. in 1994. Most of the applications are in help desk and customer support.

A.3.2. Genetic Algorithms (GA)

Genetic algorithms address the problem of finding an optimum solution without the need for exhaustive, time consuming use of computer search techniques. The GA concepts and terminology are based on biogenetic ideas where processes naturally evolve into optimized stable solutions via genetic selection processes. In GA terms, the user looks for an optimum solution by combining (mutating) the existing solutions (chromosomes) which represent specific optimization values (genes). GA offers the advantage that optimized solutions can be obtained by a limited number of mutations, in a reasonable time, using reasonable computation power. The catch is to define the problem correctly in terms of the GA operators.

The market for GA is still relatively small and nearly all commercial products are libraries of available genetic algorithms. Given that the technology is quite different from other optimization techniques, it may be necessary to introduce GA embedded in general problem solutions. Indeed, several applications have been commercially demonstrated for problems like scheduling, planning, design, recipe optimization and portfolio balancing.

In 1993, there were six vendors of GA software tools with total sales of less than one million dollars U.S.

A.3.3. Machine Learning

The term machine learning defines a group of AI technologies for automated knowledge discovery. The most advanced is induction or learning from examples. Others are learning from analogy or learning by being told. Induction techniques look for patterns in available data and induce reasonable conclusions, generalizations or rules.

Historically, machine learning was viewed as an efficient way to acquire knowledge for expert systems. Since the success of expert systems depends so much on the quality of knowledge which is difficult and expensive to obtain from human experts, machine learning was considered to offer an alternative, inexpensive way to generate expert rules from past examples, data and events. The process also eliminates problems such as experts not being available, not being aware of the knowledge they use, or unable to communicate their knowledge. Since the knowledge and experience are stored in historical data and examples, an ability to automatically acquire knowledge is very appealing.

Induction learning has been applied in many expert system and expert system shells including the DENDRAL project and several present-day hybrid expert systems which can incorporate rules solicited from human experts and rules induced from data. The inductive algorithms are also implemented in case-based reasoning tools in order to facilitate rapid retrieval of sets of cases.

The market for stand-alone inductive tools is small because standard induction techniques have several shortcomings like the inability to deal with inconsistent information and results that are very sensitive to noise. Recently techniques have been developed (CART) that overcome these disadvantages, but the impact of the new methods still remains to be assessed.

In the 1990's another application market has emerged for inductive tools - database "mining" or information harvesting. Database "mining" addresses the present information glut and the difficulty of extracting useful knowledge from data. Vendors of database mining tools have recognized that as the amount of data collected and stored by computers increases, there will be a need for tools that will help users to extract valuable information from these databases. Easy access to knowledge residing in databases will enable users to make more effective decisions or develop better business strategies. The tools would also allow users to deal with increasingly complex business processes by automating some of the decision-making and information-processing tasks. The critical emerging technologies for database "mining" are rough sets and forms of neural networks.

The current markets for database "mining" tools and their applications are less than one million dollars U.S. It is expected, however, that as the technology enters the computing mainstream, this market will become comparable to CBR markets or larger.

A.3.4. Next Wave

In contrast to the 1980's, when many AI technologies came from AI laboratories at universities, in the 1990's AI university research is not focused on new commercial applications. The advanced AI academic research in the 1990's addresses selected fundamental problems in computing. For example, research at Syracuse University hopes to make computers respond quickly in a sensory-based environment by developing biological based computer processors. At California Institute of Technology researchers are studying creation of an analog chip that would behave more like human brain cells. At Georgia Tech, researchers are studying instincts and reflexes in an attempt to create survival mechanisms for robots. If there is such a possibility, then the next wave of technologies coming out of these AI labs will truly be considered intelligent.

APPENDIX B

Intelligent Tools

The key differences between an intelligent system and conventional programming are depicted in Table B.1. These differences are somewhat exaggerated because conventional programs may also have some limited capability to handle uncertainty and use symbolic reasoning. Table B.1 provides, however, a general idea of the qualitative differences between intelligent systems and conventional programming tools.

Table B.1. INTELLIGENT SYSTEMS VS CONVENTIONAL PROGRAMS

Intelligent Systems	Conventional Programs
Makes Decisions	Calculates Results
Based on Knowledge	Based on Algorithms
Easily Handles Uncertainty	Less Flexible
Can Work with Incomplete, Inconsistent Information	Requires Complete Information
Can Provide Explanation of Results	Gives Results Without Explanation
Symbolic Reasoning	Numeric Calculations
Control and Knowledge Separated	Control and Knowledge Interlaced

The information provided on commercial tools is based on either a review of the tool or information provided by the vendors. Because of the frequent upgrades that software vendors offer, the information provided may not be 100 percent up-to-date at the time of reading this report. We recommend that readers contact the vendors whose software they are interested in.

Figure B.1. depicts how intelligent systems could be integrated with existing plant control systems. The blocks represent a plant control system, while the ovals represent intelligent systems which may be added.

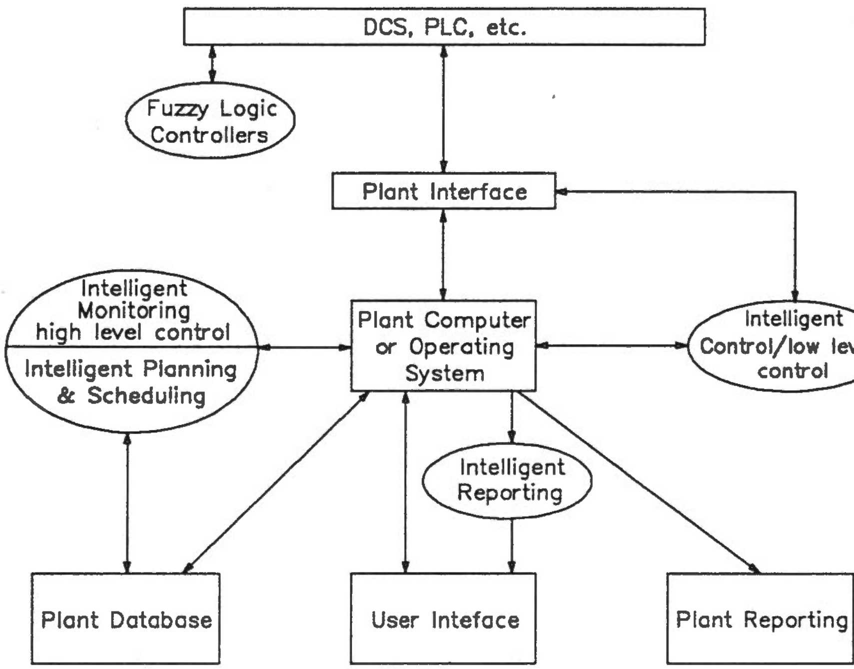

Figure B.1. SIMPLIFIED CONCEPTUAL DRAWING OF PLANT CONTROL (blocks) PLUS ADD-ON INTELLIGENT SYSTEMS (ovals)

B.1. Expert Systems

Definition: Expert systems are computer programs capable of solving problems and recommending solutions which require the use of expertise and experience. They use heuristics (rules of thumb) and problem-solving methodologies that a human expert would use. In other words, they are computer clones of human experts and the rules and methodologies are acquired from humans.

More definitions:

- knowledge base: a repository of production rules
- inference engine: a method (algorithm) to implement system logic
- working memory: a database of established facts, conclusions and data
- knowledge engineering: the field of developing expert systems
- domain: application area for which an expert system is being developed
- production rules: knowledge representation (if-then rules)

All expert systems are constructed of three major modules:

- the knowledge base
- the inference engine and working memory
- the interface

The key differences among expert systems built for different applications are usually in the knowledge base, which includes domain-specific knowledge and information, and in the interface, which reflects the area's specific requirements and conventions in working with computers. Inference engines would often be similar, e.g., forward or backward chaining, in many different expert systems.

The process of building and implementing an expert system consists of a few, well defined steps (Figure B.2). First, the knowledge of a human expert has to be acquired, catalogued and coded into the computer. After coding has been completed and validated, new data (situations) can be answered by the expert system by simply entering the new data and information into the system. The expert system will then provide a recommendation for action and explanations of how it derived the recommendation including audit of the reasoning (rules and procedures) used.

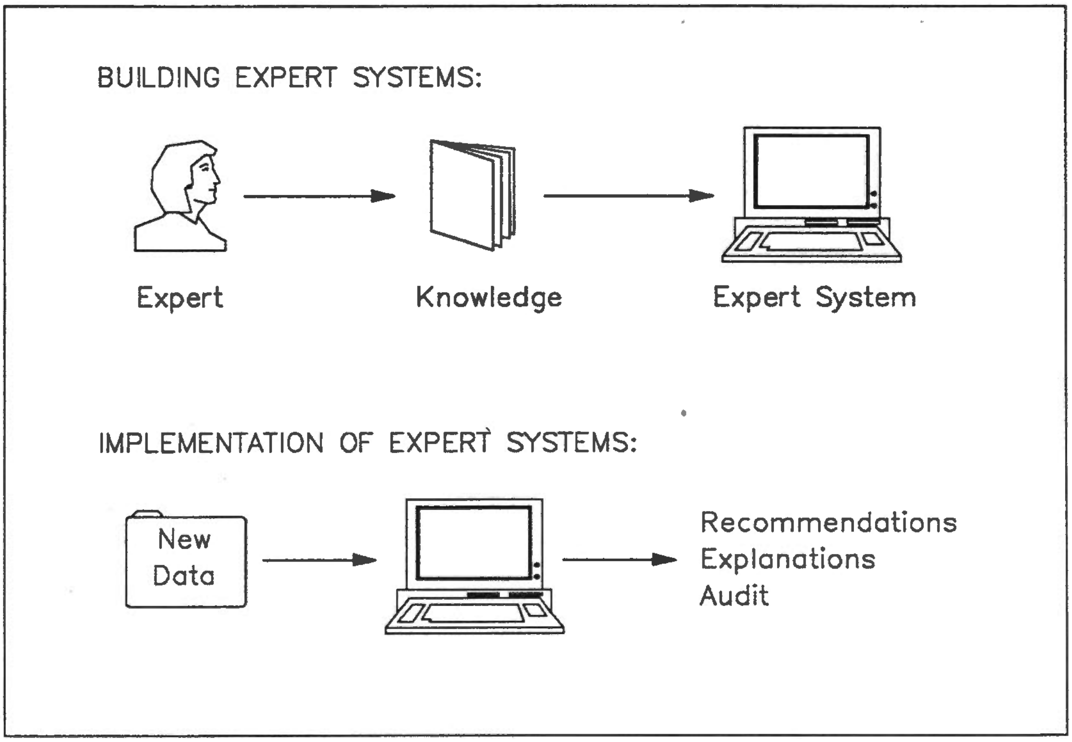

Figure B.2. BUILDING AND IMPLEMENTING EXPERT SYSTEMS

B.1.1. Benefits and Limitations of Expert Systems

Table B.2 shows selected examples of expert system applications in heavy industry. In general, these systems will fall into one of seven major application categories:

- control

- monitoring
- diagnosis
- maintenance
- scheduling
- planning

Table B.2. APPLICATIONS OF EXPERT SYSTEMS IN HEAVY INDUSTRY

Iron and Steel: scheduling of rolling sequences, resource allocation, process planning for cold forging, control of BOF, diagnosis of faults in production, blast furnace control, scheduling of continuous caster, operation planning of electric furnace, scheduling of hot-rolling process, control of electric energy consumption.

Cement: control of manufacturing, assistance in maintenance, control and optimization of plant operation, kiln optimization, optimization of materials blending, monitoring cement kiln performance, optimization of quarry operations.

Mining & Metallurgy: staffing planning, control of mine ventilation, design of processes for smelting, diagnosis of faults in coal cutting equipment, planning of surface mining methods, on-line diagnostic maintenance of continuous miner, optimizing dragline operations, control of grinding circuit, control of flotation circuit, control of mill and spiral circuit, control of flotation column, scheduling of production.

Oil and Gas: trouble-shooting refinery distillation column, process monitoring and control, process planning, resource planning, problem diagnosis in boilers.

Pulp and Paper: analysis and planning of production, paper quality management, scheduling and control of machines, production problems diagnosis, design of felt, stock blending, management of steam and power drives, diagnosis of pitch problems.

The relative frequency of these applications depends on the industry sector. However, the majority of experiences in implementing expert systems in heavy industry are in control, monitoring, diagnosis and scheduling applications. Applications like design, planning and maintenance are on the rise, but since they are often more complex to implement, their number is still relatively small.

Expert systems offer a number of benefits. They:

- provide expertise when experts are not available
- reduce the time required to carry out complex expert analysis
- upgrade performance of less experienced personnel so they can perform at the level of an expert
- capture and preserve expertise (knowledge)
- ensure that expertise is applied uniformly, objectively and consistently at all times.

The above characteristics are especially important to gain increased productivity and product quality, and to automate industrial processes and decision making.

The successful development of expert systems is dependent on several critical elements, namely:

- strong management commitment
- having the right people with experience and knowledge
- selecting the right applications
- selecting the right tools.

The large number of papers and books published on how to select the right applications underscores the importance of this issue. As a general guideline, it is better to enhance an existing application than to build a new one; it is better to select a smaller application with quick implementation, than a larger application with slower implementation.

In selecting an application for expert systems, the developer should bear in mind several limitations of expert systems. The first is that expert systems are unlikely to have all human expertise which means that they are also not likely to solve problems a human expert can not solve. Expert systems can perform faster and more consistently than human experts but not much better.

Expert systems are suitable for narrow and well-defined domains. In areas where a number of different fields are involved, like geological exploration, experience shows that expert systems often do not perform well. They also perform poorly at boundaries of a well defined domain because important knowledge often may be missing from the knowledge base. Another limitation which is of practical significance is that today's expert systems have limited learning capabilities. This means they are suitable where domain knowledge does not change frequently and where long-term systems are needed.

The characteristics of a good application would be that human expertise is available, limited success (less than 100 percent performance) is acceptable, and the human experts use heuristic reasoning that can be cloned. Because building expert systems is still relatively costly, it is also important that the potential payoff is measurable and easy to demonsatrate before development takes place.

It is evident from the preceding paragraphs that certain situations should be avoided in application of expert systems. First, applications with complex domains requiring knowledge from many areas should be avoided. Expert systems are also not suitable where:

- human experts will have little time to participate in the project
- current practice will be disturbed by introducing expert systems
- the domain is very unstable, or knowledge/procedures are no longer relevant or are quickly changing
- the project will be on the critical path for other developments
- task payoffs are not measurable.

The limitations listed above should serve as red flags. Only after careful review of the limitation and alternative strategies should development of an expert system proceed.

Whether to use available expert system shells is an important question in all expert system developments. With today's shells, building expert systems from the bottom up could be justified only if unusual requirements and features were needed. In general, available expert system tools will meet most, if not all, technical requirements for building expert systems. They will also reduce the cost of building the system by a factor of 5 to 10 depending on the in-house staff's capabilities and experience.

This review of expert system shells looks at a number of different shells available to the industry. All these systems are comprehensive professional tools and offer capabilities that a few years ago were available only on mainframe computers.

B.1.2. Commercial Expert System Tools

This section summarizes the features of available expert system shells in North America. The following are comments explaining the relevance and functions performed by various technical features listed for the shells. It is important to note that not all features and capabilities are needed for off-line, decision-support systems. However, for real-time systems, many of the listed capabilities are important and useful.

In selecting the tools a number of issues are important, many of which are discussed below. As a general guideline, the developer should make sure that:

- the tool can represent the type of knowledge and information required
- the tool's complexity matches the complexity of the application

- the tool can be integrated with the main plant system and maintained by the designated personnel.

Platforms Supported: It is important that the vendor supports several platforms. This way the user can develop the knowledge base on a PC or workstation at a lower cost and export it later to other platforms for full-scale application. Another important consideration is to have an open, distributed architecture. Distributing the functions of an application over several independent CPUs can maximize throughput and response as well as increase the performance and fault tolerance of the expert system.

Cost Elements: Three cost elements should be considered in evaluation of shells. These are software cost, annual maintenance cost and run-time cost. The cost of software and maintenance are direct and easily factored into the project cost evaluation. However, if the user wants to service more than one site then the cost of the run-time licence becomes important.

Vendor/Third Party Training: These considerations are important for inexperienced users and/or when first projects are undertaken. On the other hand, experienced users often know more about the product application in their area than the vendor.

Computing Interprocess Communication: Efficient message transfers between computing processes is conditional on server capabilities and message passing protocols. The use of industry standard protocols makes such connections easier to implement. The ability to send messages to a particular computing process or group of processes, to handle the messages at the most optimal time (using blocking or non-blocking reads), and to use predefined messages either from a library or user defined (primitives) can enhance the computing interprocesses.

Inference Processes: It is important to have flexibility and different capabilities to analyze data in the inference processes. This can be done by using objects, classes, user-defined functions, and rules. The rules can be data-driven, goal-driven or time-trigger rules giving the user further flexibility in implementing various inferencing procedures.

For complex applications, frames and blackboards facilitate easier definition of groups of objects, their association and relationships. Facilities for multiple inheritance simplify the design and accelerate the execution of the expert systems. Dynamic rule priorities allow the user to decide when low priority rules are to be considered and how to improve on the system's response.

Embeddability of inferencing procedures and knowledge bases as part of the user program is important in situations where customized, specialized designs must be met. Storing ASCII files permits the maintenance of embedded knowledge bases using standard editors such as CASE.

Human Interface: Ease of use and clarity of human interface is probably the most important factor in the acceptance of the intelligent system by the users. This assumes, of course, that the system does what it is supposed to do. A number of interface features can make development and use of the intelligent system much more efficient and effective. These features are discussed below.

A point-and-click graphical user interface (GUI) allows users to easily create drawings and complex pictures, and to display objects and charts. When supported by real-data displays, the interface provides a powerful link between the operator and the process. Features like the ability to replay historical data, the ability to pick important regions, and animation, add further efficiency and clarity to the interface.

For the developer, the ability to export the displays to different platforms and to debug the views and messages are very important for efficient development.

Finally, the user has to have the means to handle messages and to filter messages according to age, time of receipt, message content and the importance of the object the message refers to. Also, the ability to print system status indicators, including messages, using a simple postscript printer is necessary.

Data Acquisition: It is important to have a flexible data handling environment so that the user can create and modify databases, edit groups of data and create new variables. User-defined functions for data transformation are often valuable at this stage as is the ability to acquire data from more than one source at the same time. The ability to run in simulated mode offers the user the ability to replay archive data or simulate problems for training. Other important features in real-time applications are the ability to dynamically switch data when sent to different processes, and to group sensors' data before processing. Data groups can be defined based on importance of data in the application, e.g., critical operations, normal operations, system testing, etc. Finally, interfaces to distributed control systems or management information systems can greatly assist in expert system development.

Note: The features listed in this section are for real-time systems. Not all of them are essential for development of expert systems. Also, some features not listed here may be important in a specific application. The list presented here is to make the user aware of issues and features in expert system shells and, therefore, should be used only in a preliminary evaluation of the shells. The list is not intended to substitute for the user's and/or developer's own evaluation of expert system shells since shell vendors are constantly adding new features and changing prices.

In our selection of tools, we included systems that have proven applications in the industry and that offer comprehensive support for their implementation. We have also incorporated small tools for those who would like to explore smart technologies without committing tens of thousands of dollars and extensive time to learn about intelligent technologies.

Product: **EXSYS Professional**

Vendor: Exsys, 1720 Louisiana Blvd NE, Albuquerque, NM 87110, USA.

Architecture: a rule-based shell enhanced with frames and blackboards.

Major Features/Modules:

1. Inference Engine - forward and backward chaining of rules; can handle variables and fixed data; confidence and probability factors for rules; frames provide inheritance of objects; blackboards store and retrieve data; meta-rules for dynamic data.

2. Developer Interface - rule editor, debugger, automatic system validation, configuration options for tuning end user interface including custom screens, hypertext and help.

3. End User Interface - explanation facilities for how and why decisions are recommended, log of rules fired, etc.

4. Linkable Object Modules - to provide custom run-time programs, user functions for data acquisition and display, create custom windows and dialogs, embed the inference engine in the GUI applications.

5. Interfaces - built-in functions to directly read or write data in other programs (SQL databases, spreadsheets) to perform linear programming (LINDO), to call neural networks (NeuralWorks Professional), and to access plant information systems (PI process data Historian for VAX/VMS computer).

General Information:

Platforms Supported?	PC Workstation
Number of Copies Sold?	10,000
Price?	\$1,495 to \$20,000
Annual Maintenance Costs?	Free first year then 15 percent of the purchase price
Run-time License Costs?	Unlimited for PC, workstation priced \$5,500 to \$6,500
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	N/A
Third-party Training?	yes
Vendor KE Consulting?	yes, \$750 to \$1000 per day

Third-party KE Consulting? yes

Add-on Tools?

Linkable Object Modules for "C" code representation of rules and to call Exsys as "C" routine from other programs. Exsys may be transparently embedded in other applications.

Other?

An SQL Interfaces package (20 databases) is included at no charge for MS Windows platform.

Technical Information:

Interprocess Communication:

server capabilities? no

protocols TCP/IP DECNET? no

message passing? no

broadcast to groups of processes? no

blocking and non-blocking reads? no

library of predefined messages? no

primitives? no

Inference Processes:

rules? data driven, goal-driven, triggered

math functions library? trigonometry, power, exponential, roots

frames? some

blackboards? yes

multiple dynamic inheritance (several parent classes)? no

dynamic rule priorities (can be changed while running)? no

user-defined functions (external)? yes, using linkable objects

embeddability (as part of user's program)? yes

ASCII knowledge base storage? can be printed as ASCII

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? depends on rate

historical data retrieval and replay? no

drawing animation? very crude

dynamic objects (change with values of variables)? no

pick important region (display overlay, graphical rules)? no

portable displays? custom screens are portable

input objects (click commands)? mouse hotspots

message handling (acknowledge, delete, etc.)? no

debugging features (views, messages, etc.)? trace windows, rule display windows

postscript output? yes

Data Acquisition:

linked to external files and databases? yes

development environment?

user functions? link to C functions

simulated mode? PI system

multiple data sources? yes, if first fails, Exsys tries next

data grouping? yes

dynamic data switching (switch between sources)? use embedded variables

interfaces to DCS and MIS sources? no

Data Archiving:

in real-time? depends on rate, else use PI

automatic backup? use PI

Data Playback:

SQL access? for MS Windows

plotting historical data? no, use PI

interaction analysis (selected data)? no, use PI exporting data?   some

test data operation?   yes

Product: **G2 Real-Time Expert System**

Vendor: Gensym Corporation, 125 Cambridge Park Drive, Cambridge, MA 02140, USA.

Architecture: Based on client-server design to facilitate multiple users' access.

Key Features/Modules:

1. Object-Oriented Graphics - for representation of knowledge in an easy to understand form.
2. Animated Objects - to display real-time events and information flow.
3. Real-Time Graphic Display - to display real-time data as graphs, charts, dials and tables.
4. Interactive Editor - for entering rules, procedures and models using structured natural language.
5. Messages and Explanations - for displaying diagnostics, warnings, advice, real-time events.
6. Dynamic Simulation - for modelling and simulating processes, comparing actual vs ideal behavior, etc.
7. Real-Time Connectivity - Bridges to standard PLCs, DCSs, and databases.

Other Products:

G2 Diagnostic Assistant (GDA)
Dynamic Scheduling Package (DSP)
NeurON-Line
Telewindows

General Information:

Platforms Supported?	Workstation Mini PC4.0 to be released
Number of Copies Sold?	>2,000
Price?	\$15,000 to \$42,000
Annual Maintenance Costs?	20 %
Run-time License Costs?	\$15,000
Vendor Support?	worldwide

Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	yes
Vendor KE Consulting?	yes
Third-party KE Consulting?	yes

Add-on Tools?

GDA, NeurOnline

Technical Information:

Interprocess Communication:

server capabilities? yes

protocols TCP/IP DECNET? yes

message passing? yes

broadcast to groups of processes? yes

blocking and non-blocking reads? yes

library of predefined messages? yes

primitives? no

Inference Processes:

rules? data driven, goal-driven, triggered

math functions library? yes

frames? yes

blackboards? user implemented

multiple dynamic inheritance (several parent classes)? yes

dynamic rule priorities (can be changed while running)? yes

user-defined functions (external)? yes

embeddability (as part of user's program)? yes

ASCII knowledge base storage? yes

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? yes

historical data retrieval and replay? user implemented

drawing animation? yes

dynamic objects (change with values of variables)? yes

pick important region (display overlay, graphical rules)? yes

portable displays? yes

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? user implemented

debugging features (views, messages, etc.)? yes

postscript output? yes

Data Acquisition:

linked to external files and databases? yes

development environment? C

user functions? yes

simulated mode? yes

multiple data sources? yes

data grouping? yes

dynamic data switching (switch between sources)? yes

interfaces to DCS and MIS sources? most DCS & PLCs

Data Archiving:

in real-time? yes

automatic backup? yes

Data Playback:

SQL access? yes

plotting historical data? yes

interaction analysis (selected data)? yes exporting data? yes

test data operation? yes

Product: **Goldworks III**

Vendor: Gold Hill Inc. 26 Landsdowne Street, Cambridge, MA 02139, USA.

Architecture: a Lisp based OOP shell for PC AT, Sun SPARC and IBM RS6000.

Key Features/Modules:

1. Inference Engine - rules bi-directional, frames, demons to define actions, multiple inheritance, rule sets, automatic retraction of facts that are no longer true, agendas, rule priorities.

2. Developers Interface - rule editor, browser, debugging tools, graphics layout tool, object-oriented programming.

3. Menu Interface - exploration facility for increased programming productivity.

4. Graphics Toolkit - creates MS Windows interface without programming, dynamic images.

5. External Interfaces - allows access to codes written in other languages, direct argument passing, dynamic data exchange, databases.

General Information:

Platforms Supported?	PC Workstation
Number of Copies Sold?	6,000+
Price?	$6,000 up
Annual Maintenance Costs?	$1,200
Run-time License Costs?	flat one time
Vendor Support?	yes
Vendor Training?	yes, custom
On-site Training?	yes, custom
Vendor Hotline?	yes, under maintenance
Third-party Training?	no
Vendor KE Consulting?	yes, custom
Third-party KE Consulting?	yes

Add-on Tools?

with FFI, DDE and SQL can add on a variety of 3rd party tools.

Other?

Golden Connection SQL and Runtime

Technical Information:

Interprocess Communication:

server capabilities? no

protocols TCP/IP DECNET? 3rd party software

message passing? yes

broadcast to groups of processes? no

blocking and non-blocking reads? yes

library of predefined messages? no

primitives? no

Inference Processes:

rules? data driven, goal-driven, triggered

math functions library? yes

frames? yes

blackboards? no

multiple dynamic inheritance (several parent classes)? yes

dynamic rule priorities (can be changed while running)? yes

user-defined functions (external)? yes

embeddability (as part of user's program)? no

ASCII knowledge base storage? yes

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? yes

historical data retrieval and replay? no

drawing animation? yes

dynamic objects (change with values of variables)? yes

pick important region (display overlay, graphical rules)? yes portable displays? yes

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? yes

debugging features (views, messages, etc.)? yes

postscript output? through Windows print manager

<u>Data Acquisition</u>:

linked to external files and databases? dBase reader, etc.

development environment? Lisp

user functions? yes

simulated mode? no

multiple data sources? multiple database connections

data grouping? no

dynamic data switching (switch between sources)? yes

interfaces to DCS and MIS sources? several supported sources

<u>Data Archiving</u>:

in real-time? no

automatic backup? no

<u>Data Playback</u>:

SQL access? yes

plotting historical data? no

interaction analysis (selected data)? no

exporting data? yes

test data operation? no

Product: **Level5 Object**

Vendor: Information Builders, 503 Fifth Avenue, Indialantic, FL, USA.

Architecture: based on a client-server model of computing, essentially distributed.

Major Features/Modules:

1. Object Editor - to create and edit classes, write methods, rules and demons.
2. Agenda Editor - to create a list of goals for inference engine during run time.
3. Database Editor - to define access to databases.
4. Display Editor - to create and edit displays, or edit rules, demons and methods.
5. Methods/Rules/Demons Editor - to edit, select and view methods, backward-chaining rules, demons, etc.
6. Windows Editor - to customize application interface.

General Information:

Platforms Supported?	PC Workstation Mini Mainframe
Number of Copies Sold?	>25,000
Price?	$ 995 up
Annual Maintenance Costs?	none
Run-time License Costs?	$220
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	yes
Vendor KE Consulting?	yes
Third-party KE Consulting?	yes

Add-on Tools?

Business Packs, Tape1.5

Technical Information:

Interprocess Communication:

server capabilities? yes

protocols TCP/IP DECNET? yes

message passing? yes

broadcast to groups of processes? yes

blocking and non-blocking reads? yes

library of predefined messages? yes

primitives? yes

Inference Processes:

rules? data driven, goal-driven, triggered

math functions library? yes

frames? yes

blackboards? no

multiple dynamic inheritance (several parent classes)? no

dynamic rule priorities (can be changed while running)? yes

user-defined functions (external)? yes

embeddability (as part of user's program)? yes

ASCII knowledge base storage? yes

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? yes

historical data retrieval and replay?

drawing animation? yes

dynamic objects (change with values of variables)? yes

pick important region (display overlay, graphical rules)?

portable displays? yes

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? no debugging features (views, messages, etc.)? yes

postscript output? yes

Data Acquisition:

linked to external files and databases? yes

development environment? PRL

user functions? yes

simulated mode? yes

multiple data sources? yes

data grouping? no

dynamic data switching (switch between sources)? no

interfaces to DCS and MIS sources? no

Data Archiving:

in real-time? no

automatic backup? no

Data Playback:

SQL access? yes

plotting historical data? yes

interaction analysis (selected data)? no

exporting data? yes

test data operation? yes

Product: **RT/Expert**

Vendor: Integrated Systems Inc., 2500 Mission College Blvd, Santa Clara, CA 95054, USA.

Architecture: runs under ISI's System Build modelling and simulation product.

Key Features/Modules:

1. Database - holds raw information acquired during operation and control signals send to RT/Expert.

2. Inference Engine - timing and output posting, match, select and execute rules, forward and backward chaining.

3. Knowledge Base - rules, frames and semantic networks.

Other Products:

System Build - modelling and simulation including interactive animation module, RT/Fuzzy, HyperBuild module

Matrix/Xmath - object oriented mathematical analysis tool for X windows with a programmable GUI

AC-100 - an integrated CAE/CASE system for automation of real-time, embedded control software development.

General Information:

Platforms Supported?	Workstation
Number of Copies Sold?	not disclosed
Price?	$5,000 but requires System Build
Annual Maintenance Costs?	$1,000
Run-time License Costs?	not available
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	no
Vendor KE Consulting?	yes

Third-party KE Consulting? no

Add-on Tools?

Fuzzy Logic, State Transition Diagrams, etc

Real-time operating system PSOS for interprocess communication.

Technical Information:

Interprocess Communication:

server capabilities? yes

protocols TCP/IP DECNET? yes

message passing? yes

broadcast to groups of processes? no

blocking and non-blocking reads? no

library of predefined messages? no

primitives? no

Inference Processes:

rules? data driven

math functions library? yes

frames? no

blackboards? no

multiple dynamic inheritance (several parent classes)? no

dynamic rule priorities (can be changed while running)? no

user-defined functions (external)? no

embeddability (as part of user's program)? yes

ASCII knowledge base storage? yes

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? yes

historical data retrieval and replay? using history file drawing animation? yes through IA

dynamic objects (change with values of variables)? no

pick important region (display overlay, graphical rules)? no

portable displays? X/math graphics

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? yes

debugging features (views, messages, etc.)? yes, through history file

postscript output? yes

Data Acquisition:

linked to external files and databases? (specify) files only, LNX to access databases

development environment? (specify)

user functions? X/math LNX, Math Script

simulated mode? yes

multiple data sources? no

data grouping? basic data manipulation provided

dynamic data switching (switch between sources)? yes

interfaces to DCS and MIS sources? no

Data Archiving:

in real-time? no

automatic backup? no

Data Playback:

SQL access? no

plotting historical data? yes

interaction analysis (selected data)? through IA

exporting data? ASCII, binary

test data operation? through simulation mode

Product: **NEXPERT Object**

Vendor: Neuron Data, 156 University Avenue, Palo Alto, CA 94301, USA.

Architecture: Based on a client-server model of computing, essentially distributed.

General Information:

Platforms Supported?	PC Workstation Mainframe
Number of Copies Sold?	>16,000
Price?	$8,000
Annual Maintenance Costs?	none
Run-time License Costs?	varies
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	yes
Vendor KE Consulting?	no
Third-party KE Consulting?	yes (partners)

Add-on Tools?

UDB, DAE

Technical Information:

Interprocess Communication:

server capabilities? through 3rd party

protocols TCP/IP DECNET? yes

message passing? yes

broadcast to groups of processes? through 3rd party tools

blocking and non-blocking reads? through 3rd party tools

library of predefined messages? yes

primitives? through toolkits

Inference Processes:

rules? data driven, goal-driven, triggered

math functions library? yes

frames? yes

blackboards? 3rd party

multiple dynamic inheritance (several parent classes)? yes

dynamic rule priorities (can be changed while running)? yes

user-defined functions (external)? yes

embeddability (as part of user's program)? yes

ASCII knowledge base storage? yes

Human-Computer Interface:

GUI builder (point-and-click)? yes

real-time display of data? through customization or script

historical data retrieval and replay? journaling function

drawing animation? 3rd party tools

dynamic objects (change with values of variables)? yes

pick important region (display overlay, graphical rules)? yes

portable displays? yes

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? yes

debugging features (views, messages, etc.)? yes

postscript output? yes

Data Acquisition:

linked to external files and databases? yes

development environment? specific editors

user functions? full SQL support

simulated mode? journaling functions

multiple data sources? (specify) yes

data grouping? no

dynamic data switching (switch between sources)? yes

interfaces to DCS and MIS sources? through 3rd party tools

Data Archiving:

in real-time? 3rd party

automatic backup? can be coded

Data Playback:

SQL access? yes

plotting historical data? C/C++ coding and chart widgets

interaction analysis (selected data)? no

exporting data? yes

test data operation? yes

Product: **RTworks**

Vendor: Talarian, 444 Castro Street, Mountain View, CA 94041, USA.

Architecture: based on a client-server model of computing, essentially distributed.

Key Features/Modules:

1. RTserver - to communicate with other RTworks modules and with user - defined processes.
2. RTie - inference engine processes, trading functions, analyzes history and current data in real-time.
3. RThci - point-and-click graphical user interface to an operator.
4. RTdaq - data acquisition and management.
5. RTarchive - data archive processes.
6. RTplayback - plays back data, messages.
7. RTgen - allows generation of test data for RTworks processes.
8. RTdraw - two-dimensional drawing editor.

General Information:

Platforms Supported?	PC Workstation Mini Mainframe
Number of Copies Sold?	not disclosed
Price?	$15,000 & up
Annual Maintenance Costs?	10 %
Run-time License Costs?	variable
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes, custom
Vendor Hotline?	yes
Third-party Training?	no
Vendor KE Consulting?	yes
Third-party KE Consulting?	no

Add-on Tools?

Technical Information:

Interprocess Communication:

- server capabilities? yes
- protocols TCP/IP DECNET? yes
- message passing? yes
- broadcast to groups of processes? yes
- blocking and non-blocking reads? yes
- library of predefined messages? yes
- primitives? yes

Inference Processes:

- rules? data driven, goal-driven, triggered
- math functions library? yes
- frames? yes
- blackboards? yes
- multiple dynamic inheritance (several parent classes)? yes
- dynamic rule priorities (can be changed while running)? yes
- user-defined functions (external)? yes
- embeddability (as part of user's program)? yes
- ASCII knowledge base storage? yes

Human-Computer Interface:

- GUI builder (point-and-click)? yes
- real-time display of data? yes
- historical data retrieval and replay? yes
- drawing animation? yes
- dynamic objects (change with values of variables)? yes
- pick important region (display overlay, graphical rules)? yes
- portable displays? yes

input objects (click commands)? yes

message handling (acknowledge, delete, etc.)? yes

debugging features (views, messages, etc.)? yes

postscript output? yes

Data Acquisition:

linked to external files and databases? yes

development environment?

user functions? yes

simulated mode? yes

multiple data sources? yes

data grouping? yes

dynamic data switching (switch between sources)? yes

Interfaces to DCS and MIS sources? some

Data Archiving:

in real-time? yes

automatic backup? yes

Data Playback:

SQL access? yes

plotting historical data? yes

interaction analysis (selected data)? yes

exporting data? yes

test data operation? yes

B.2. NEURAL NETWORKS

Definition: Neural networks (NN) are computing systems consisting of a large number of interconnected processing elements which process information by determining the values of output signals based on the values of input signals.

The processing elements or neurons acquire their ability to process information through training, i.e., by being shown examples of input and output values they learn the response values of the output as a function of the input. Individual processing units have a limited number of responses available. For example, they can fire when the input value exceeds a certain threshold value, can sum or take a product of input values with weighing coefficients, can take a logarithm of the input values, etc. The network of processing elements can, however, perform many of these functions and can adjust its response during the process of training.

Neural networks are often described as analogs of the brain cells. Brain cells or neurons carry on (fire) a signal to the next neuron if the sum of input signals exceeds a threshold value (Figure B.3). Since neurons are interconnected, firing one neuron can send a signal across many interconnected neurons. In a similar manner, artificial neural networks also pass on a message or signal if the sum of input values exceeds a certain threshold (Figure B.4).

Neural networks can be fully designed, that is they can have a predetermined structure and parameters to perform a very specific computation. More often, however, only the structure is predetermined while the parameters are adjusted through training to perform the desired computations.

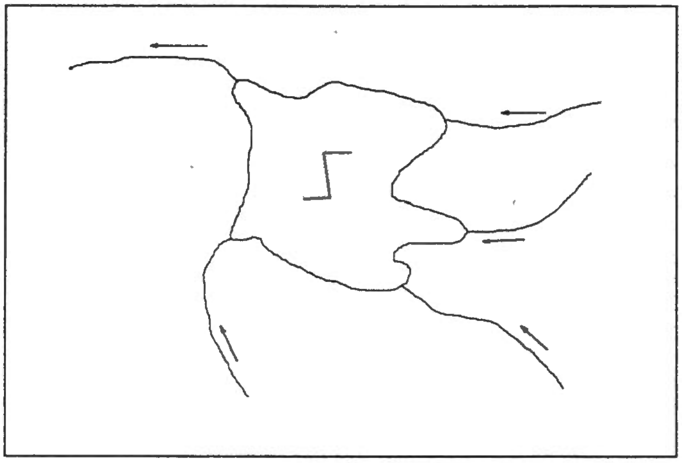

Figure B.3. GRAPHICAL REPRESENTATION OF A NEURON

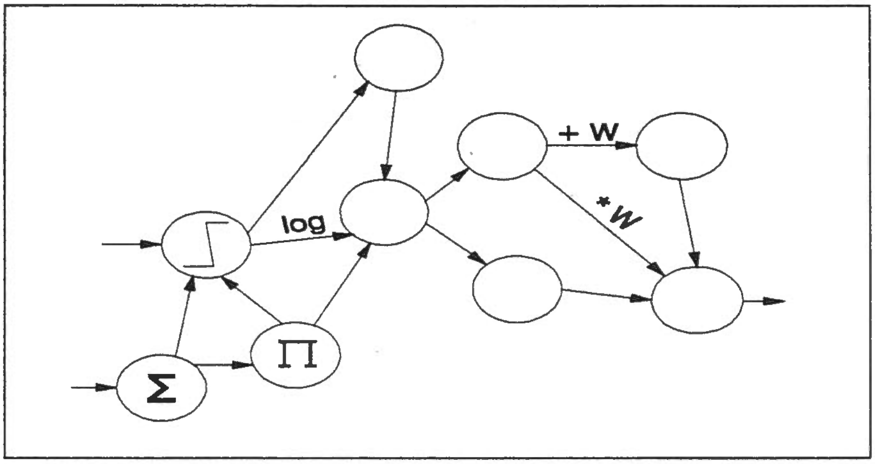

Figure B.4. GRAPHICAL REPRESENTATION OF A NEURAL NETWORK

Developing neural networks applications requires neural network software and a database of training examples to build trained neural networks. The trained network can then perform computations for new data (Figure B.5). The network then has a defined structure and the computational parameters.

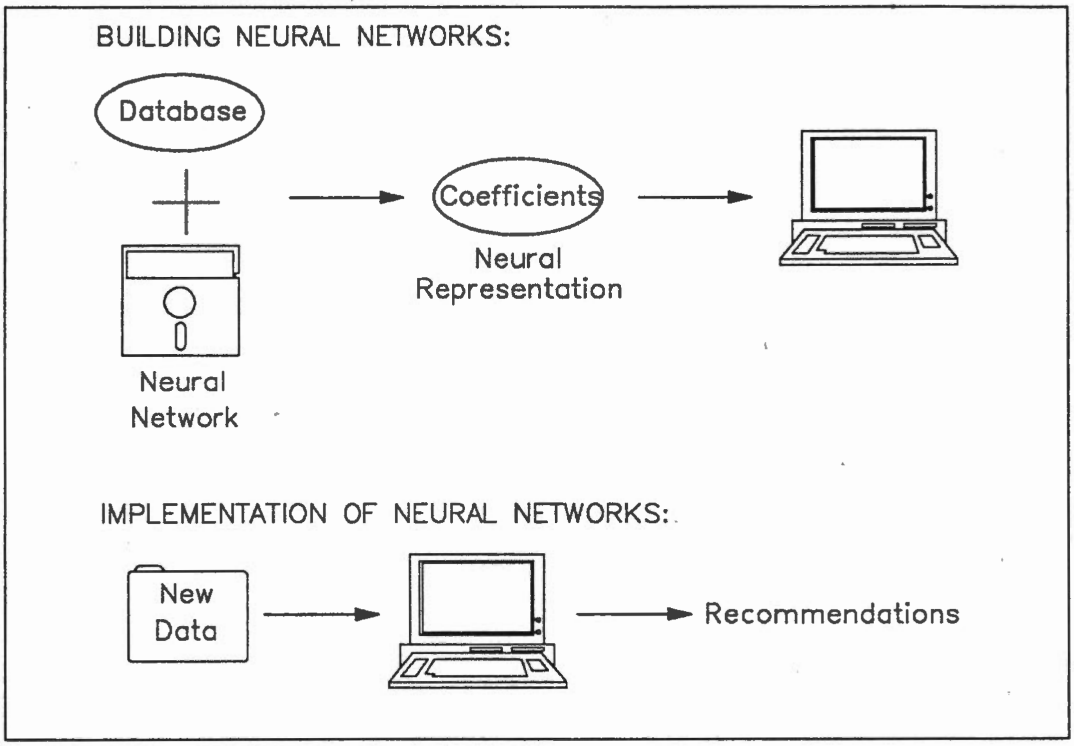

Figure B.5. BUILDING AND IMPLEMENTING NEURAL NETWORKS

B.2.1. Benefits and Limitations of Neural Networks

Table B.3 shows selected examples of applications of neural networks in heavy industry. In general, the applications fall within these categories:

- predictive modelling
- forecasting
- pattern recognition (diagnosis)
- classification
- signal processing
- monitoring.

Table B.3. APPLICATIONS OF NEURAL NETWORKS IN INDUSTRY

Iron and Steel: recognition of characters stenciled on slabs, control of heat in a continuous caster, prediction of breakouts in continuous casters, strip-thickness control, control of blast furnace abnormalities, shape control of rolling mills, control of electric furnace electrodes.
Mining and Metallurgy: suggested-signal processing, noise filters, pattern recognition, data forecasting, modelling simulation, control and optimization, control of a hydrocyclone classifier, control of carbon activity in gold absorption, control of grinding circuit.
Pulp and Paper: control of brownstock washer, acoustic vibration control.

The majority of neural networks applications are for predictive modelling, classification and pattern recognition. Recently, applications have been developed in signal processing and process monitoring.

The most often mentioned benefit of neural networks is their potential for massive parallelism, i.e., the ability of neurons to work independently of each other. Neural network computations are local with many neurons operating at the same time and with no need for shared memory. However, parallel computing is very expensive and not practical for most industrial applications.

Neural networks can learn from examples by making changes in the parameters until the network produces the correct output. This capability is important in process control where volumes of data are available. Neural networks can develop models which can be used to diagnose misoperation, to tune the controllers, and to use adaptive control.

Neural networks are very slow to train on serial computers which sometimes makes their use impractical. However, once trained, neural networks can respond with high speed.

Interestingly, the same characteristics that make neural networks attractive also impose some limitations. For example, the increased complexity of a neural network increases its robustness but robustness also causes ambiguity in terms of what neural networks do. This makes it difficult, if not impossible, to understand neural networks' models and predictions. In a sense neural networks act as black boxes which can process signals but provide little insight into the underlying patterns or relationships.

Neural networks are also deceivingly simple. For a novice user it is easy to overfit the data or find only "local" optimization conditions. Despite these shortcomings, neural networks provide a powerful tool for process control applications.

When designing neural network applications it is, therefore, important to keep in mind their benefits and their limitations. The characteristics of good candidate application areas are:

- There are plenty of training examples.
- The problem represents a complex yet well-defined task for which no knowledge or decision heuristics exist.
- A first principle model is difficult to build or use.
- There is a need for rapid prototyping or model development.
- The problem being modeled represents a support task in a larger expert system. For example, the neural network approach may be preferable to regression equations or other parametric modelling where interactions among variables are highly non-linear.

The developer should also watch for situations where neural networks may have some weaknesses in application. For example:

- Training data may be incomplete, inconsistent or ambiguous.
- Good tests can not be designed to evaluate the performance of a trained network.

- There is a need to understand/explain the results of analysis and decisions.

In all these situations, machine learning offers an attractive alternative because it, like neural networks, learns from examples but also addresses neural networks limitations.

B.2.2. Commercial Tools

This section reviews the key features of selected neural network commercial tools. The list is not exhaustive for there are many PC-based vendors offering a variety of neural networks add-ons. The products reviewed focus either on industrial applications or on general tools suitable for industrial work. The latter do not offer comprehensive process control interfaces and other facilities, but are designed to help develop neural networks components which can be embedded in the process control software.

Product: **NeurON-Line**

Vendor: Gensym Corporation, 125 Cambridge Park Drive, Cambridge, MA 02140, USA

NeurON-Line is an object-oriented software for building neural networks for real-time applications. It has been applied in a several manufacturing plants. It requires Gensym G2 Real-Time Expert System or Diagnostic Assistant for implementation. NeurON-Line is integrated with the existing plant control system through G2 Bridge modules for DCS, PLCs and databases.

Major Features/Modules:

1. Vector Blocks - to consolidate and manipulate time series and other real-time data.
2. Data Set Blocks - for collecting, filtering, summarizing and archiving the incoming data.
3. Training Blocks - for real-time network training and validation, four neural network paradigms.
4. Neural Net Blocks - to compute output values in forecasting and control problems.
5. Incremental Retraining - updates the model as data are accumulated.

General Information:

Platforms Supported?	PC (next release) Workstation Mini
Number of Copies Sold?	not disclosed
Price?	\$8,000 to \$16,000 (needs G2)
Annual Maintenance Costs?	20% of purchase price
Run-time License Costs?	varies, about 20% of purchase price
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	yes
Vendor Consulting?	yes
Third-party Consulting?	no

Add-on Tools?

Gensym Diagnostic Assistant

Product: **Process Insight**

Vendor: Pavillion Technologies Ltd., 3500 West Balcones Center Drive, Austin, TX 78720, USA.

Process Insight has been applied in a variety of industrial situations including mining (gold recovery models, acid conditioning optimization), pulp and paper (paper machine optimization) utilities (emission modeling, load forecasting), software continuous emission monitoring (gas-fired boilers, incinerators, coal fired boilers), etc.

Key Features/Modules:

1. Format - to load plant historical data, read, edit, merge data from multiple sources, etc.

2. Preprocess - to transform data into a different format, remove outlying data, convert data into the same time scale, etc.

3. Model - to automatically build neural network models based on selected inputs and outputs, display model performance as it is built.

4. Analyze - to carry "what-if" analysis, determine optimum set points for the process, view actual vs predicted values, perform sensitivity analysis.

General Information:

Platforms Supported?	Workstation Mini
Number of Copies Sold?	not disclosed
Price?	$50,000 up
Annual Maintenance Costs?	varies
Run-time License Costs?	varies
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	yes
Vendor Consulting?	yes
Third-party Consulting?	yes
Add-on Tools?	none

Product: **NeuralWorks Professional II**

Vendor: Neural Ware, Penn Center West, Building IV, Pittsburgh, PA 15276, USA.

NeuralWorks Professional is primarily designed for neural networks developers. The prime application areas are business and science; however, the tool can provide good neural networks embedded systems in industrial controls through its "C" routines.

Major Features/Modules:

1. InstaNet - supports 28 neural network paradigms for analysis and modelling of data.
2. FlashCode - creates ANSI standard C code with fully trained network.
3. SaveBest - automatically trains network to an optimum degree based on user defined criteria.
4. ExplainNet - shows which variables have the most impact on the outcome.
5. Batch Interface - provides capability for automating the development process.

General Information:

Platforms Supported?	PC Workstation
Number of Copies Sold?	not disclosed
Price?	starts at $1,995
Annual Maintenance Costs?	15% of purchase price
Run-time License Costs?	$1,995 (Designer Pack)
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	yes
Vendor Hotline?	yes
Third-party Training?	no
Vendor Consulting?	yes
Third-party KE Consulting?	no

Add-on Tools?

User-Defined Neuro-Dynamics to create own neural network paradigms

NeuralWorks Designer Pack to develop stand-alone applications

NeuralWorks Genetic Reinforcement to construct non-linear, feed-forward neural networks

NeuralWorks Explorer for learning about neural networks

NeuralWorks DataSculpture to create data translation and analysis tools

NeuralWorks Design Advisor to model and analyze steady-state processes

B.3. Fuzzy Logic Systems

Fuzzy Logic Systems are computer hardware and software capable of solving problems and recommending solutions based on heuristics rules containing ambiguous (fuzzy) linguistic variables. The rules have an if-then form and are acquired from human experts.

<u>More definitions</u>:

- membership functions - functions describing fuzzy sets for each variable
- fuzzy implication - "then" part of rules
- defuzzification - calculation of specific (crisp) value for decision variable or "then" part of rules.

Fuzzy systems contain:

- fuzzy set operation
- knowledge base
- inference engine and working memory
- interface

Different fuzzy systems may have different membership functions, interfaces or knowledge bases, and different inference procedures. The knowledge base and membership functions will reflect the specific domain of application. The inference procedure will be determined by selecting the most appropriate techniques for the problems being solved. Better known inference techniques are Max-Min Inference or Maz-Product Inference procedures.

The process of building a fuzzy logic system (a fuzzy expert system) consists of well defined steps. First, as in an expert system (see Figure B.2), the developer has to define the problem in terms of its objectives and, where possible, category of problems, e.g., diagnostic, control, etc. We can benefit from others' experience by examining the knowledge base structure, success and limitations of using fuzzy sets for similar problems. After the problem has been defined, the linguistic variables are identified and defined by the human expert. For each fuzzy variable including its adjectives (values), the expert has to define approximate quantitative ranges of the variables and select fuzzy functions for mapping those variables. Several standard functions can be used at this stage.

Once the fuzzy variables and adjectives have been defined, the expert has to define the fuzzy rules of the fuzzy knowledge base. This step is similar to the acquisition of rules in the expert systems. Often, at this stage, fuzzy hedges are introduced. These are adverbs like "very", and "somewhat" that modify the adjectives and require some changes to the membership function distribution. The next two steps are to program and test the system for consistency. Following the testing, the system will often be tuned by further adjustment of the membership functions. Yet, one should note that fuzzy systems often exhibit quite satisfactory performance even with a rough definition of fuzzy sets or rules. The tuning process can, however, improve the system performance by comparing its response to actual data. Tuning of the fuzzy system usually involves adding rules, adjectives to variables or hedge operators, or a shape adjustment of the membership functions.

In general, building fuzzy systems, like building expert systems, is an iterative process where performance improvement is achieved through testing, tuning and retesting of the system.

B.3.1. Benefits and Limitations of Fuzzy Systems

Table B.4 shows selected examples of applications of fuzzy systems in industry. In general, fuzzy systems are used for control and monitoring of industrial processes or equipment. There are just a few examples of using fuzzy sets for scheduling or planning.

Table B.4. APPLICATIONS OF FUZZY SYSTEMS IN INDUSTRY

Iron and Steel: performance/adaptive controllers for continuous casting, control of blast furnace, control of basic oxygen furnace, diagnosis of quality problems in continuous casting of steel billets, control of temperature in box annealing furnace, shape control of rolling mills, control of hot stove, control of tension setup of rod and bar rolling, modelling blast furnace smelting process

Cement: rotary kiln control, control of cement mills

Mining and Metallurgy: prototypes - slope design system for open pit mines

Oil and Gas: integrated oil exploration

Pulp and Paper: control of sulfite bleach

The use of fuzzy systems depends also on the type of industry (see Chapter 1 of this report). It seems that this pattern is primarily determined by the historical development of fuzzy technology and the familiarity of the developer with different industries. One would expect that a developer would select the most profitable industries, but selection is also greatly influenced by the developer's business and technical background. We see, therefore, a large number of fuzzy systems in the cement industry, while very few systems have been developed in other sectors.

The key benefits offered by fuzzy systems are that they:

- capture and present knowledge in terms of everyday language

- provide a means for reasoning with vague and ambiguous terms in a computer
- are simple to construct and easy to maintain
- have the ability to handle conflicting and ambiguous conditions well
- are stable and robust under unexpected conditions.

These benefits mean good applications are found where process knowledge is limited and process control has been based on experience and described by linguistic strategies. The characteristics of good applications are:

- Experts use fuzzy reasoning.
- Precise solutions are difficult or impossible.
- First principle models are difficult to build or use.
- The problem is a complex task for which simple heuristics exist.

When selecting fuzzy set applications the developer should also remember the limitations of the fuzzy systems. The most important is that the membership functions are precise yet the rules are imprecise. This is perhaps the biggest weakness in the theoretical foundation of fuzzy sets. Other limitations are that fuzzy inferencing is somewhat complex and not intuitive. Also, tuning rules and membership functions leave an impression of fitting the system to known solutions.

The above limitations of fuzzy sets mean that certain situations and applications should be avoided. These are applications where first principle models are available, there is a large number of significant variables to consider or experts can not agree on fuzzy rules, adjectives or membership functions.

B.3.2. Commercial Fuzzy Logic Tools

This section summarizes major commercial fuzzy systems available in North America. As in the case of neural networks, the list includes integrated industrial systems like LINKman and smaller development tools that can be embedded in control software applications.

Product: **LINKman**

Vendor: ABB LINKman, 221-224 Beckenham Road, Beckenham, Kent BR3 4UF, United Kingdom.

LINKman has been used for automation of cement plants. The attractive feature of this product is the delivery of full implementation services and the very good understanding of cement plant operations by the company engineers. LINKman is offered in two versions: 1) LINKman Classic based on conventional programing technology, and 2) LINKman Graphics based on object-oriented technology.

Major Features/Modules (LINKman Graphics):

1. Object Oriented Strategy Building - to build dynamic pictures and diagrams for control strategies.
2. Information System - total plant information system including self reporting, active mimics and survey pages.
3. Auto Diagnostics - automatic diagnosis of plant operating problems including on-line help.
4. Windows Access - to overview, amend and tune the control strategies.
5. Bridge Codes - to interface with most DCS, PLC systems, training simulator, etc.

General Information:

Platforms Supported?	Workstation
Number of Copies Sold?	50; 100 on order
Price?	$300,000 up - full technology implementation
Annual Maintenance Costs?	$30,000
Run-time License Costs?	not offered
Vendor Support?	full 10 year support
Vendor Training?	yes, inclusive in price
On-site Training?	optional
Vendor Hotline?	yes
Third-party Training?	yes
Vendor Consulting?	yes
Third-party Consulting?	yes

Add-on Tools?	none

Product: RT/Fuzzy

Vendor: Integrated Systems Inc (ISI), 2500 Mission College Boulevard, Santa Clara, CA 95054, USA

Real-Time Fuzzy Logic (RT/Fuzzy) in a part of ISI's SystemBuild modelling and simulation product for implementation of industrial control. RT/Fuzzy is designed for applications which require high processing speed. It supports rapid prototyping and embedded applications.

Major Features/Modules:

1. Rapid Prototyping - to model the performance of control modules.
2. On- Line Applications - can aid the operator in determining various control values where qualitative rules describe the control actions.
3. Embedded Applications - generates optimized Ada or C codes.
4. Control System Evaluation - can be used to model performance heuristics in determining overall performance factors.
5. User-definable Functionality - to evaluate fuzzy logic knowledge bases.
6. Self-Documentation - for easily loading, saving, and listing knowledge bases, databases, and other information.

General Information:

Platforms Supported?	Workstation
Number of Copies Sold?	not disclosed
Price?	$5,000 (but requires $16,495 SystemBuild)
Annual Maintenance Costs?	$1,000
Run-time License Costs?	no
Vendor Support?	yes
Vendor Training?	yes, $1,850/class
On-site Training?	yes, $2,500/day
Vendor Hotline?	yes
Third-party Training?	no

Vendor Consulting?	yes
Third-party Consulting?	no
Add-on Tools?	none

Product: **TILShell**

Vendor: Togai InfaLogic Inc., 5 Vanderbilt, Irvine, CA 92718, USA

TILShell is a Windows-based development tool for design, debugging and testing fuzzy logic expert systems including embedded control systems.

Major Features/Modules:

1. Graphical Project Editor - to define inputs and outputs, overall flow of information, project block diagrams.
2. VAR/Member Editor - for editing member objects and functions.
3. Membership Function Editor - to edit and run model, design of membership functions.
4. Rule Matrix and Table Editor - to define, edit, debug and test rules.
5. Real-time Code Generation - to generate embeddable "C" control codes.

General Information:

Platforms Supported?	PC
Number of Copies Sold?	not disclosed
Price?	$1,995
Annual Maintenance Costs?	n/a
Run-time License Costs?	n/a
Vendor Support?	yes
Vendor Training?	yes
On-site Training?	no
Vendor Hotline?	yes
Third-party Training?	no
Vendor Consulting?	no
Third-party Consulting?	no

Add-on Tools?

- TILGen Development Tool
- FuzzyCLIPS
- Fuzzy Computational Acceleration System

B.4. EMERGING TECHNOLOGIES

Case-Based Reasoning - to retrieve "similar" historical events, data, methods, etc. from large databases.

Product: CBR Express
Vendor: Inference Corporation
550 North Continental Blvd
EL Segundo, CA 90245,
USA

Product: Esteem
OXKO Corporation
175 Admiral Cochrane Drive
Annapolis, MD 21401
USA

Genetic Algorithms - to solve optimization problems without the need for an exhaustive computational search of all possible solutions.

Product: Evolver
Vendor: Axcelis Inc
4668 Eastern Avenue North
Seattle, WA 98103
USA

Product: MicroGA
Vendor: Emergent Behavior
635 Wellsbury Way
Palo Alto, CA 94306
USA

Machine Learning - to acquire (automatically) expert rules from data and reduce the time and cost of expert systems development. Machine learning can also be used for building predictive models and for analysis of huge databases.

Product: DataLogic/R
Vendor: REDUCT Systems Inc.
4010 Pasqua Street, Suite 402
Regina, SK S4P 3L7
Canada.

APPENDIX C

References to Journals and Books

Journals and Magazines

1. *AI Magazine*, Publication of the American Association of Artificial Intelligence, 445 Burgess Drive, Menlo Park, CA, USA.

2. *AI Expert*, Miller Freeman Publications, 600 Harrison St., San Francisco, CA, USA.

3. *PC AI*, Knowledge Technology Publications, 3310 W. Bell Rd., Suite 119, Phoenix, AZ, 85023.

4. *Canadian Artificial Intelligence*, Publication of Canadian Society for Artificial Intelligence.

Books

1. J. Martin & S. Oxman, *Building Expert Systems: A Tutorial*, Prentice Hall, Englewood Cliffs, New Jersey.

2. J. Giarratano, *Expert Systems: Principles and Programming*, PWS-Kent Publishing Company, Boston, 1989.

3. D.A. Waterman, *A Guide to Expert Systems*, Addison-Wesley Publishing, Addison-Wesley Publishing Co., 1986.

4. J. Durkin, *Expert Systems: Design and Development*, MacMillan Publishing Company, 1994.