# Expert systems and simulation in industrial applications

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## ABSTRACT

The role of expert systems and simulation, and their combination, is considered in the context of integrated manufacturing systems (IMSs). The information processing system for an IMS is considered and the relations discussed between the: organizational structure; human-computer interface; communication protocols; remote communications; computation; databases; control systems; instrumentation systems; knowledge bases; expert systems; and simulation.

## INTRODUCTION

Expert systems (ESs) have become widely accepted as a significant new computing technology with high commercial potential and important industrial applications. However, there is a paradox in current ESs, for in their greatest strength lies their greatest weakness. The encoding of the superficial, "what to do", knowledge underlying the performance of a skill, rather than the deep, "why to do it" knowledge underlying the generation of optimal algorithms, has allowed ES technology to be applied to a variety of problems that were previously intractable. However, "what to do" knowledge is subject to far more rapid obsolescence with change than is "why to do it" knowledge, and the problem of keeping ESs up-to-date may more than offset their advantages in many applications. There are also many problems where neither the superficial nor the deep approaches alone are adequate.

The most difficult problem for the computing industry currently is to determine what classes of applications are amenable to ESs. Similar problems do not necessarily have similar solutions. One application may be eminently suited to the ES approach and another that differs apparently in only minor details may be intractable. Our conceptual models of the application domain give it a topology that is full of holes. We need to reconceptualize our approach to the use of information technology in decision and control problems.

Simulation technology has been based largely on encoding the deep mathematical models underlying physical processes and the extension of ESs to incorporate simulation is one step towards strengthening ESs. However, to create hybrid ES/simulation systems alone will leave holes in the applications domain that are still non-obvious. We need deeper foundations that give us both powerful and comprehensible technologies. This paper considers the development of systems integrating ESs, simulation and other information technologies, analysing the role of each technology, its strengths and weaknesses, alone and in combination.

### The ES Paradigm Shift

The change in approach represented by ES can be seen in the context of the classical decision and control paradigm: first model the system then optimize decision and control against that model. The ES breakthrough was to realize that in certain problems where the controlled system cannot be modeled but people can do the task, it is possible to automate by modeling the person--that is, the new paradigm is to model the controller not the plant (Gaines & Shaw 1985b).

This new paradigm has proved very powerful in enabling a number of effective decision and control systems to be developed for problems that were previously intractable (Gaines & Shaw 1984). At last year's meeting we exemplified this with fuzzy control of steam engines, lime kilns and pig-iron smelting, with medical decision making for microbial infections, and with a wide variety of other ES applications (Gaines & Shaw 1985a). The range of ES applications is now very wide and and it is possible to see some patterns in successful systems.

Hayes-Roth (1984) typifies successful ES applications as problems with the following characteristics:

1) The organization requires more skilled people than it can recruit or retain;
2) Problems arise that require almost innumerable possibilities to be considered;
3) Job excellence requires a scope of knowledge exceeding reasonable demands on human training and continuing education;
4) Problem solving requires several people because no single person has the needed expertise;
5) The company's inability to apply its existing knowledge effectively now causes management to work around basic problems.

All these characteristics presume that:

a) the knowledge required is available to the organization;
b) the problem is ineffective use of the knowledge through lack of people or lack of coordination;
c) the knowledge can be made overt (knowledge engineering);
d) the knowledge can be encoded for use in an ES (power of ES shell).

The strength of ES applications has been in the large number of situations that satisfy a) through d). The weakness is the limitations of current ES technology that make d) a major impediment to many applications. These limitations stem from the very paradigm shift that was noted above as the breakthrough created by ESs, modeling the controler or decision-maker rather than the plant, or system about which decisions are being taken. Current ES shells can

**only** operate within this paradigm and hence they do not have the capability to incorporate the knowledge that was the basis of most classical decision and control systems, the physical models of the relevant worlds.

In the ES literature this has been termed the problem of **deep knowledge** (Chandrasekaran & Mittal 1984), of going beneath the pragmatic rules used by people to carry out a skilled task and incorporating the foundational premises on which those rules are based. The problem shows up in systems like MYCIN for diagnosing microbial infections (Buchanan & Shortliffe 1984), where the rules pre-suppose fixed universes of infections, diagnostic techniques and drugs. If any of these universes changes then the system has no way to respond. It is not just a problem of adding some additional rules. The existing rules may need to be edited because they pre-suppose that certain conditions do not exist. The entire rule base may have to be developed again as a result of apparently minor changes.

Superficial knowledge may be able to represent an existing skill but inadequate to adapt to change. Individual people show similar characteristics in coping with change. However, society as a whole has the capability to adjust to new conditions and disseminate the knowledge required to cope with change. ESs could be incorporated in this process by posting updates to their rule-bases through a communications network; this will happen for large-scale applications. However, the task of keeping very large numbers of highly specialized and customized ESs up-to-date by editing rule-bases at the current level of superficiality is impossible. The developmental pressure is towards deeper knowledge and the integration of ESs with existing information technologies, particularly numeric computation, databases and simulation.

This paper examines the integration of expert systems technology with other information processing technologies, particularly simulation. A companion paper discusses this from a cognitive science point of view developing the second theme of last year's paper, the role of ESs and simulation as communication media within society (Shaw & Gaines 1986). This paper counterbalances the generality of that paper by taking a highly specific situation, that of industrial automation and the modern factory, and analysing the roles of ES and simulation as part of a total information processing system.

## INTEGRATED MANUFACTURING SYSTEMS

We are in the midst of an intellectual revolution in manufacturing. Developments in numerical-control (NC) of machine tools, in materials handling, in industrial robotics, and in the understanding of human aspects of productivity and quality-assurance, have led to new approaches to manufacturing whose cumulative effect is revolutionary rather than evolutionary (Gomersall & Farmer 1984, Hartley 1984, Kafrissen & Stephans 1984, Rathmill et al 1985, Beni & Hackwood 1985). A number of major changes in manufacturing technology are apparent:-

i) There has been a shift from mass-production transfer lines highly optimized for long runs of a particular product towards flexible manufacturing lines coping cost-effectively with shorter runs of a range of products (CSDL 1984).
ii) There has been a shift from production of piece parts, perhaps at different specialist sites with sub-assembly and assembly at other sites, towards single-site integrated manufacturing (Kolodny 1985).
iii) There has been a shift from discrete manufacturing processes towards continuous flow processes based on robotic materials handling (Engelberger 1980, Heginbotham 1984).
iv) There has been a shift from high-volume, single-site manufacturing and widespread geographic distribution towards lower-volume manufacturing replicated at multiple sites chosen to minimize distribution costs (Kolodny 1985).
v) There has been a shift from the use of people as attachments to production lines with emphasis on small repetetive sub-tasks towards the use of people in a supervisory role with emphasis on responsibility for complete products (Kolodny 1985).

Computer-based integrated manufacturing systems (IMSs) allow automation and mass-production techniques to be applied to fairly short runs of diverse items compared with the long runs of limited variety required in the past (Groover & Zimmers 1984). IMSs allow many changes to occur in approaches to manufacturing and are highly significant for both Western economies and the developing world. However, the flexibility of such systems and the need for rapid set-up for different products means that the management of IMSs requires different skills from those previously associated with production management. In a sense the production line is subject to continual re-design and the information flows involved are high and complex. Management support systems for IMSs involve the combination of ES and simulation-based decision aids with numeric computation, databases, communications, instrumentation and control systems.

These changes in manufacturing practice may be seen as technology-driven by the availability of computers, advanced machine tools and robotics. However, technology springs out of social needs, and changes in manufacturing technology reflect the changing role of manufacturing in society. Toffler (1980) uses flexible manufacturing as an example of **third wave** phenomena, emphasizing its potential to use mass-production techniques to provide highly-customized, individualized products in small volumes. It is these possibilities and the consequences that flow from them that indicate that we are seeing an "intellectual" revolution in manufacturing.

Flexibility, customization and localization all sound like positive trends in keeping with our times. However, the information flows required in manufacturing increase greatly with the diversity of product being handled and the rapidity of change between products. The knowledge required to manage these information flows is of paramount importance yet not readily available. Setting up a flexible production line requires different and higher-level skills than those required to operate it once running. Worse still is the meta-level problem of designing a flexible manufacturing system (FMS) capable of handling a diversity of products (Gunn 1981, Morgan 1984, Kusiak, Vannelli & Kumar 1985).

## INFORMATION SYSTEMS IN INTEGRATED MANUFACTURING

Figure 1 shows the information systems in a modern production unit using IMS techniques. The outer ring shows eight basic information technologies, including ES and simulation, that together support the IMS and its interface to the factory and business world. The centre shows the firm itself with its corporate structure and the rings surrounding it show the human interfaces and communication protocols necessary for the systems management and integrated operation. The figure has been simplified to the minimum structure necessary to support an effective IMS. The residual complexity illustrates the need to consider ES and simulation within the total context of IMS information technology. Such a system will not necessarily succeed if any one component, or even several, are advanced, state-of-the-art technologies. However, it will certainly fail if one component is inadequate or the total system is not well-integrated.

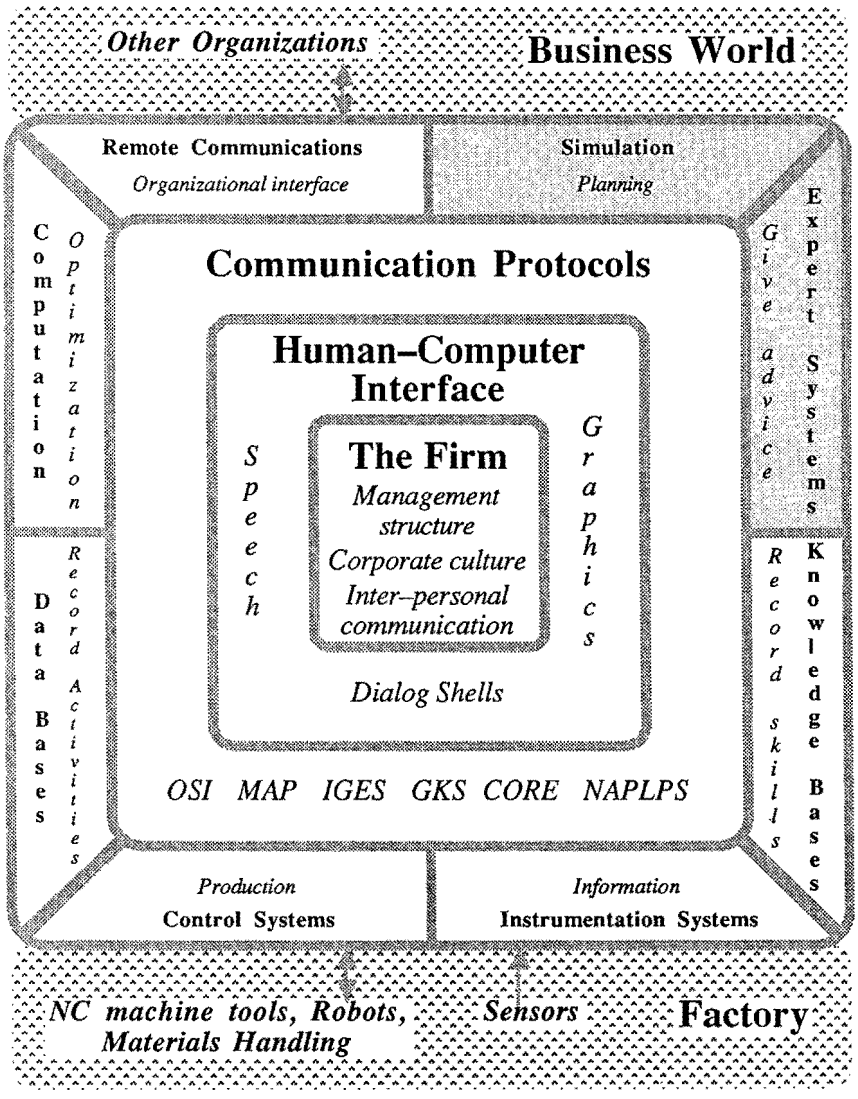


**Fig. 1 Integrated Manufacturing System**

### The Firm

The central core is the non-technology part of the system, the people that manage and operate the plant, their organization and value systems. The overt operation of the IMS is part of the **technical culture** of the firm in Hall's (1959) terms. It can be communicated, documented and partially programmed. It can also be changed fairly readily in response to new requirements, techniques and technologies. The management structure of the firm is part of its **formal culture.** Only part of it is overt and documented and it is resistant to change. What has come to be called the "corporate culture" (Deal & Kennedy 1982) is what Hall terms the **informal culture.** It pervades the organisation, is communicated by example, rarely documented, and changes only slowly or under drastic pressures of survival.

The managerial structures and social processes of the firm are not normally treated as part of its information technology. However, in order to be successful other systems must be consistent with these structures and processes. This applies particularly to inter-personal communications where computer networks will not be used if they violate the managerial and social norms of the firm, and to decision and control paths which have conform to conform to existing authority and procedures that are not necessarily those of the organization chart.

### Human-Computer Interface

Recognition that the managerial and social structure of the firm dominates its style of operation draws attention to human-computer interaction (HCI) as a critical technology. Advances graphics, voice input/output and intelligent terminals have improved the technical repertoire for HCI. Widespread contact with low-cost personal computers has increased computer literacy and user acceptance of the technology. Human factors studies are taking place with FMS systems (Mitchell et al 1984). However, much remains to be done to bring the human engineering of computer-based systems to the same level of professionalism as hardware and software engineering (Gaines & Shaw 1985c, 1986).

For decision and control systems involving expert systems and simulation, information presentation and ease of communication are of prime importance. A technically powerful system will be wasted unless it is comprehensible and accessible to its users, and gives them confidence in the basis of its operations.

**Communication Protocols**

The days of single-vendor, special-purpose systems designed against a static, well-defined specification are long gone. IMSs integrate together all aspects of the operation of a firm, from its financial planning and accounting, through its inventory control, customer, order, delivery and payment records, production planning, scheduling, control and monitoring, to its liaison with other organizations concerned with distribution, marketing, environmental control, and so on. Equipment from many vendors, purchased at different times, for different purposes, by different parts of the organisation, has to operate together. In this lies the major practical obstacles to the creation of effective IMSs at present.

The technical problems are beginning to be resolved at the lower levels by the adoption of industry standards in communication protocols such as the open systems interconnection (OSI) standard (Day & Zimmerman 1983), the provision in data-processing and database packages for the import and export of data from "foreign" systems, and the provision of data-communications for parameter-setting and data-collection in control and instrumentation systems. These alone are necessary but not sufficient to allow the widespread creation of IMSs. They provide a syntactic framework for system integration but no coherent semantics in which to express it.

The **manufacturing automation protocol** (MAP) has been developed to give application-level semantics to the OSI standard by General Motors (1984) as the major corporation most affected by IMS developments. It was sponsored by the GM Engineering and Manufacturing Computer Coordination activity in late 1979, placed in the public domain as a cooperative effort across computing, manufacturing equipment and manufacturing industries, and has attracted widespread industry support. MAP defines an application-layer protocol for OSI specific to IMS requirements.

**The Applications Ring: Basic Technologies**

The outer ring in Figure 1 shows the main information technologies in IMSs and their typical applications. Moving counter-clockwise around the ring:

**Remote Communications:** are necessary to interface the factory with its suppliers and consumers. A particular firm is part of an industrial infrastructure each part of which is trying to optimize its productivity, profitability and stability. This can best be achieved if suppliers are aware of consumers needs and projected needs and consumers are aware of the production and delivery schedules of suppliers.

**Computation Systems** perform the classical number-crunching tasks under the control of algorithms that with modern software engineering have a high degree of accuracy, conformity to specification and reliability.

**Database Systems** have become the classic core of a firm's information system, recording all its activities in a co-ordinated fashion and making the information available on a controlled basis to those systems and people with a legitimate need to know.

**Control Systems** began to be integrated with information systems as numerically-controled (NC) machine tools came into use and with the development of industrial robots capable of part-handling, tool-changing and materials movement, total automation of production has come into widespread use.

**Instrumentation Systems** have had to increase in capability to compensate for the fewer people observing the manufacturing process and the increased need for timely information on the state of the plant, tool wear, and so on, to enable the IMS to optimize overall operation.

**The Applications Ring: Decision Technologies**

**Knowledge Bases** are distinguished from databases by containing inference rules rather than facts. The rules may necessarily be heuristic in nature, generating plausible advice rather than hard facts. If databases may be said to record a firm's activities then knowledge bases may be said to record its skills, particularly its management skills.

**Expert Systems** are the means to apply a knowledge base to the solution of a particular problem. They stand in relation to the knowledge base as does conventional computation to the data base. They differ in that their role as advisors and dependence on heuristics makes accountability and comprehensibility of major importance. An ES has to be able to justify and explain the basis of its advice.

ES technology can be applied at a number of levels in IMSs including on-line process control (Brown et al 1985). However, the problem of major concern is the design stage at which the IMS has to be specified in terms of its performance and a range of diverse machine tools have to be brought together in an integrated system design. This stage presents a number of major conceptual difficulties currently that are impeding the rapid diffusion of IMS technology into appropriate industries.

**Simulation** has been separated from other forms of computation because it is computation based on a model of some other system and it is the relation of the simulated model results to that of the system modeled that is of paramount importance. As already noted the models used in simulation to infer the behavior of a system are generally deeper than the models used in ESs to infer the proper advice about a system, even though both may be concerned with the same system.

Simulation technology can also be applied at a number of different levels in IMS. However, the planning stage for flexible manufacturing is one of the most significant. A FMS involves the integration of a number of different tools, probably from different manufacturers and possibly in a way not previously encountered by the manufacturers. There is a variety of semi-standard FMS configurations recommended or used to demonstrate possibilities but the permutations required in practice go far beyond these. A FMS usually involves the integration

of new technologies with older ones. The newer technologies are particularly in materials handling (Mangold 1981, Edson 1984) and in computer-based communication and software support for the overall system (Bruno et al 1984). These are not well-understood and problems of matching flow-rates between machines, and data-rates and formats between equipment controllers, are severe. Simulation provides a manager with a way of experimenting with configurations and coming to understand the potentials of different tools.

**The Significance of Simulation in Decision Aids**

The significance of the model relationship in simulation is highlighted in interactive decision-making applications. Whereas for automatic optimization it is sufficient to model the input-output relations of the modeled system, for human interaction it is important that explanations may be given, and possibilities examined, based on the internal structure of the modeled system. The simulation must provide an adequate **analog** of this structure. This is the true meaning of the term **analog computing**--the early electronic analog computers by using physical integrators gave access to all the state variables of the system modeled.

In digital modeling this is not an automatic feature--we may choose to compute input/output relations directly without simulating all the state variables of the physical model (Gaines 1968). However, if we give users interactive access then we need to simulate in a way that is analogous to their conceptual models so that the internal variables of those models are available within the simulation (Gaines 1975, Gaines & Shaw 1982).

Why use simulation in decision-making? It would seem feasible to ascertain the requirements and then use non-interactive computation to provide an optimal solution. This is an attractive approach if the requirements are well-defined and hard. However, it is often the case that a number of possibilities are open of diverse types, such as manufacturing at alternative sites or using different tools and sequencing. It is also often the case that the requirements are soft in that they will change as the simulation and decision process proceeds and the manager come to understand the problem space better.

These considerations are not so much defects of the human decision process as limitations of decision systems that do not have adequate sensitivity analysis. If I knew in using an algorithm for grouping tools that a particular constraint I had applied was reducing the throughput by 20% then I might relax that constraint. However, it would place an excessive burden on the decision maker to require that all such trade-offs were specified in advance. The relevant "what-ifs" constitute only a small subset of all possibilities. Interactive, sequential decision-making is an efficient method for determining such relevance.

It is in this area that the combination of optimization, simulation and ES technologies becomes most attractive. An ES can aid the formulation of requirements. The optimization can give optimal solutions. The simulation can show those solutions in action so that the manager gains a feel for the sensitivities involved. A second ES can suggest variations in the simulation that might give improvements. The overall decision-support system might include:

a) eliciting the critical factors in the requirements range for a FMS such as throughput, workpiece sizes, machining activities, precision requirements and so on;
b) matching the requirements range against a variety of machine tool and materials handling configurations;
c) determining, probably through simulation, operating parameters such as set-up times, throughput rates, tolerance range, failure rates, and so on, for a variety of jobs within the requirements range;
d) when reasonable matches between requirements and performance are found, refining the design at a greater level of detail including operational factors and overall cost-effectiveness for a variety of job mixes and production runs;
e) finally, producing full specifications of the FMS including set-up procedures.

**CONCLUSIONS**

Developments in computers, robotics, communications, electronics and materials are occurring at an increasing pace and have widespread impact on industrial manufacturing processes. In particular the combination of these new technologies offers opportunities for integrated manufacturing systems that increase productivity through improved reliability, reproducibility, flexibility, human factors and cost/effectiveness. IMSs are applicable to a spectrum of industry from comparatively small firms up to large organizations. However, it is difficult for firms to keep up with the flow of information and experience on these rapidly changing new technologies.

ESs for IMSs present particular problems for today's ES technology because manufacturing involves the dynamics of physical processes and requires knowledge-based systems that combine simulation techniques with those of current ESs. They also present challenges in coordination because the expertise required is dispersed across a number of disciplines, between universities and industry, and between equipment manufacturers and users.

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**REFERENCES**

Beni, G. & Hackwood, S., Eds. (1985). **Recent Advances in Robotics.** New York: John Wiley.

Brown, T., Alexander, S.M., Jagannathan, V. & Kirchner, R. (1985). Demonstration of an expert system for manufacturing process control. Birtwistle, G., Ed. **AI, Graphics and Simulation,** 110-113 (January). La Jolla, California: Society for Simulation Research.

Bruno, G., Demartini, C. & Valenzano, A. (1984). Communication and programming issues in robotic manufacturing cells. **International Conference on Robotics, 84CH2008-1,** 361-367.

Silver Spring, Maryland: IEEE Computer Society Press.

Buchanan, B.G. & Shortliffe, E.H., Eds. (1984). **Rule-Based Expert Systems: The MYCIN experiments of the Stanford Heuristic Programming Project.** Reading, Massachusetts: Addison-Wesley.

Chandrasekaran, S. & Mittal, S. (1984). Deep versus compiled knowledge approaches to diagnostic problem-solving. Coombs, M.J., Ed. **Developments in Expert Systems.** pp. 23-34. London: Academic Press.

CSDL (1984). **Flexible Manufacturing Systems Handbook.** Park Ridge, New Jersey: Noyes Publications.

Day, J.D. & Zimmerman, H. (1983). The OSI reference model. **Proceedings IEEE, 71**(12), 1334-1340 (December).

Deal, T.E. & Kennedy, A.A. (1982). **Corporate Cultures: The Rites and Rituals of Corporate Life.** Reading, Massachusetts: Addison-Wesley.

Edson, D. (1984). Bin-picking robots punch in. **High Technology, 4**(6), 57-61 (June).

Engelberger, J.F. (1980). **Robotics in Practice: Management and Applications of Industrial Robots.** New York: Amacom.

Gaines, B.R. (1968). Varieties of computer - their applications and interrelationships. **Proceedings of IFAC Symposium on Pulse-Rate and Pulse-Modulation Computers.** Budapest (April).

Gaines, B.R. (1975). Analogy categories, virtual machines and structured programming. Goos, G. & Hartmanis, J., Eds. **GI - 5.Jahrestagung. Lecture Notes in Computer Science, 34**, 691-699. Berlin: Springer Verlag.

Gaines, B.R. & Shaw, M.L.G. (1982). Analysing analogy. Trappl, R., Ricciardi, L. & Pask, G., Eds. **Progress in Cybernetics and Systems Research Vol.IX.** pp. 379-386. Washington: Hemisphere.

Gaines, B.R. & Shaw, M.L.G. (1984). Logical foundations of expert systems. **Proceedings of IEEE International Conference on Systems, Man and Cybernetics, 84CH2063-6,** 238-247 (October). Halifax, Nova Scotia.

Gaines, B.R. & Shaw, M.L.G. (1985a). Expert systems and simulation. Birtwistle, G., Ed. **AI, Graphics and Simulation,** 95-101 (January). La Jolla, California: Society for Simulation Research.

Gaines, B.R. & Shaw, M.L.G. (1985b). From fuzzy sets to expert systems. **Information Systems,** To appear.

Gaines, B.R. & Shaw, M.L.G. (1985c). From timesharing to the sixth generation: the development of human-computer interaction part I. **International Journal of Man-Machines Studies, 23**(6), To appear (December).

Gaines, B.R. & Shaw, M.L.G. (1986). Foundations of dialog engineering: the development of human-computer interaction part II. **International Journal of Man-Machines Studies, 23**(6), To appear (December).

General Motors (1984). General Motors Manufacturing Automation Protocol. Warren, Michigan: General Motors Corporation.

Gomersall, A. & Farmer, P. (1984). **Robotics: The International Bibliography with Abstracts.** Bedford, UK: IFS Publications.

Groover, M.P. & Zimmers, E.W. (1984). **CAD/CAM: Computer-Aided Design and Manufacturing.** Englewood Cliffs, New Jersey: Prentice-Hall.

Gunn, T.G. (1981). **Computer Applications in Manufacturing.** New York: Industrial Press.

Hall, E.T. (1959). **The Silent Language.** New York: Doubleday.

Hartley, J. (1984). **Flexible Automation in Japan.** Bedford, UK: IFS Publications.

Hayes-Roth, F. (1984). The industrialization of knowledge engineering. Reitman, W., Ed. **Artificial Intelligence Applications for Business.** pp. 159-177. Norwood, New Jersey: Ablex.

Heginbotham, W.B., Ed. (1984). **Programmable Assembly.** Bedford, UK: IFS Publications.

Kafrissen, E. & Stephans, M., Eds. (1984). **Industrial Robots and Robotics.** Reston, Virginia : Reston.

Kolodny, H.F. (1985). Three bases for QWL improvements. University of Toronto: Faculty of Management Studies.

Kusiak, A., Vannelli, A. & Kumar, K.R. (1985). Grouping problems in scheduling flexible manufacturing systems. **Working Paper 84-16** (February). University of Toronto: Department of Industrial Engineering.

Mangold, V. (1981). The industrial robot as a transfer device. **Robotics Age, 3**(4) (July).

Mitchell, C.M., Govindaraj, T. & Ammons, J.C. (1984). Human-machine interface in the control of flexible manufacturing systems. **Proceedings of IEEE International Conference on Systems, Man and Cybernetics, 84CH2063-6,** 59-62 (October). Halifax, Nova Scotia.

Morgan, C. (1984). **Robots: Planning and Implementation.** Bedford, UK: IFS Publications.

Rathmill, K., MaConail, P., O'Leary, S. & Browne, J., Eds. (1985). **Robotic Technology and Applications.** Berlin: Springer Verlag.

Shaw, M.L.G. & Gaines, B.R. (1986). A framework for knowledge-based systems unifying expert systems and simulation. Birtwistle, G., Ed. **AI, Graphics and Simulation,** to appear (January). La Jolla, California: Society for Simulation Research.

Scott, P.B. (1984). **The Robotics Revolution.** Oxford: Basil Blackwell.

Toffler, A. (1980). **The Third Wave.** New York: Bantam.

Tver, D.F. & Bolz, R.W. (1983). **Robotics Sourcebook and Dictionary.** New York: Industrial Press.