THE DESIGN OF EXPERT SYSTEMS FOR PLANNING FLEXIBLE MANUFACTURING

Brian R. Gaines

Department of Computer Science, University of Calgary
University of Calgary,
Calgary, Alberta, Canada T2N 1N4.
&
Department of Industrial Engineering,
University of Toronto

ABSTRACT

A system combining expert system, database and simulation techniques is described which acts as a decision support system for planning flexible manufacturing. The system interacts with the manager of an integrated manufacturing system both at the equipment procurement stage and at the system operation stage to aid him in planning machine acquisition, placement and operation. It consists of four modules: a database of machinery; a machine grouping optimizer; a simulator of FMS configurations; and an expert system shell containing advisory rules on FMS. This paper gives the design considerations for the system, analysing the interplay between various forms of information technology in manufacturing, describing the expert system architecture, and outlining the knowledge engineering considerations involved in its development.

INTRODUCTION

We are in the midst of an intellectual revolution in manufacturing. Developments in numerically-controlled machine tools, materials handling, industrial robotics, and 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 [2, 28, 32, 36, 53, 57, 75]. 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 units coping cost-effectively with shorter runs of a range of products [8].

ii) There has been a shift from discrete manufacturing processes towards continuous flow processes based on robotic materials handling [13, 35].

iii) 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 [1, 41].

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 [41, 70].

v) There has been a shift from the use of people as attachments to production lines doing small repetitive sub-tasks towards the use of people in a supervisory role with emphasis on responsibility for complete products [41, 56].

Computer-based integrated manufacturing systems (IMSs) support such shifts by allowing 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 [29]. The flexibility, customization and localization offered are attractive but generate a new class of management problems [73]. 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 not readily available. Setting up a flexible production line requires different and higher-level skills than those required to operate it once running. Additional skills are required to design a flexible manufacturing system capable of handling a diversity of products [30, 42, 51].

Management support systems are needed for the planning, implementation, configuring and operation of IMSs [12, 48, 52]. Expert systems (ESs) provide a technology to cope with the diversity and complexity of the information involved [38, 43, 47]. However, an ES alone cannot cope with the volume of information about different machine tools and robots, the computation required in grouping and the provision of numeric simulations for interactive planning and testing. An adequate support system for managing IMSs involves the combination of ES and simulation-based decision aids with numeric computation, databases, communications, and, if it is to be used in operations [44, 54, 72], instrumentation and control systems. This paper is concerned with the development of such systems.

The next section gives an overview of the roles and interactions of different forms of information technology in supporting the management of a modern production unit. The final section describes a system combining a number of these technologies to provide a decision support system for planning flexible manufacturing.

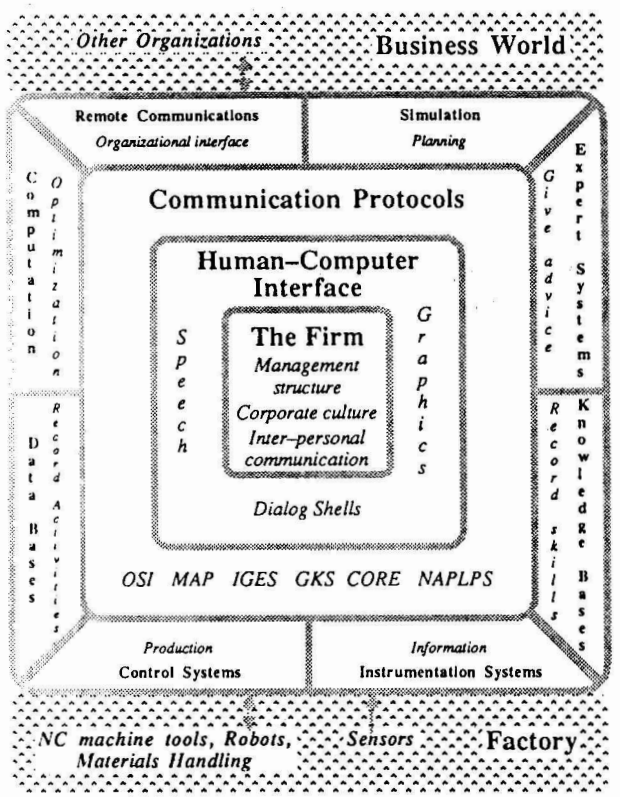

Fig. 1 Integrated Manufacturing System

INFORMATION SYSTEMS IN INTEGRATED MANUFACTURING

Figure 1 shows the information systems in a modern production unit using IMS techniques. The outer ring comprises eight basic information technologies 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, and the residual complexity shows the need to consider 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.

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 terms [31]. 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" [10] is in Hall's terms the *informal culture* of the firm. It pervades the organisation, is communicated by example, rarely documented, and changes only slowly or under pressures of survival.

The managerial structures and social processes of the firm are not normally treated as part of its information technology. However, it is possible to develop models of organisations that encompass both the people and the information technology supporting them, and Hall's cultural model is significant to knowledge engineering for expert systems [68]. In particular, in order to be successful the technical systems must be consistent with the organizational 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 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 operation highlights human-computer interaction as a critical technology. Advances in graphics, voice input/output and intelligent terminals have improved the technical repertoire for HCI [18, 65]. Contact with low-cost personal computers has increased computer literacy and user acceptance of the technology. The human factors of FMS systems are being studied [5], but 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 [24, 25]. 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 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 [9], 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 [27] as a major corporation 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. It is particularly significant in system design in offering the capability to collect operational and performance data on a scale currently impracticable [46].

The Applications Ring: Basic Technologies

The outer ring in Fig. 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 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-controlled 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

Three technologies in the outer ring of Fig. 1 are particularly relevant to decision aids for planning IMSs.

Knowledge Bases are distinguished from databases by containing inference rules rather than facts. The rules may 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 product design [39], FMS justification [74], job-shop scheduling [14], simulation [6], on-line process control [4] and robot control [40]. 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 conceptual difficulties currently that are impeding the rapid diffusion of IMS technology into appropriate industries. It is typical of the problems that because of their complexity and diffuseness they have to be "managed" and are very susceptible to support through ESs [33].

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. 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 [19, 58].

Simulation technology can be applied at a number of different levels in IMS [71]. However, the planning stage for flexible manufacturing is one of the most significant [78]. Designing a FMS involves the integration of a number of different tools, probably from different manufacturers and possibly in ways 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 [11, 45] and in computer-based communication and software support for the overall system [5]. 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 [15, 77].

The interactive decision-making process supported by ESs and simulation is a natural way in which to manage FMS implementation. It would seem feasible to ascertain the requirements and then use non-interactive computation to provide an optimal solution, but requirements are rarely well-defined and hard. Usually, a number of possibilities are open which are 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 comes 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 a designer knew in using an algorithm for grouping tools that a particular constraint he had applied was reducing the throughput by 20% then he 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-if"s constitute only a small sub-set of all possibilities. Interactive, sequential decision-making is an efficient method for determining such relevance.

A TECHNOLOGY MANAGEMENT SYSTEM FOR PLANNING FMS

The considerations in the first section of this paper and the systems analysis in the second section have led to the design of a decision support system for planning FMS which is part of a larger project on the development of *Technology Management Systems*. The system combines database, optimization, simulation, knowledge base, expert system and human-computer interaction technologies in the decision-support system shown in Figure 2. The system is designed to:

a) provide a simple, straightforward human-computer interface to a variety of tools for the design and management of an FMS;

b) use a knowledge-base of FMS design and procurement procedures to elicit the critical factors in the requirements for a FMS such as throughput, workpiece sizes, machining activities, precision requirements and so on;

c) use an expert system to advise on the feasibility of the applications, possible configurations and the types of equipment required;

d) use a database of machine tools and robots to match the requirements range against a variety of tool and materials handling configurations;

e) compute the optimum grouping of tools to meet the specified requirements;

f) make available 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;

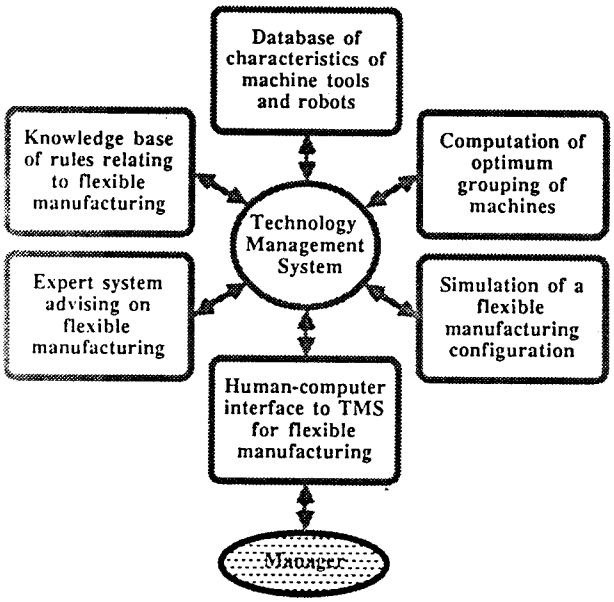

Fig. 2 Technology Management System for Planning Flexible Manufacturing Systems

g) when reasonable matches between requirements and performance are found, refine the design at a greater level of detail including operational factors and overall cost-effectiveness for a variety of job mixes and production runs;

h) finally, produce full specifications of the FMS including set-up procedures.

Knowledge Engineering for an FMS Technology Management System

The systems analysis required for a system encompassing the specified capabilities is a major task. This type of analysis has come to be termed *knowledge engineering* in the expert systems literature because it involves eliciting from experts the detailed knowledge processes that they use in performing the tasks involved [21, 22, 23, 34, 66, 67]. What is characteristic of major real-world systems, however, is that the knowledge required for their operation is not localised within a single expert but distributed over a number of specialists with diverse skills in different parts of the organisation. In expert system terms knowledge engineering is required over a very wide domain which cannot be encompassed by one person.

To cope with this problem it is necessary to fragment the problem domain into a number of *knowledge islands* which are characterized by their internal coherence—within an organization they usually correspond to functional specialities. The knowledge engineering for each island generally involves interviews with only one person or, if the relevant material is well-codified, analysis of a particular handbook or manual—the *Flexible Manufacturing Systems Handbook* [8] is a prime example of such codified knowledge. We have implemented techniques for carrying out the interviews automatically through computer interaction with the experts that elicit their constructs, their basic dimensions of thinking [16, 18, 59, 60, 61, 62, 63, 64], and are developing techniques for deriving the construct systems embodied in text automatically. The implicational structure of the construct systems can also be derived automatically and used to generate rules priming an ES shell [3, 26].

Knowledge Islands for FMS

Figure 3 shows a preliminary analysis of the main knowledge islands involved in a technology management system for planning FMS.

The ***overall requirements specification*** is the starting point of any feasibility study of FMS. The key constructs here were found to be the obvious pair: *low-volume—high-volume* and *low-variety—high-variety*, but other significant constructs were also elicited that affect the feasibility of FMS implementation such as *FMS-already-in-use—FMS-not-in-use* and *committment-to-existing-machines—new-plant*. The experience dimension and the difference between restructuring and green-field situations are obviously relevant to the decision-making but could be missed in an analysis that concentrated only on quantititative parameters.

The experience/resources dimension refines naturally to the knowledge island concerned with ***overall resources and constraints***. The volume/variety dimension refines to a quantitative description of the ***parts specification*** in parts per year and the number of different parts.

Figure 4 shows the conventional wisdom about the suitability of different forms of automated manufacturing dependent on the parts specification. Coding the knowledge involved for a computer shows up several features that tend to be forgotten in the conventional analysis. For example, what advice do you give when a requirement falls outside all the boxes?—the answer is to restructure the requirement by grouping or splitting as shown by the gray areas in Fig.4. Another complication is that part variety is not adequately represented by number of different parts—similarities between parts are very significant in system organization and feasibility so boundaries based on numbers alone are necessarily fuzzy. They can be modified by qualitative considerations of part groupings well before they are refined to detailed considerations of machining requirements.

Consideration of the resources and parts islands can give enough information to prime the ***overall system architecture*** island based on a more detailed version of Fig.4. This is in its turn can lead to ***rough performance*** estimates. Surprisingly it can also provide sufficient data for ***rough simulation*** using the fuzzy linguistic model approach [20, 76]. The performance estimates and simulation presentation form a basis for conclusions about the feasibility of an FMS for a particular requirement and the six knowledge islands involved may be grouped together as a *feasibility study area*. This sub-system is already a useful tool for the preliminary stages of FMS planning.

The knowledge islands described may be refined to a further level of detail on two main paths. The macro description of resources and constraints may be refined to a micro description that lists floor-plans, personnel, machines and so on. Much of this will be available in existing corporate administrative databases but some information will probably be missing. The macro description of parts may be refined to a micro description that completely characterizes each part and its manufacturing process [7]. Much of this will be available in existing corporate engineering and production databases but again some will be missing.

The ***parts specification*** leads naturally to a ***manufacturing techniques*** knowledge island which itself leads to that for ***tools required*** [37]. The parts and tools islands form another useful sub-system, the *grouping area*, where the ***optimum tool grouping*** knowledge island takes the detailed specification of parts and their machine utilization requirements and uses these to derive nearly optimal groupings of machinery.

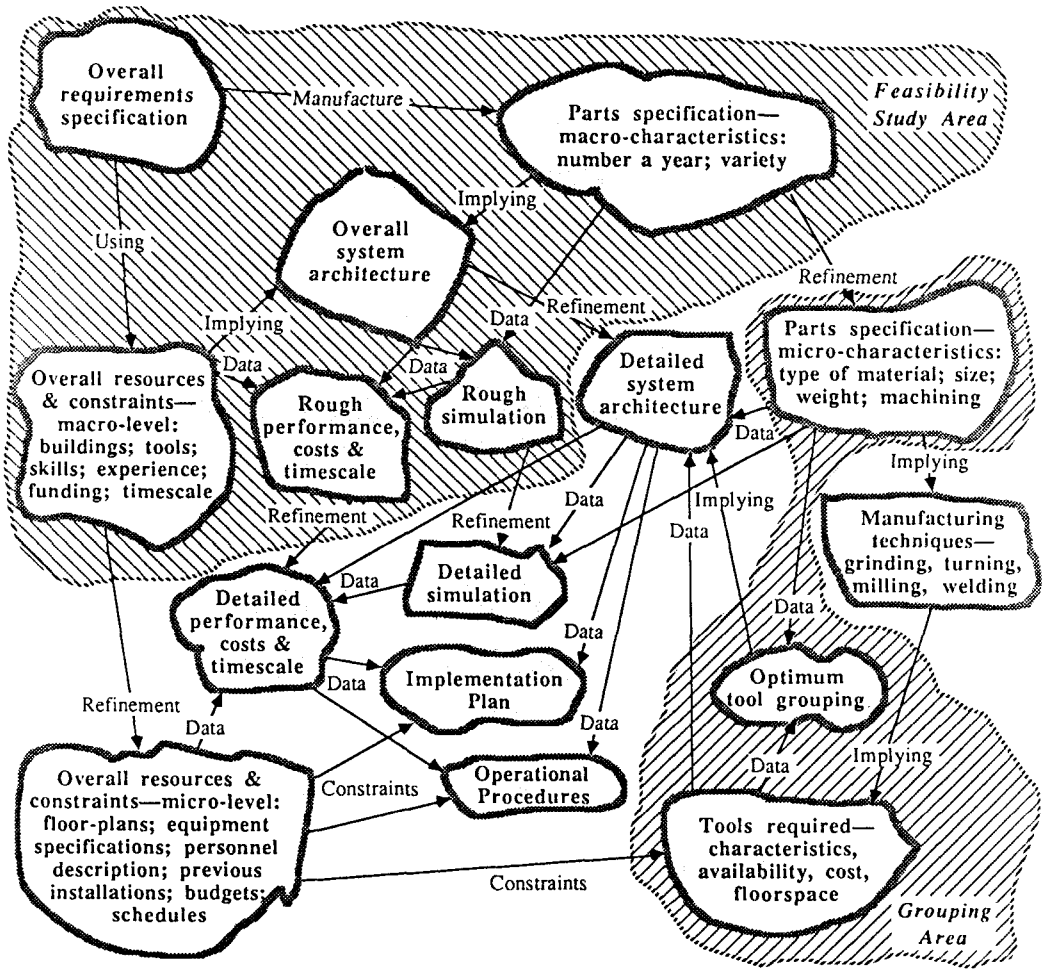

Fig. 3 Knowledge Islands and Areas in Expert Systems for Planning Flexible Manufacturing Systems

The central region of detailed architecture, performance and simulation is complicated more by the data requirements than by the complexity of computation required. It is unlikely to be cost-effective for any organization to gather the detail required on a wide range of machines and field-experience (although as widespread use of MAP develops much more data is potentially available at low cost). The knowledge islands in this area will evolve through successive refinements of those already described in a way determined by mainstream industry trends and cost-effectiveness. The phenomenon where leading suppliers tend to be used again because there is more knowledge of their products is one phenomenon of this region.

Implementation

The *feasibility study area* is being implemented on an Apple Macintosh in the *Nexpert* expert system shell which offers highly interactive facilities for forward and backward inference, hypothesis formation, explanation and graphical presentation of the structure of inferences and the knowledge base [55]. Figure 4 shows a Macintosh running a consultation in Nexpert on the overall requirements specification and system architecture. The database of machine tools and parts specifications will require facilities that go beyond those of this system [49] and is being implemented on a Sun 3. The FMS simulation is being written in SIMSCRIPT II.5 [69] as a module which takes in the conclusions of the expert system and gives a dynamic graphic presentation of the FMS operation and its performance parameters using SIMFACTORY. The *grouping area* sub-system is being implemented using algorithms previously described [42] on a Xerox 1108 Lisp machine in the ***Loops*** language which offers good facilities for simulation, graphic interaction and rule-based expert system specification. The integration of these sub-systems will be ad hoc through a communications network initially, with the decision on final configuration deferred to take advantage of new systems under development.

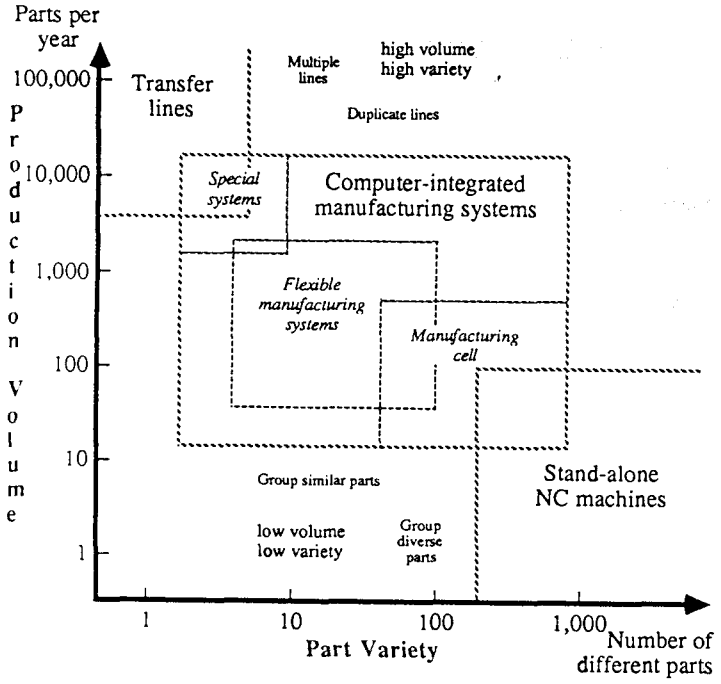

Fig. 4 Primary Variables Affecting Choice of Manufacturing Systems, and Strategies when Outside Ranges

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.

Decision support systems 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. However, the relevant technologies and knowledge are now at a stage where practical systems may be developed. The refinements of these systems through experience in their use, further analysis and data collection, will lead to the evolution of the totally-integrated manufacturing system.

ACKNOWLEDGEMENTS

Financial assistance for this work has been made available by the National Sciences and Engineering Research Council of Canada. I am grateful to my colleagues, Drs Kolodny, Moray, Shaw, Turksen and Vanelli for discussion and comments.

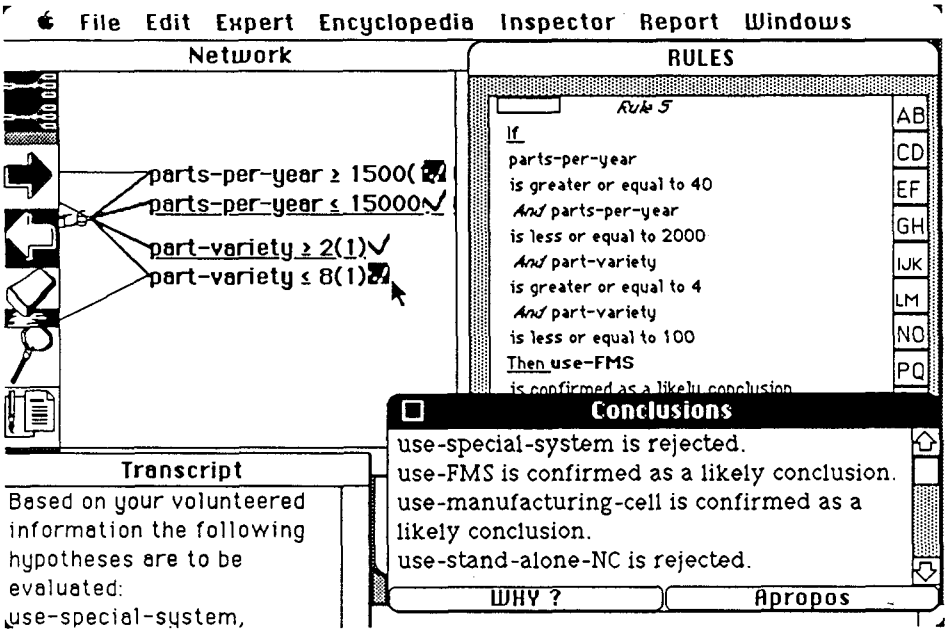

Fig. 5 Expert System Advising on FMS Feasibility

REFERENCES

[1] Aguren, S. & Edgren, J. (1980). **New Factories**. Stockholm: Swedish Employers' Confederation.

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

[3] Boose, J.H. (1984). Personal construct theory and the transfer of human expertise. **Proceedings AAAI-84**, 27-33. California: American Association for Artificial Intelligence.

[4] 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 Computer Simulation.

[5] 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.

[6] Bruno, G., Elia, A. & Laface, P. (1985). A rule-based system for production scheduling. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 35-39 (September). Montreal.

[7] Carringer, R.A. (1985). Integrating manufacturing systems using the product definition interface. **Autofact'85, SME Technical Paper MS85-1111**, 1-17 (November).

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

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

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

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

[12] Elavia, J.D. (1985). Where do I start with CIM? **Proceedings of Autofact'85**, 1.1-1.21 (November). Detroit, Michigan: Society of manufacturing Engineers.

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

[14] Fox, M.S. (1985). Knowledge representation for decision support. Methlie, L.B. & Sprague, R.H., Eds. **Knowledge Representation for Decision Support Systems**. pp. 3-26. Amsterdam: North-Holland.

[15] Gaines, B.R. (1986). Expert systems and simulation in industrial applications. Luker, P.A. & Adelsberger, H.H., Eds. **Intelligent Simulation Environments**, pp. 144-149 (January). La Jolla, California: Society for Computer Simulation.

[16] Gaines, B.R. & Shaw, M.L.G. (1981). New directions in the analysis and interactive elicitation of personal construct systems. Shaw, M.L.G., Ed. **Recent Advances in Personal Construct Technology**. pp. 147-182. London: Academic Press.

[17] Gaines, B.R. & Shaw, M.L.G. (1984). Dialog shell design. **Proceedings of INTERACT'84: First IFIP Conference on Human-Computer Interaction, 1**, 344-349. Amsterdam: North-Holland.

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

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

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

[21] Gaines, B.R. & Shaw, M.L.G. (1985). Foundations of expert systems. Kacprzyk, J. & Yager, R.R., Eds. **Management Decision Support Systems Using Fuzzy Sets and Possibility Theory**. pp. 3-24. Rheinland: ISR Interdisciplinary Systems Research, Verlag TUV.

[22] Gaines, B.R. & Shaw, M.L.G. (1985). Foundations of logic and reasoning in knowledge-based systems. Bezdek, J., Ed. **Proceedings of International Conference on Fuzzy Information Processing**. To appear. CRC Press.

[23] Gaines, B.R. & Shaw, M.L.G. (1985). Systemic foundations for reasoning in expert systems. Gupta, M.M., Kandel, A., Bandler, W. & Kiszka, J.B., Eds. **Approximate Reasoning in Expert Systems**. 271-281. Amsterdam: North-Holland.

[24] Gaines, B.R. & Shaw, M.L.G. (1986). From timesharing to the sixth generation: the development of human-computer interaction part I. **International Journal of Man-Machines Studies, 24**(1), To appear (January).

[25] 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, 24**(2), To appear (February).

[26] Gaines, B.R. & Shaw, M.L.G. (1986). Induction of inference rules for expert systems. **Fuzzy Sets and Systems**, To appear (April).

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

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

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

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

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

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

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

[34] Hayes-Roth, F., Waterman, D.A. & Lenat, D.B., Eds. (1983). **Building Expert Systems**. Reading, Massachusetts: Addison-Wesley.

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

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

[37] Kawabe, S., Okano, A. & Yoshida, T. (1985). Robot task planning system based on product modeling. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 471-476 (September). Montreal.

[38] Kempf, K.G. (1985). Manufacturing and artificial intelligence. **Robotics, 1**(1), 13-25 (May).

[39] Kim, S.H. & Suh, N.P. (1985). On an expert system for design and manufacturing. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 89-95 (September). Montreal.

[40] Kirschbrown, R.H. & Dorf, R.C. (1985). KARMA - a knowledge-based robot manipulation system. **Robotics, 1**(1), 3-12 (May).

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

[42] 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.

[43] Liu, D. (1985). Intelligent manufacturing planning systems. **Autofact'85, SME Technical Paper MS85-1070**, 1-17 (November).

[44] Maimon, O. (1985). FMS real time operational control. **Proceedings of Autofact'85**, 6.31-6.58 (November). Detroit, Michigan: Society of manufacturing Engineers.

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

[46] McCarthy, J.J. (1985). MAP's impact on process plants. **Control Engineering, 32**(11), 67-69 (October).

[47] McDonald, M.E. (1985). The smart foreman - expert systems for manufacturing. **Autofact'85, SME Technical Paper MS85-1112**, 1-9 (November).

[48] Miller, R.D. (1985). Simplification, management control, then intelligent automation. **Autofact'85**, 1-14 (November).

[49] Mills, R.B. (1985). Database machines tackle the CAD/CAM glut. **Computer-Aided Engineering, 4**(10), 61-64 (October).

[50] 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.

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

[52] Nassr, J.J. (1985). Considerations in establishing a CIM environment. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 68-72 (September). Montreal.

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

[54] Rhodes, J.S. (1985). The development of integrated control systems for flexible manufacturing systems. **Proceedings of Autofact'85**, 6.11-6.29 (November). Detroit, Michigan: Society of manufacturing Engineers.

[55] Roy, J. (1986). Expert systems in Nexpert. **MacTutor**, 2(2), 48-51 (February).

[56] Rubenowitz, S., Norrgren, F. & Tannenbaum, A.S. Some social psychological effects of direct and indirect participation in ten Swedish companies. **Organization Studies, 4**(3), 243-259.

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

[58] Shannon, R.E., Mayer, R. & Adelsberger, H.H. (1985). Expert systems and simulation. **Simulation, 44**(6), 275-284 (June).

[59] Shaw, M.L.G. (1980). **On Becoming a Personal Scientist.** London: Academic Press.

[60] Shaw, M.L.G. (1984). Interactive knowledge elicitation. **Proceedings of CIPS SESSION 84.** pp. 202-208. Calgary: Canadian Information Processing Society (May).

[61] Shaw, M.L.G. & Gaines, B.R. (1983). Eliciting the real problem. Wedde, H., Ed. **Adequate Modelling of Systems.** pp. 100-111. Berlin: Springer Verlag.

[62] Shaw, M.L.G. & Gaines, B.R. (1983). A computer aid to knowledge engineering. **Proceedings of British Computer Society Conference on Expert Systems**, 263-271 (December). Cambridge.

[63] Shaw, M.L.G. & Gaines, B.R. (1984). Deriving the constructs underlying decision. Zimmermann, H.J., Zadeh, L.A. & Gaines, B.R., Eds. **Fuzzy Sets and Decision Analysis. TIMS Series Studies in the Management Sciences, 20**, 335-355. Amsterdam: North-Holland.

[64] Shaw, M.L.G. & Gaines, B.R. (1984). Some experience in eliciting knowledge structures for expert systems. Smith, A.W., Ed. **Proceedings of the Society for General Systems Research International Conference.** pp. 605-614. California: Intersystems.

[65] Shaw, M.L.G. & Gaines, B.R. (1985). Developments in dialog engineering. **Proceedings of National Computer Conference, 54**, 493-499. Arlington, Virginia: AFIPS Press.

[66] Shaw, M.L.G. & Gaines, B.R. (1985). Knowledge engineering for expert systems. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 45-49 (September). Montreal.

[67] Shaw, M.L.G. & Gaines, B.R. (1985). Knowledge engineering tools for expert systems. Mitra, G., Ed. **Computer Models for Decision Making.** To appear. Amsterdam: North-Holland.

[68] Shaw, M.L.G. & Gaines, B.R. (1986). A framework for knowledge-based systems unifying expert systems and simulation. Luker, P.A. & Adelsberger, H.H., Eds. **Intelligent Simulation Environments**, pp. 38-43 (January). La Jolla, California: Society for Computer Simulation.

[69] **SIMSCRIPT II.5 Programming Language.** Los Angeles: CACI (1983).

[70] Skinner, W. (1974). The focussed factory. **Harvard Business Review**, 113-121 (May).

[71] Smith, C.A. (1985). The role of simulation analysis in improving the manageability of integrated systems. **Proceedings of Autofact'85**, 11.1-11.10 (November). Detroit, Michigan: Society of manufacturing Engineers.

[72] Spur, G. & Mertins, K. (1985). Interactive production control in CAM. **Proceedings COMPINT'85, IEEE 85CH2136-O**, 572-576 (September). Montreal.

[73] Sullivan, W.A. (1985). Computer integrated manufacturing program justification. **Proceedings of Autofact'85**, 2.34-2.55 (November). Detroit, Michigan: Society of manufacturing Engineers.

[74] Sullivan, W.G. & LeClair, S.R. (1985). Justification of flexible manufacturing systems using expert system technology. **Proceedings of Autofact'85**, 7.1-7.13 (November). Detroit, Michigan: Society of manufacturing Engineers.

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

[76] Wenstop, F. (1981). Deductive verbal models of organizations. Mamdani, E.H. & Gaines, B.R., Eds. **Fuzzy Reasoning and its Applications.** pp. 149-167. London: Academic Press.

[77] Wichmann, K.E. & Lenz, J. (1986). Integration of a Fortran-based simulation program and a Prolog-based expert system for intelligent manufacturing systems simulation simulation. **Conference on Intelligent Simulation Environments** (January). La Jolla, California: Society for Computer Simulation.

[78] Wortman, D.B. & Miner, R.J. (1985). The role of simulation in designing manufacturing systems. **Proceedings of Autofact'85**, 11.11-11.20 (November). Detroit, Michigan: Society of Manufacturing Engineers.