EXPERT SYSTEMS AND SIMULATION IN THE DESIGN OF AN FMS ADVISORY SYSTEM

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A system combining expert system, database and simulation techniques is described which acts as a decision support system for flexible manufacturing systems. The system interacts with the manager of a computer 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 optimiser; a simulator of flexible manufacturing system configurations; and an expert system shell containing advisory rules on flexible manufacturing systems. This paper gives the design considerations for the system, describing the expert system architecture, presenting the knowledge engineering considerations involved in its development, and illustrating its operation.

Expert systems (ESs) have become widely accepted as a significant new computing technology with high commercial potential and important industrial applications[45,57]. 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 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 reconceptualise 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 stengthening 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.

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 optimise decision and control against that model. The ES breakthrough was to realise that in certain problems where the controlled system cannot be modelled but people can do the task, it is possible to automate by modelling the person – that is, the new paradigm is to model the controller not the plant[15,16].

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[14,15]. The range of ES applications is now very wide and it is possible to see some patterns in successful systems. Hayes-Roth typifies successful ES applications as problems with the following characteristics[23]:

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

All these characteristics presume that:

- The knowledge required is available to the organisation.
- The problem is ineffective use of the knowledge through lack of people or lack of coordination.
- The knowledge can be made overt (knowledge engineering).
- 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 these requirements. The weakness is the limitations of current ES technology that make the last one, knowledge representation, a major impediment to many applications. These limitations stem from the very paradigm shift that was noted above as the breakthrough created by ESs, modelling the controller 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*[8], of going beneath the pragmatic rules used by people to carry out a skilled task and incorporating the more foundational premises on which those rules are based. The problem shows up in systems like MYCIN[6] for diagnosing microbial infections, 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 adequate to represent an existing skill but inadequate to encode the capability to adapt to change. Individual people may 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, and this will happen for some large-scale applications. However, the task of keeping very large numbers of highly specialised and customised 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[45].

This paper examines the integration of expert systems technology with other information processing technologies, particularly simulation, in the context of an advisory system concerned with the design and management of computer-integrated manufacturing systems. In particular, the knowledge engineering involved in the overall system design is described.

Computer-integrated manufacturing

We are in the midst of an intellectual revolution in manufacturing. Developments in numerically controlled machine tools, material handling, industrial robotics, and the understanding of human aspects of productivity and quality assurance, have led to new approaches to

manufacturing, the cumulative effect of which is revolutionary rather than evolutionary[2,22,25,29,44,48,56].

A number of major changes in manufacturing technology are apparent:

- There has been a shift from mass-production transfer lines highly optimised for long runs of a particular product towards flexible manufacturing units coping cost-effectively with shorter runs of a range of products[9].
- There has been a shift from discrete manufacturing processes towards continuous flow processes based on robotic material handling[11,28].
- There has been a shift from production of piece parts, perhaps at different specialist sites with subassembly and assembly at other sites, towards single-site integrated manufacturing[1,34].
- 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 minimise distribution costs[34,52].
- There has been a shift from the use of people as attachments to production lines and doing small repetitive sub-tasks towards the use of people in a supervisory role with emphasis on responsibility for complete products[34,47].

Computer-integrated manufacturing (CIM) 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[23]. The flexibility, customisation and localisation offered are attractive but generate a new class of management problems[54]. 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. A variety of additional skills are required to design a flexible manufacturing system capable of handling a diversity of products[24,35,42].

Management support systems are needed for the planning, implementation, configuring and operation of CIM[10,41,43]. Expert systems provide a technology to cope with the diversity and complexity of the information involved[31,36,39,40]. However, an expert system 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 CIM involves the combination of expert system and simulation-based decision aids with numeric computation, databases, communications, and, if it is to be used in operations, instrumentation and control systems[37,46,53].

Expert system technology can be applied at a number of levels in CIM including product design[32], flexible manufacturing system (FMS) justification[55], job-shop scheduling[12], simulation[5], on-line process control[4] and robot control[33]. However, the problem of major concern is the design stage at which the manufacturing system 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 that are currently impeding the rapid diffusion of new manufacturing 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 expert systems[26].

The following section describes the development of advisory systems combining expert system, database and simulation technologies in order to support the decision processes of managers responsible for configuring FMSs.

A technology management system for FMS planning

The considerations above 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, optimisation, simulation, knowledge base, expert system and human-computer interaction technologies in the decision-support system shown in Fig. 1.

The Technology Management System is designed to:

- Provide a simple, straightforward human-computer interface to a variety of tools for the design and management of an FMS.
- Use a knowledge-base of FMS design and procurement procedures to elicit the critical factors in the requirements for an FMS such as throughput, workpiece sizes, machining activities, precision requirements, and so on.
- Use an expert system to advise on the feasibility of the applications, possible configurations and the types of equipment required.
- Use a database of machine tools and robots to match the requirements range against a variety of tool and material handling configurations.
- Compute the optimum grouping of tools to meet the specified requirements.
- 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.
- 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.
- Finally, produce full specifications of the FMS including set-up procedures.

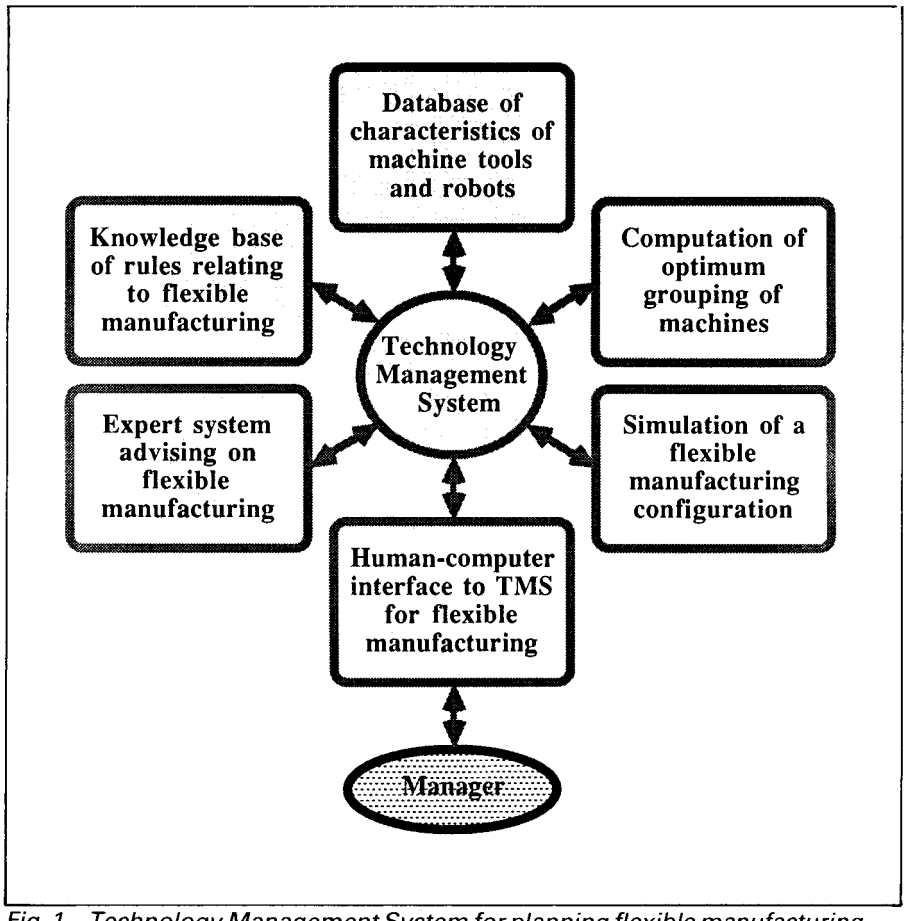

Fig. 1 Technology Management System for planning flexible manufacturing systems

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[17,18,19,27,50,51]. 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 characterised by their internal coherence – within an organisation 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*[9] 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[13,14,50,51], 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 expert system shell[3,20].

Knowledge islands for FMS

Fig. 2 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

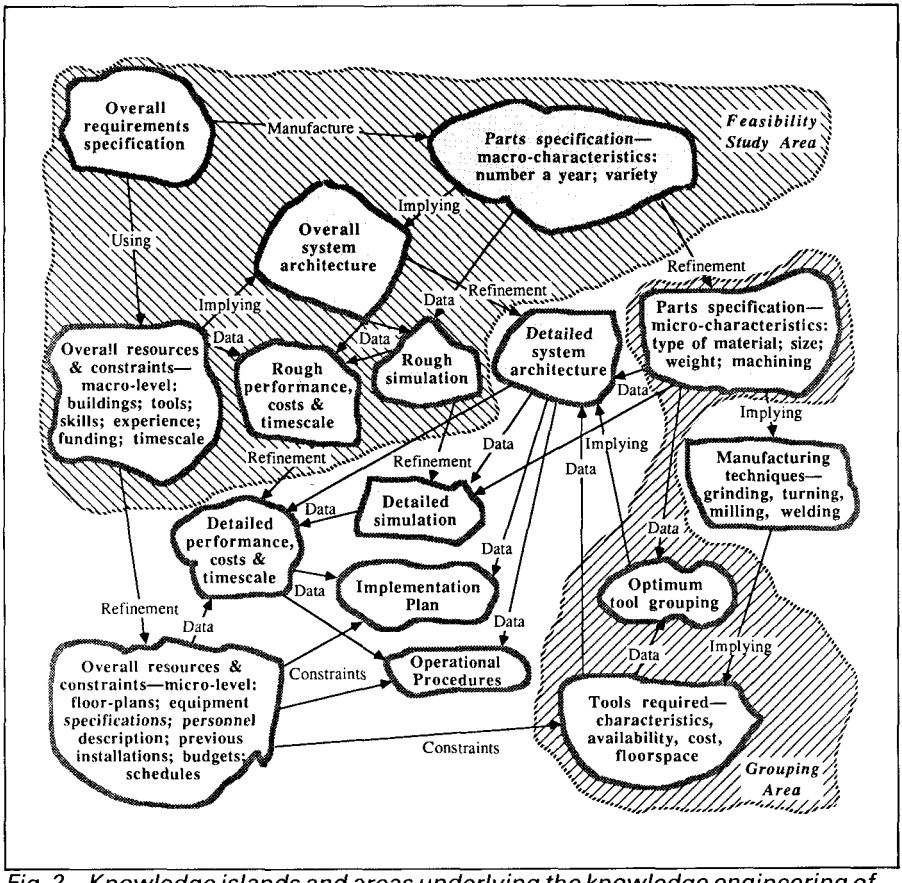

Fig. 2 Knowledge islands and areas underlying the knowledge engineering of expert systems supporting the planning of flexible manufacturing systems

obvious pair: *low-volume – high-volume* and *low-variety – high-variety*, but other significant constructs were also elicted 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 quantitative 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. Fig. 3 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

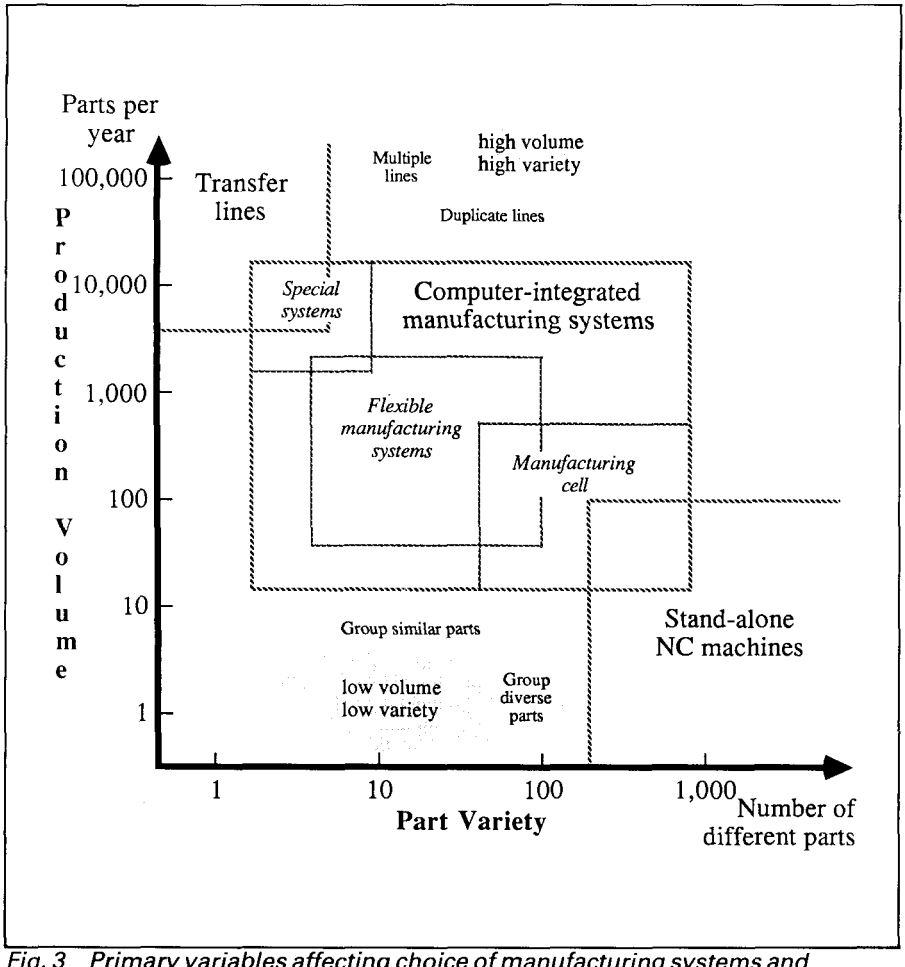

Fig. 3 Primary variables affecting choice of manufacturing systems and strategies when outside ranges

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 grey areas in Fig. 3. Another complication is that part variety is not adequately represented by number of different parts – similarities between parts are very significant in system organisation and feasibility so boundaries based on numbers alone are 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. 3. This 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[16,58]. 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 subsystem 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 administrative databases but some information will probably be missing. The macro description of parts may be refined to a micro description that completely characterises 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[30]. The parts and tools islands form another useful subsystem, the grouping area, where the optimal tool grouping knowledge island takes the detailed specification of parts and their machine utilisation requirements and uses these to derive nearly optimal groupings of machinery.

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 organisation to gather the detail required on a wide range of machines and field-experience (although as widespread use of the manufacturing automation protocol, MAP[21,38], develops much more data is potentially available economically). 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.

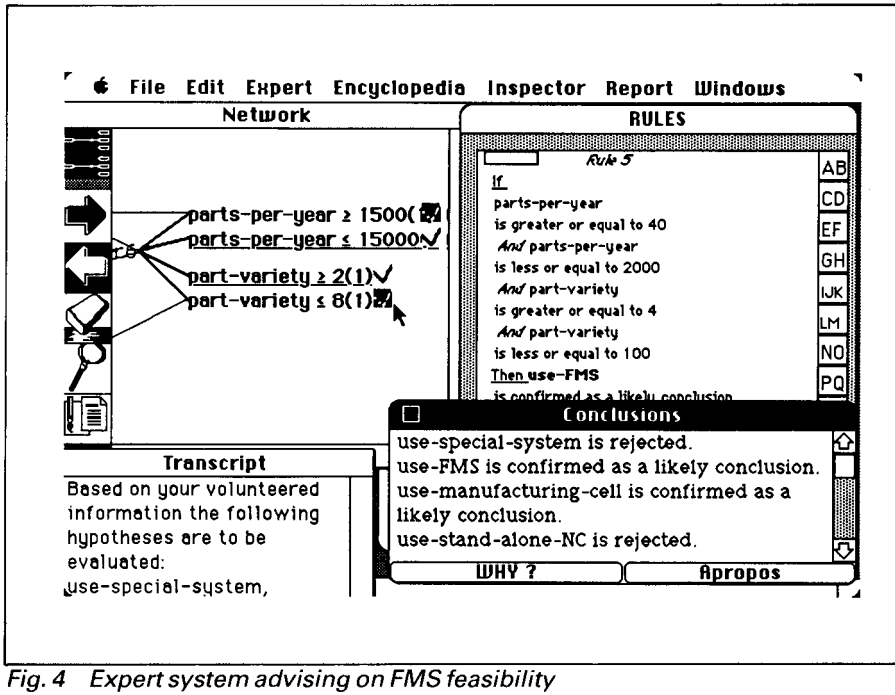

Fig. 4 Expert system advising on FMS feasibility

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. Fig. 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 either of these systems[41] and is being implemented on an Appollo network. The FMS simulation is being written in SIMSCRIPT II.5[59] 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. The *grouping area* subsystem is being implemented using algorithms previously described[35] on an Appollo workstation which offers good facilities for simulation, graphic interaction and rule-based expert system specification.

Concluding remarks

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. CIM is applicable to a spectrum of industry from comparatively small firms up to large organisations. 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 CIM present particular problems for today's expert system technology because manufacturing involves the dynamics of physical processes and requires knowledge-based systems that combine simulation techniques with those of current expert systems. 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.

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