COMPUTER-INTEGRATED MANUFACTURING: RESEARCH DIRECTIONS

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One of the most pressing issues in modern manufacturing industry is factory automation. High labour costs in many industrialised countries are forcing management to automate industrial plants in an attempt to increase productivity and competitiveness. This has created a massive market for the technology required for the so-called "Factory of the Future", incorporating such elements as Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Aided Manufacture (CAM), Programmable Controllers (PC), Computerised Numerical Controls (CNC), Robotics, Computer Aided Test (CAT), Automated Materials Handling, Communications Networks and Management Information Systems (MIS).

General Electric in the United States forecast a world market for factory automation of £21 billion by 1991. Another forecast, by Creative Strategies International in their report *"Western European Robotics,"* suggests a Western European market in robotics alone of £550 million by 1986. Computer Integrated Manufacturing (CIM) is a general term describing the integration of the above elements into an automated factory. When automated, the factory can be regarded as a Flexible Manufacturing System (FMS).

Robots are central to the concept of factory automation. Japan is pre-eminent in the league of robot users, followed by the United States, West Germany, Sweden and Britain. In the UK alone, it is estimated that there will be 2,000 robot installations by the end of 1983. The cost of robotics is only part of the cost of complete factory automation, however. Adaptability and flexibility are important aspects of automation and require an integrated approach such as that provided by a CIM system. In this respect, Japan is way ahead of all other industrialised countries. While the entire United States boasts about 30 flexible manufacturing systems, the Toyota Machine Tool Company of Japan alone has 30. Apart from the show-pieces of Japanese automation,

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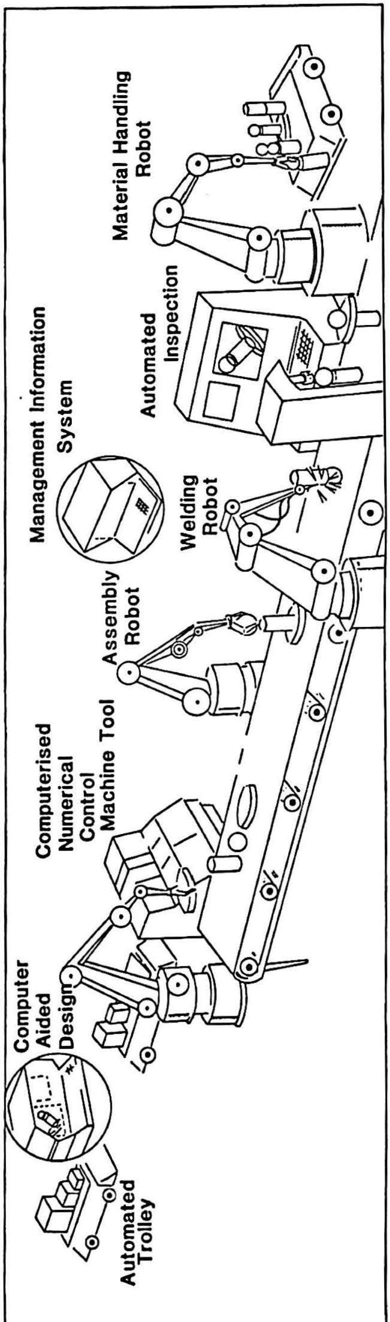
such as electric motor manufacturer Fanuc Ltd, and lathe/machine centre parts manufacturer Yamazaki Ltd, which operate very advanced automated factories, a wide range of manufacturing industry in Japan is highly automated. The United States boasted the first flexible manufacturing systems, one of which was developed by Cincinnati Milacron about ten years ago. Although the US still retains world leadership in the technology of automation, the Japanese have led the world in building and applying CIM technology.

This article examines some recent trends and developments in this area with particular emphasis on information system developments. Specifically, the need for a new approach to the development of Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP 2) systems for the automated factory is highlighted, in view of the superior information flow and accuracy inherent in automated plants.

Components of a CIM System

Figure 1 illustrates the individual components of a CIM system integrated into a single manufacturing plant. If a new product is to be designed, or if a modification is to be made to an existing product, a CAD system can be used. CAD systems were developed extensively in the 1960s and 1970s, particularly in engineering design applications involving product design and modification. The CAD system provides a means of easily examining various alternative designs interactively. In recent years quite sophisticated systems have become available. These can contain such features as graphical display in 2 and 3 dimensions, multiple user-defined viewpoints, zooming and rotation of views, and angular pictures with appropriate scaling. For particular products, the paths for machine tool cutting can be defined and interactively adjusted to produce a desired programme for a numerically controlled machine tool. Specialist calculations, such as finite element analysis, kinematic design, surface modelling etc., can be called up if appropriate. And the final product design can be linked to a Bill of Materials (BOM) from which engineering documentation can be produced and which can form an integral part of a Material Requirements Planning (MRP) system. CAD systems are now widely used in the design of microelectronic circuits, linking the design process to the processing and final tests of integrated circuits. Typically, wafers are processed through diffusion to a point where they await metallised interconnections of blocks (CMOS) and basic cells (bi-polar). The CAD system provides the design specifying the final interconnections. The designs are simulated and then automatically laid-out, fabricated, and tested. Such processes

Figure 1: *Computer Integrated Manufacturing*



are available commercially for both LSI (large scale integration) and VLSI (very large scale integration) technologies.

Materials handling has been automated by use of free ranging trucks and vehicles capable of moving materials about on a factory floor under some form of navigational control, and by the use of robotic handling of materials into and out of machining centres. Robots dedicated to this latter task have until recently been dumb ("pick and place") robots, but more intelligent second and third generation robots, guided by vision and touch, are being developed. Typically, micro-based robots operate on a three-coordinate (Cartesian or polar) system with optional rotations. The programmable control could be via a high level language with analog sensor inputs and high levels of accuracy and reliability, though with modest speed and acceleration capabilities, particularly for the movement of heavy loads.

Robotic developments in recent years have tended towards the development of robots generic to specific operations, such as loading and unloading machine tools, spraying, arc welding, spot welding and so on. For example, sensors have been developed at Oxford for controlling arc welding to make reliable joints in thin sheet metal even when the position of the edges to be joined is not known accurately. This is carried out by having a small sensor containing a laser and semiconductor camera chip which controls the welding arc, yet which can survive just a few centimetres from the intense heat of the arc.

Developments in the area of intelligent vision systems enable 100% quality control to be carried out by inspecting very large numbers of randomly oriented parts per minute. Production can be monitored at every key point on manufacturing lines, identifying characters on individual parts and finished products to ensure proper product identification. This use of computers to extract information using visual and other sensors is generally referred to as pattern recognition and image processing (PRIP). This covers such areas as robot vision, automatic inspection and measurement, surveillance, picture communications and optical character recognition. In industrial applications, the sensor generally used is a linear photo-diode array or a TV camera. By typically sensing the size and position of objects in the field of view, it is possible to control the manufacturing operation using a robot to ensure quality standards are achieved.

Finally, the supervisory management and control of the automated factory is effected via integrated management information systems covering stocks, master production schedules, bills of materials and material requirements planning, amongst others. These provide the necessary information for monitoring and controlling the entire system. Some of the developments in this area will be examined later.

The subsystems described above are typically interacting in terms of informations flows throughout the manufacturing operations. For example, a product modification incorporated in the CAD subsystem can be linked to the Bill of Materials or product structure file in the MIS subsystem to provide details of the modified product structure. Automatically the materials needed for the modified product can be obtained and the necessary changes to the manufacturing operations reprogrammed. The Computer Aided Test subsystem can be provided with modified test parameters, and ultimately test statistics fed back to the design office to be used for examining the effectiveness of the modification in terms of quality control. Such accurate and fast reporting allows the MIS subsystem to provide the basis for more effective control of operations. After the design modification, operations can then continue on the modified line at any specified volume with high levels of efficiency. Although there may be a learning curve in new product design, there is none on the factory floor. Clearly when the CIM subsystem elements can be interlinked in various ways for different subassemblies the possibilities arise for very rapid response to market changes and very efficient manufacture in small flexible units close to the market place. The implications for productivity improvements and competitiveness compared with conventional manufacturing operations are obvious.

Developments in CIM Research

In a recent paper presented to the Royal Society of Arts, Peter Davey of Oxford University Engineering Department outlined some areas in current Robotics research [Davey, 1983].

Future developments towards the fully automated factory are constrained by limitations in automation technology in three broad areas: perception, decision making, and action. Perception is necessary if a more "intelligent" form of robot is to be developed. For such second generation robots, the robot must have a model of its surroundings programmed into it, and also a model of any objects it is likely to encounter in its surroundings. It will not know these objects exactly but will use its sensory power to understand them. Unfortunately, current sensors have serious limitations. While they give good lateral information, they provide poor range information. If viewing techniques such as cameras or ultrasound scanners are used, it is necessary to process, understand, and analyse these objects in three dimensions, a task which involves computer speeds which were unattainable until very recently.

Once the robot can understand what is happening in its surroundings, it requires even more computer power in the controlling computer to derive the correct decision on future actions in real time. Such computations require again a three-dimensional model of all objects likely to enter the robot's shpere of action, and involves computations of considerable complexity. Even when decisions are arrived at, there are mechanical limitations on the actions of the robot. These range from problems of wear, imprecision and calibration, to serious difficulties which can arise when the robot arm carrying a heavy load deviates from a computed theoretical path with obvious dangers of severe collisions.

The limitations on hardware for robots used in factory automation, as has been mentioned, have resulted in the evolution of specialised generic robots for specific operations in specific industries. Robots have become dedicated to particular operations, e.g. spray painting in car manufacture, or assembly of circuit boards. Here the robot fixtures become specific to a particular product, and generally the speed of operation can be quite slow. Robots are still a long way from competing with the high speeds of dedicated "hard" technologies such as exist in textile manufacturing. The increased specialisation which has taken place in robotics hardware stands in contrast with software trends towards communicating subsystems within the factory linked by networks. One of the most powerful recent products is General Electric's CALMA 170 which allows designers to communicate not only to each other but also to other CIM subsystems.

Research over the next few years will concentrate on transferring the current "dumb" robots into second generation "commonsense" robots within the next five years, and into third generation "intelligent" robots within the next 15 years or so [Davey, 1983]. This will take place in parallel with a number of other related research developments. These will include improvements in conventional sensor technology for use in such applications as welding, and in the development of "smart" sensors capable of image processing and, for example, high speed factory inspection. Improvements will also be made in manipulators and materials handling technology used before, during, and after manufacturing operations. GEC Electrical Projects in Rugby have recently developed some highly innovative vehicles for moving materials about the factory floor.

From the conputational point of view, emphasis will be placed on software developments to enable three-dimensional modelling for determining, for example, if two mechanical parts occupy the same location, and also in geometric reasoning. While these calculations can be done offline, there is a need to develop on-line software for optimal robotic decision making and control.

One final area of research relates to the actual nature of the product being made and the cost effectiveness of each of the stages of manufacture. Each product feature has a value in functional terms and a cost in terms of robotics technology to make it. By product decomposition it is possible to isolate features which are expensive to manufacture and low in value terms to the customer. Work in this area is being carried out by Dr. G. Pitts at the University of Southampton.

MIS Requirements in the Manufacturing Environment

The MIS exists to support planning, decision-making, and control. Relevant MIS subsystems for manufacturing include capacity planning, master production scheduling, inventory control, shop floor control and costing. Because of the integrated nature of computer-based MIS, manufacturing subsystems must be considered in conjunction with other major subsystems with which there are strong interdependencies, such as sales forecasting, customer order entry, purchasing, general accounting, and so on.

The application of computers to information systems has taken place independently of the developments in the industrial automation area. There was a major stimulus in relation to manufacturing MIS in the early 1970s with the development of the concept of Material Requirements Planning (MRP) [see Orlicky, 1975]. MRP initially addressed itself to the problem of time-phased requirements for items which can be categorised as subject to dependent demand, e.g. the demand for components or raw materials, which is said to be dependent on the demand for the sub-assemblies or final products in which they are incorporated. The technique was well supported by the advances taking place in data base and related technologies, so MRP was embraced by the computer industry and software packages were developed and enthusiastically marketed.

Problems With MRP Systems

Applications of computer-based MRP systems were less than wholly successful, however. A 1975 survey indicated that only 44% of manufacturing companies believed that their new computerised manufacturing control systems were cost-effective [Sirny, 1977]. Table 1 indicates some of the main factors which might explain this relative lack of success [Barnard, 1982]. Miller (1981) attributes the modest performance of MRP systems to the following:

1. At the technical level, inaccuracy of the data base supporting material ordering;
2. Insufficient management commitment to the implementation of MRP;
3. Failure of managers to ensure that systems developed are consistent with strategic and organisational requirements of the company.

Table 1: *Factors Inhibiting Successful MRP Systems*

Invalid Master Schedules
Inaccurate Stock/On-Order Status
Inaccurate Bills of Material
Poor Engineering Change Control
Inappropriate Batching Rules
Shortage Levels
Undisciplined Suppliers
Inconsistent Batch Sizes/Timing

In many cases the basic concept of MRP and its likely ramifications were not properly understood by managers. A study by Morecroft (1983), using a system dynamics approach, indicated that ". . . when lead time of parts and materials is a function of load, faster responding schedules result in more variable lead times which, coupled with rapid MRP lead time updating, cause self-induced inventory cycles and a lowering of manufacturing efficiency".

The basic MRP concept is intuitively appealing, however. The technique has been extended to support order scheduling, capacity requirements planning, master production control, and has been developed into a total system which enables the company to effectively plan and monitor all factory and supplier operations. This overall system has increasingly been referred to as manufacturing resource planning, or MRP 2. It integrates into corporate financial and business planning systems, is capable of value and physical unit reporting for financial and operational control, and generally includes a simulation capability to test alternative plans and approaches.

Integration of Production and Information Technology

A logical area of development is the integration of production and information technology into an integrated computer-based system including computer-aided design (CAD), progressing through computer-assisted manufacturing (CAM) and the other activities noted earlier, and extending to include the manufacturing management information systems.

A possible technical infrastructure underlying such a system, as suggested by Young (1981), is shown in Figure 2. This hierarchical computer network relies upon powerful micro-processors linked to each other and to a higher-level computer by means of a communications network known as a local area network (LAN). At the first level are the process control computers which communicate directly with the process. The level 2 computer controls the microprocessors, and also interacts with a mainframe computer (Level 3), which handles most of the higher-level information system requirements of the organization. Sophisticated operating systems/communications software is obviously necessary for the system to operate effectively and efficiently as a whole.

CIM Implications for MIS

When fully implemented, the first major advantage in terms of MRP-type systems would appear to be the automatic creation, updating, and availability of the bill of materials (BOM) to all programmes which need it. This will have been made available through the CAD module of the CIM. Design changes will, as a matter of routine, be reflected in the BOM.

Immediate and automatic feedback of operational data from the work area to the higher-level computers is an obvious feature of the system described above. In this connection, the function of earlier shop-floor data collection devices is subsumed into the CIM. This in itself, if properly implemented, represents a major improvement over earlier systems from an information systems point of view. The exact location of every part and tool in the computerised system is known in real time, as is the work status of every CNC machine or robot, and the input, output and backlog for each operation. All this information is available to the manufacturing resource planning system, suitably aggregated at the higher levels, and to a level of accuracy that remedies some of the problems in earlier MRP implementations listed in Table 1.

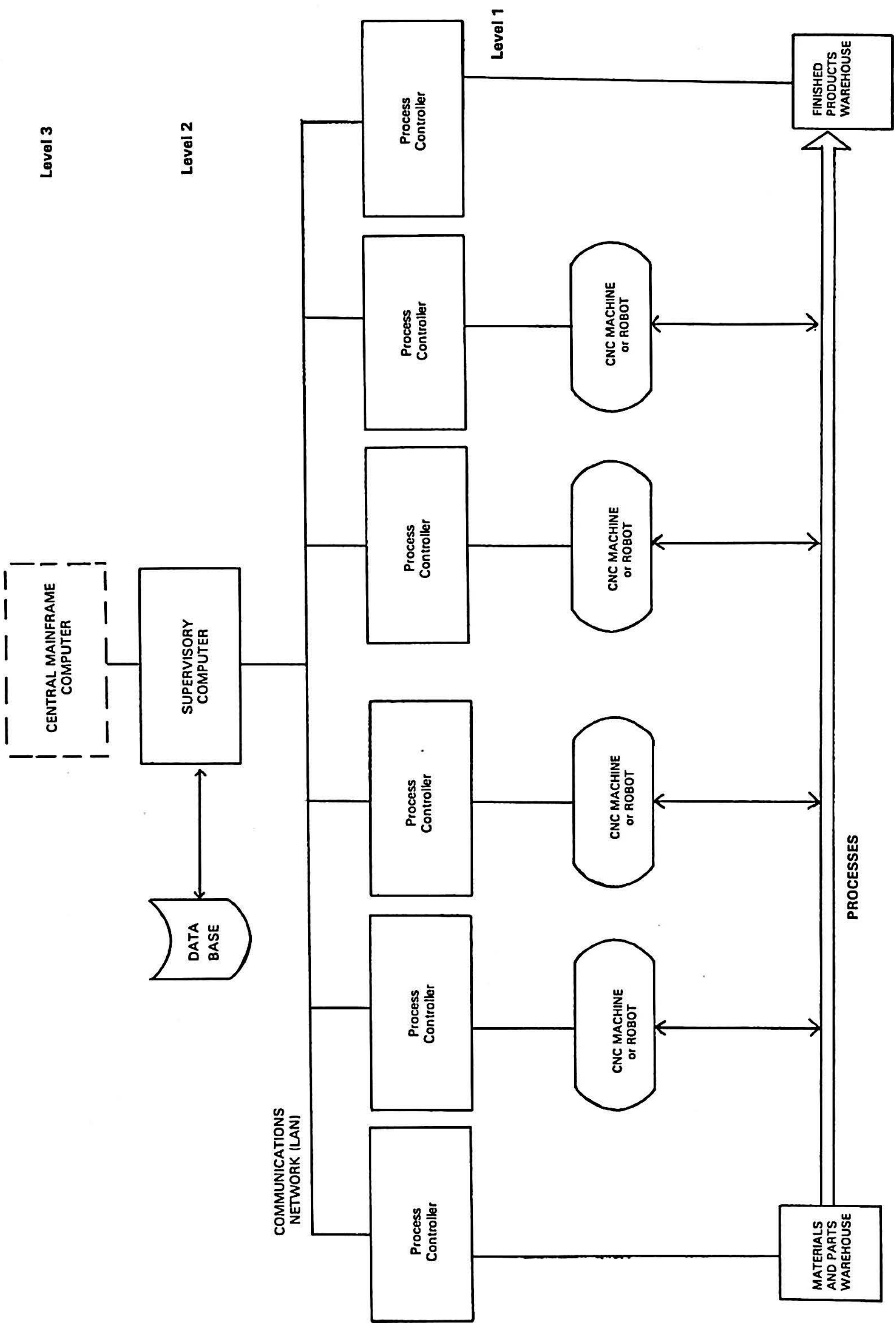


Figure 2: *Flexible Manufacturing System — Outline Structure*

Lead time (for both production and purchase ordering) may be monitored very closely, and if necessary, automatically adjusted by computer. Performance data by machine or work centre is also available on a current and cumulative basis, and this is an important input to other computer subsystems such as planned maintenance and capacity planning.

Decision support for management is also a feature of the CIM. Simon (1977) classified decisions across a continuum from programmed to non-programmed. The main characteristic of programmed decisions is that a definite procedure has been worked out to handle them so that they do not have to be treated 'de novo' each time they occur. Decisions are non-programmed to the extent that they are "novel, unstructured and unusually consequential".

In the completely automated factory, the same spectrum of problems from structured to non-structured must be addressed. Bullers et al. (1980) state " . . . such systems address decision-making only for structured problems. At the same time they provide little or no support to management for ill-defined, unstructured problems. When problems arise which have not been anticipated, control systems must search for appropriate responses through exploration of models and data which combine to form the basis for a reasonable decision." Production scheduling and sequencing problems, for instance, are generally quite complex, particularly in an environment where a number of machines (in this case computer-controlled) can perform a range of operations on a variety of parts, the operations necessarily taking place in a predetermined sequence. The CIM typically has a library of algorithms (stored as programmed routines) on the basis of which it selects and implements the appropriate decision: if the problem cannot be handled by a programmed decision, the system reports the problem for direct managerial intervention and resolution.

It is likely that the more global or aggregate type of decision will continue to be made by man rather than machine, but the thrust of much of the research in this area is to take more and more of the problems confronting operations management amenable to automatic solution. For higher-level decisions, computer-based decision support systems will tend to produce sets of alternative options, using advanced modelling software to guide management where this can be achieved profitably.

Future MIS-Related Research

Hardware/Software Optimisation

The tendency is for different hardware vendors to supply their own specialized system components, e.g. the computers at different levels in Figure 2 above are typically supplied by different vendors: the CAD system might be supplied by yet another vendor, specific robotics devices by others, and so on. The integration of these units into cohesive total systems requires sophisticated software and communications. This can be approached through laboratory environments which use full-size software and simulation techniques, to optimize the overall system.

Data Representation

Logical Data Models: This involves the determination of the nature of the data in an operations data base, the extent and type of interrelation of different data concepts or items, and the building of logical models that adequately represent these data and relationships. Simple file structures were sufficient in early computer-based systems: the development of data base management systems with its major data models – hierarchical, network and relational – added a new dimension: now, with knowledge bases oriented towards automatic problem-solving, more complex data structures and their underlying relationships, involving for instance semantic network models, are being developed.

Physical Data Organisation: Methods of storing, updating, retrieving and protecting the data in a more efficient manner are being advanced as a result of ongoing research into data base management systems physical design.

Generalised Problem-Processing and Solution Procedures

Research in this area considers the following questions – How is a problem represented (for the purposes of automatic solution)? What kind of software is necessary to identify the problem? How are solutions represented and stored? What algorithms govern the selection of a solution? How is the solution executed? Can the system 'learn' (automatically) from experience?

These questions involve the representation of knowledge within the system, the representation of logical procedures and an intelligence capability to select the right procedure. Basic research using the concepts of artificial intelligence is being increasingly applied to these problems. [See Bonczek et al. Ch. 5 (1981) for a generalized description of a number of problem-solving approaches in this context].

Development of Man-Machine Language Interfaces

It is necessary for humans to communicate with automated systems, to specify and change priorities and goals, to accept and interpret system feedback, and to intervene to cope with situations for which there is no programmed response. Natural (in this context 'near English') languages are regarded as desirable as the basis for this man-machine communication. In the operations area, language interfaces tend to be characterized by rigid syntax requirements, and this can inhibit the smooth operation of the system.

System Integration

There is a need for proper integration of detailed operational-level planning and control with higher-level information system functions such as forecasting, aggregate production planning, and finance and accounting. This involves the development of models which incorporate (i) specification of organisational and management goals, (ii) activities necessary to support these goals, and (iii) information system support for these activities. Information systems in this context would tend to be hierarchical in nature, along the lines drawn in Figure 2 above. A 'top-down' approach is typically applied.

Conclusion

Rapid advances are taking place in the development of computer-integrated manufacturing (CIM) systems, in relation to both production, and control/information technology. By its nature, research into this topic should be inter-disciplinary, involving specialists from operations management, computer science, artificial intelligence, decision and control theory, and other disciplines. A significant proportion of the research may be conducted in laboratory environments where systems can be simulated and evaluated. There is a clear need to identify products or sectors amenable to CIM in the Irish context, and to channel resources into appropriate research.

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