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Foreword
ICL manufacturing and logistics

ICL Manufacturing and Logistics (M & L) is an organisation of approximately 4000 people located on five major UK sites – in Kidsgrove (Staffordshire), Ashton under Lyne (Greater Manchester), Reading (Berkshire) and Letchworth and Stevenage (Hertfordshire). The Division, as part of the newly formed Product Operations, is responsible for supplying to ICL customers worldwide the full range of ICL products, whether in software or in hardware.

Supplying products to customers requires an organisation that not only manufactures those products but also delivers them to the customers, either from internal manufacture of from third-party suppliers. The organisation that supports these objectives consists of five major functions: Manufacturing, Systems Logistics, Purchasing, Spares and Engineering & Information Technology.

Within Manufacturing, products such as terminals and DRS Personal Workstations are assembled in Letchworth, medium and large systems in Ashton and printed circuit boards, network products and software are supplied by the Component & Software organisation based in Kidsgrove.

Purchasing is responsible for the procurement of all internally used commodities such as silicon, peripherals, printers and terminals.

System Logistics is responsible for the management of customer orders, from receipt of the order to delivery of the product, and of all ICL inventory worldwide.

Worldwide Spares is responsible for ensuring that the customer support units throughout the world have the material required to service ICL customers; this organisation includes a number of product repair centres.

Engineering & Information Technology (EIT) is the technical arm of Manufacturing and Logistics, responsible for setting technological direction as well as supplying a service in IT and product design.

The majority of the papers in this issue of the Technical Journal are written by members of EIT staff and reflect the range of technical subjects that are of particular interest to M & L business. M & L is concerned with the management of complex processes at controlled cost, a problem that can only be solved by the application of information technology. For this reason the Division has the largest IT spend in ICL, exceeding £10 million 1988 and covering the development costs associated with traditional Information Systems programming work, design and manufacturing integration, design productivity tools, 'Fifth Generation' computing and on-going systems support.

It is critically important that the Division is ready to support product designers and marketing groups in the manufacture, procurement and supply of new products. Reduction of the time to market is an important competitive weapon and vital to the Company's success. To achieve this the organisation must be forward looking, and the Engineering and Information Technology Group, being responsible for Manufacturing and Logistics' technical direction, has a particular interest in ensuring that world-class tools are available to ensure that this is achieved efficiently.

I hope all this is reflected in the papers that follow.

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FLEXIBLE MANUFACTURING

Flexible manufacturing at ICL's Ashton plant

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Abstract

ICL's manufacturing plant at Ashton-under-Lyne, Manchester, assembles the Series 39 mainframe and the S25 mini-computer ranges. The plant is nearing completion of an ambitious implementation of Flexible Manufacturing Systems (FMS) as the means of securing Just In Time manufacture.

1 Background

An account of the first phase of the Ashton plant, the Mercury production line for the automated assembly and test of the ICL Series 39 Level 30 machine, was given in the paper by R.K. Shore in the May 1985 issue of this journal (Ref. 1). Since then the functions of the plant have been considerably extended; the present paper summaries its present state.

The approach taken has been to subdivide the plant into a number of manufacturing cells based on process and size of product. Each cell is given its own control system, which ensures that the cell operates in accordance with a pre-defined inventory plan. Figure 1 is a simplified diagram showing the layout and material flow; here the box labelled "$1m^3$ ASSEMBLY FMS" represents the original Mercury line.

Products are "pulled" from the final assembly cells to meet firm customer orders. As the product kits are consumed by the assembly process the empty containers are returned to the upstream feeder cell output stores, and to MAIN STORES, for refilling.

Note that there is no box labelled OUTPUT STORE – the plant does not produce complete systems for storing. There is however an output store for SUB-ASSEMBLY FMS, and the refilling of containers with product kits results in the automatic raising of manufacturing orders to restore stocks here to the planned level, where appropriate. The execution of these orders then places a demand on MAIN STORES for the replenishment of the corresponding component kit. Planned stock levels are reviewed regularly and adjusted to conform to customer requirements.

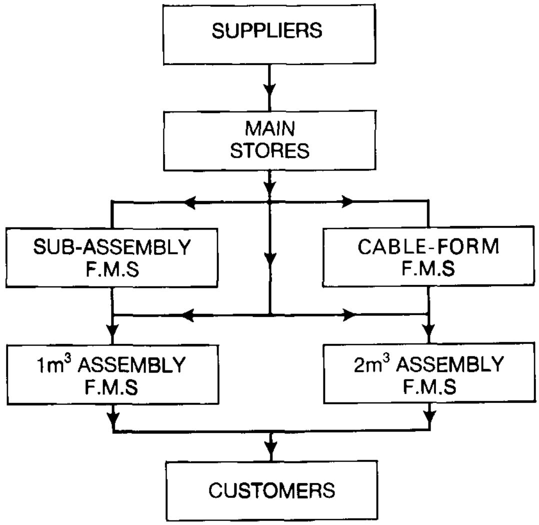


Fig. 1 Plant layout and materials flow

Clearly the whole process is "market driven", in that manufacture cannot occur except in response to an actual customer order. Further, before any manufacture is initiated the system checks that all the resources are available that are needed to ensure completion. This means that Production Management are freed from the traditional constant juggling of manufacturing schedules and reallocation of materials in line with ever-changing output forecasts. They can now concentrate on the process itself, to secure improvements in quality, costs and process times. Indeed, each cell is considered a business in its own right and is measured on the level of customer service achieved from the resources employed.

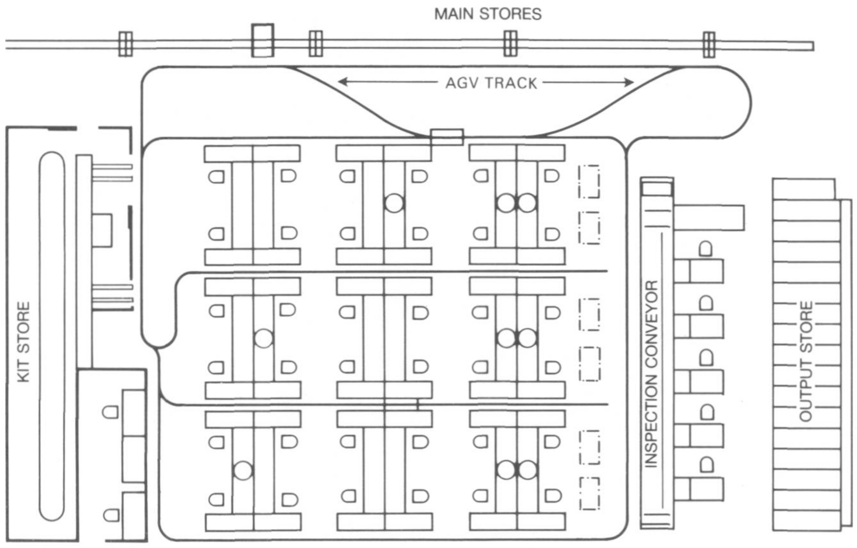
The $1m^3$ ASSEMBLY FMS and the SUB-ASSEMBLY FMS are complete; the $2m^3$ ASSEMBLY FMS and CABLEFORM are scheduled for completion in the autumn of 1988. As already mentioned, the first of these, the Mercury line, has been described earlier (Ref. 1); the remainder of this paper describes the SUB-ASSEMBLY FMS.

2 The SUB-ASSEMBLY FMS: Layout

This is shown diagrammatically in Fig. 2.

The major elements are as follows:

Automatic Kit Store. Based on a horizontal carousel and incorporating a pick/place device; this is used for storing sub-assembly kits in "totes", of dimensions 600 × 400 × 220 mm.



Sub-assembly FMS — Layout

Fig. 2 Sub-assembly FMS – Layout

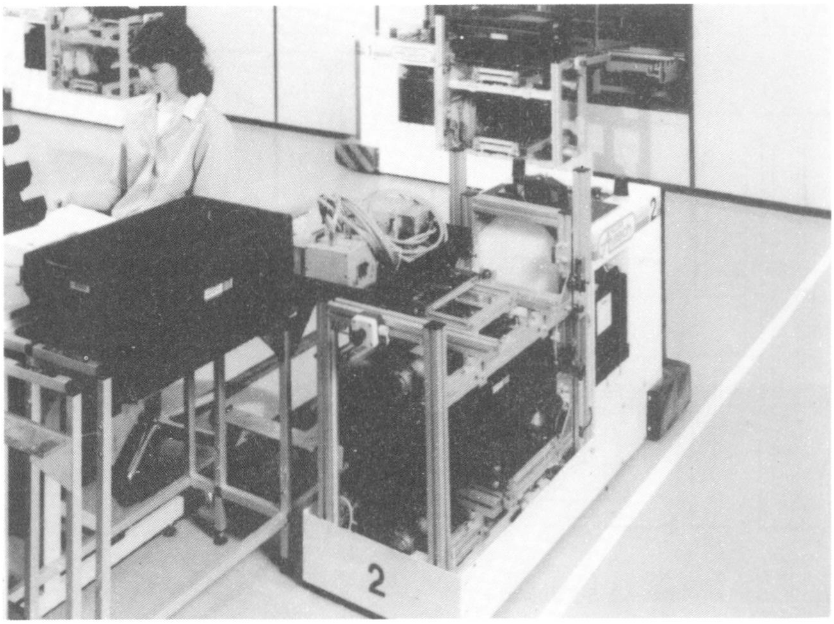
Assembly Benches. The cell has 36 Flexible Work Benches: these are flexible in that they are of standard design, each with stocks of a standard set of point-of-use materials. Any sub-assembly type may therefore be made at any bench, following delivery of the relevant kit tote.

Inspection Conveyor. This is a circulating conveyor provided for the receipt of completed sub-assemblies on trays, prior to their being placed in the Output Store. Whilst the process is largely "self inspect", certain products require a specialised test. Five benches are provided along the length of the conveyor for this purpose.

Output Store. This is provided for storing completed sub-assemblies on trays in gravity-fed racking which promotes "First In First Out" (FIFO) picking to the next build stage.

Transport. All transport within the cell is by Automatic Guided Vehicles (AGVs) controlled by signals carried by cables sunk in the floor. Their tasks include:

- delivery of kit totes, including trays, from MAIN STORE to Kit Store
- delivery of kit totes from Kit Store to Assembly Benches
- delivery of empty kit totes from Assembly Benches to MAIN STORE for refilling
- delivery of trays of completed sub-assemblies from Assembly Benches to Inspection Conveyor/Output Store
- delivery of empty trays from Output Store to MAIN STORES for inclusion with future kitted totes.



Automatic Guided Vehicles (AGVs) in the Ashton assembly plant.
AGV1 Delivering a refilled kit tote into the carousel
AGV2 Collecting finished subsystems (top transfer) and empty tote (bottom transfer) from a work bench
AGV3 Collecting a kit tote for delivery to a work bench

3 System architecture

This is shown diagrammatically in Fig. 3; the roles of the various units are as follows:

Cell Controller. Controls the operations of the cell by means of 2-way communication with the other units. The software is written in IAS COBOL and is implemented on an ICL S25.

Communication with:

AGV Controller is over RS232 via an ICL Stencil Box
Carousel Controller is by Network Designers' Tango Gate communications package
Factory Data Collection terminals is over RS422 via a proprietary Network Interface Box.

AGV Controller. Schedules AGV tasks in response to movement requests from Cell Controller or from local sensors. This is written in "C" and runs on an ICL Personal Work Station (PWS) under the QNX operating system.

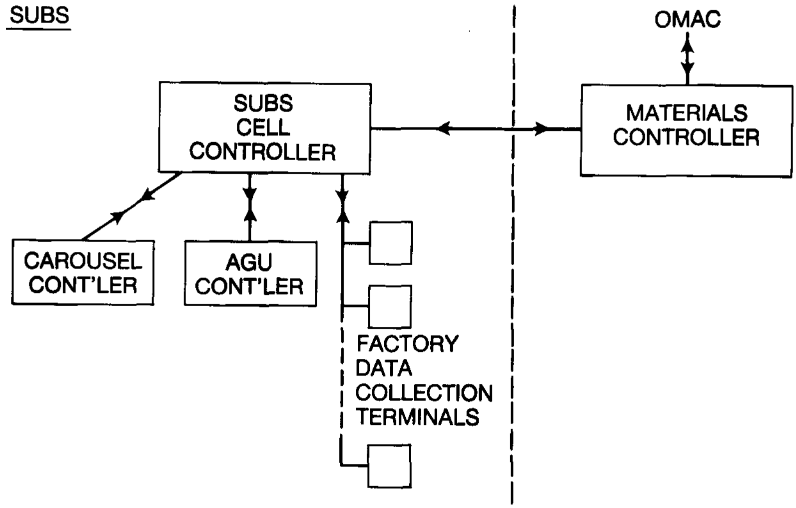


Fig. 3 System architecture

Carousel Controller. This is written in Pascal and runs on an ICL Quattro under CCPM. There are three modules that run concurrently and share a common database:

COMMS: Responds to all kit requests initiated by Cell Controller. Totes are assigned by number to specific requests, on the FIFO principle. The module does not withdraw the totes selected, but passes the requests on to AUTO for action.

AUTO: Handles all tote movements into and out of the carousel; withdrawals are made via a Request Queue maintained by COMMS and MANUAL (see below). As well as servicing requests for tote output the module constantly monitors the arrival of new totes from MAIN STORE.
Each tote is identified by a unique bar coded number which is checked by a Laser Scanner on the Pick/Place devices.

MANUAL: This module enables the operator to communicate with the system through the VDU terminal; this can be for enquiry, to "quarantine" a tote thought to contain suspect components or to request the withdrawal of a tote. The withdrawal can be from a specified Work Bench or from the Output Store audit point for checking quality or stock level. Again, the module does not withdraw the tote but passes the request to AUTO.

4 System operation

4.1 Operation parameters

The cell is set to operate in line with a planned level of inventory in terms of components and completed sub-assemblies. This level is determined by

MATERIALS CONTROLLER, which notes actual customer demand (from OMAC) and the inventory targets set by management and expressed as number of days' stock of each product type, from which it can calculate for each type the quantity that should be in store and the number of kit totes that should be in circulation.

4.2 Operating procedures

Empty containers are delivered from downstream cells by the AGV inter-cell transport system. The container number is entered into MATERIALS CONTROLLER and a Kitting List is produced. Confirmation of the pick is confirmed by entering the container number again, which reduces the balances of sub-assembly stock and advises the transport system that the container is ready for collection. At this point the container may either be returned to its "home cell" or be routed to MAIN STORE (for bought-out items) and/or to CABLEFORMS for (naturally) cableforms.

As sub-assemblies are issued to the kit for the next stage MATERIALS CONTROLLER monitors the actual stock balance against the planned stock and advises Cell Controller of any need for replenishments. The need to build is represented in Cell Controller as a prioritised list of product build records; this is sequenced in descending order of the percentage understocked and is adjusted in real time as build is initiated.

Each Work Bench has its own data collection terminal. An operator notifies the system when further work is required by pressing a single JOB SELECT key, which results in a suitable job being selected. The selection process first notes the operator involved (identified by a unique operator number through a sign-on procedure at the start of the session) and identifies the product set that that operator is permitted to build. In principle, all operators can build all products and the system holds a standard set that can be assigned to any operator; in practice, however, a particular operator may be permitted to build more than the standard set – in the phased introduction of a new product – or less – when in training.

Once the permitted set is established Cell Controller selects the highest priority job for which there is a free kit in the carousel. Selection terminates with a display of the job details on the operator's screen and a request to Carousel Controller to withdraw the selected tote. Once the tote has been withdrawn Cell Controller is informed and AGV Controller is requested to pick this up and deliver it to the correct bench.

Job completion is signalled by the operator pressing the appropriate key on the terminal, and, with a wand, entering the quantity built and the number bar-coded on the tray that will carry the completed sub-assembly. Acceptance of a completion message will result in Cell Controller automatically restarting any job that has been buffered at the Work Bench, thus enabling a new job to be selected for buffering.

Finally, collection by an AGV is requested. The tray of completed sub-assemblies is collected and delivered to Inspection Conveyor and the empty tote returned to MAIN STORE. Input of the tray number at Inspection reduces the Work in Progress count and increases Output Store stocks. Input of the tote number at MAIN STORE results in a review of the need to refill the tote in the light of the latest known demand.

5 Conclusion

At the time of writing (July 1988) the system described has been operating for only a few weeks, so it is too early to reach a firm conclusion concerning its performance. Early indications, however, are that it is achieving its objectives. Only those jobs are started which are required and for which there are no shortages of supplies, with the result that we are beginning to observe lower levels of Work in Progress and increased operator efficiencies.

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INFORMATION TECHNOLOGY IN MANUFACTURING

Knowledge based systems in computer based manufacturing

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Abstract

Computer Integrated Manufacturing (CIM) is a philosophy and a strategy for improving the competitiveness of a manufacturing business through automation and integration of all aspects of the business. The field of Artificial Intelligence (AI), and particularly the constituent discipline of Knowledge Based Systems (KBS), has a major part to play in making CIM possible. The range and scope of applications of KBS in manufacturing is large; this paper concentrates on those areas considered to be of high strategic value to companies that design and manufacture products in small batches, of which ICL's Manufacturing & Logistics organisation is representative. The areas reviewed are grouped into two domains of CIM, described as geometry oriented and administration oriented respectively. A summary of relevant developments in ICL is given.

1 Introduction

Manufacturing in its widest sense has been defined as 'a series of inter-related activities and operations involving the design, materials selection, planning, manufacturing production, quality assurance, management and marketing of the products of manufacturing industries'[1].

Manufacturing companies face a considerable variety of problems in the battle to survive and maximise profits in markets that are often fiercely competitive and ever-changing. In the 1960s and 1970s, with the growth of electronic logic circuits and microprocessors, leading manufacturers began to exploit some of the benefits of automating the physical process of manufacturing. In parallel with this, mainframes and minicomputers began to be used for planning of manufacture, for stock control, for financial and commercial transactions and for administration and management information. However, in the 1980s manufacturing industry throughout the world began to recognise that isolated applications of computers – the so-called 'islands of automation' – provided only limited benefits. Much greater benefits in terms of increased throughput, reduced operating costs and increased profits can be achieved through total integration of all the systems involved in manufacturing – Computer Integrated Manufacturing.

Today, CIM has taken on a wider meaning than it had in the 1970s and early 1980s. It is now often seen as an all-embracing philosophy and a strategy for being competitive in manufacturing; in many circles the concept of 'World Class Manufacturing' is being used to represent this competitive aspect of CIM strategies.

Most CIM solutions for integration of these 'islands' have involved the development of hierarchical architectures of applications and of communications networks which break down the applications into strategic, operational and physical levels. Examples in ICL are the Mercury system in the Ashton-under-Lyne assembly plant[2] and the KIDMAP ('Kidsgrove Manufacturing Automation Protocol') programme at the Kidsgrove printed circuit board production plant. These and similar applications outside ICL illustrate the current status and capability of CIM to provide flexible and responsive systems.

The ESPRIT CIM-OSA programme is aimed at defining the European CIM Open Systems Architecture, which will provide an all-embracing conceptual framework, adaptable to any actual situation. This will allow CIM uses to evolve in an open and decentralised manner: it will allow suppliers to aim for a well defined target in defining new products, and system houses to establish migration paths from existing applications towards more and more fully integrated systems.

2 The role of knowledge based systems in CIM

The diverse problems of manufacturing are not adequately addressed by conventional applications of computers, for the reason that their solution requires the simultaneous application of a range of both qualitative and quantitative knowledge. The field of Artificial Intelligence (AI) offers the potential for overcoming these limitations of conventional CIM applications.

The problems that have been addressed by AI methods can be categorised into one or other of the following: speech and vision recognition, natural language understanding, robotics, learning, theorem proving and Knowledge Based Systems. These are not exhaustive, nor are they completely disjoint, but they serve to provide a useful guide to the range of activities that come under the evolving discipline of AI[3].

AI aims to emulate the human intelligent and knowledgeable responses and control, by skilful application of heuristics. The field of AI that is particularly relevant to this paper is that of Knowledge Based Systems (KBS). These differ from other AI-based programs and from conventional optimisation techniques in that their performance is based on knowledge that is specific to a given problem domain. Such knowledge is programmed into the system as a declaration upon which separate control and problem solving mechanisms act; in a KBS, domain knowledge is explicit and is separated from other knowledge. As shown in Fig. 1, KBS form a subset of AI technology, and

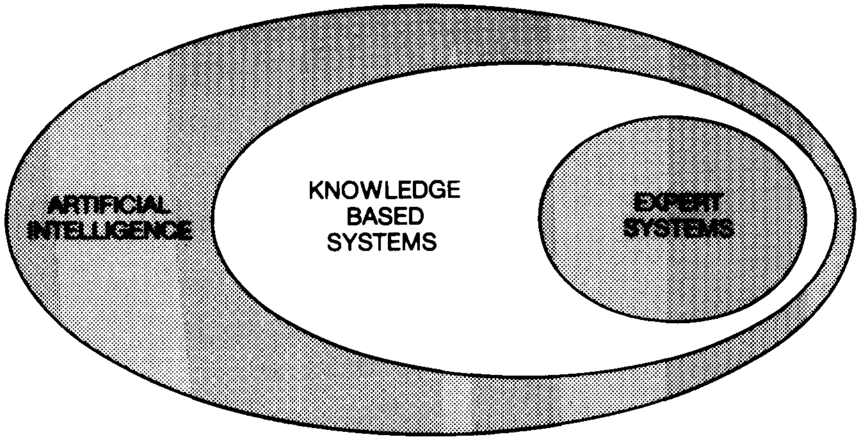

Fig. 1 Knowledge based systems

Expert Systems are a subset of KBS, aimed at using computer programs to apply expert knowledge in a narrow problem domain.

A KBS consists of a knowledge base, an inference engine and a user interface. The knowledge base contains the knowledge that is specific to the domain of application and includes simple facts, rules that describe the relations between the phenomena in the domain, and often methods, heuristics and ideas for solving problems. This knowledge can be represented in a number of formalisms, of which the two most commonly used are:

- *rule based* in which knowledge is represented as rules of the form 'IF condition THEN action'
- *frame based* using a network of nodes connected by relations and organised in a hierarchy; each node represents a concept that may be described by attributes and values associated with that node.

In a rule based system a rule interpreter compares the IF portions of the rules with the facts in the knowledge base and executes those for which this portion matches the facts; when a match is found the action specified by the THEN portion is performed.

There are two important inference methods that can be used by a rule-based system:

- *forward chaining* in which the rules are matched against the facts so as to derive new facts
- *backward chaining* in which the system starts with what it wants to prove and tries to establish the facts needed to prove it.

Knowledge Based Systems can be used for preserving and distributing perishable or rare expertise, managing complexity and change and solving complex and strategic problems that defy not only traditional programming techniques but also the more straightforward structured programming approaches.

Since manufacture in general, and CIM in particular, is such a broad field, Knowledge Based Systems are applicable here in many different areas. Spur, as reported by Crookall[4], distinguishes between functionally different types of data flow in CIM, a distinction that provides a convenient basis for understanding and grouping problem areas. There are characterised by:

- *geometry oriented* data flow: concerned with functions such as design, process planning, production processes, robotics, process control, quality control
- *administration oriented* data flow: concerned with marketing, order intake, procurement, purchasing, manufacturing planning and control, financial control, warehousing, distribution, after-sales service.

This is shown diagrammatically in Fig. 2.

The next sections give some examples of KBS applications in these two domains of data flow.

2.1 KBS applications in the geometry oriented domain

A large number of Computer Aided Design (CAD) systems are being used today in all areas of manufacturing industry. These applications offer immediate productivity increases but use only the designers' know-how and experience and/or empirical equations. Their effectiveness is therefore constrained by the limitations of the human designer. In many cases designers will lack knowledge about developments in other technologies such as materials, components and other manufacturing, with the consequence that companies may have to make considerable changes in product design and/or end up with an inferior design with lower than expected performance and costing more than the optimum design would have done.

In the geometry oriented domain most KBS applications so far have been in two main areas:

- *Computer Aided Engineering* (CAE), concerned with preliminary design and analysis for the optimum
- *Computer Aided Process Planning* (CAPP), concerned with producing an interface between CAD and CAM (Computer Aided Manufacturing). CAD–CAM together provide tools for automatic preparation of drawings and manufacturing data; CAPP involves interpreting geometric and topological data and the application of manufacturability know-how, to produce plans for the economic manufacture of products. One proprietary CAPP system, C-PLAN, is described in the paper by Jackson in this issue.

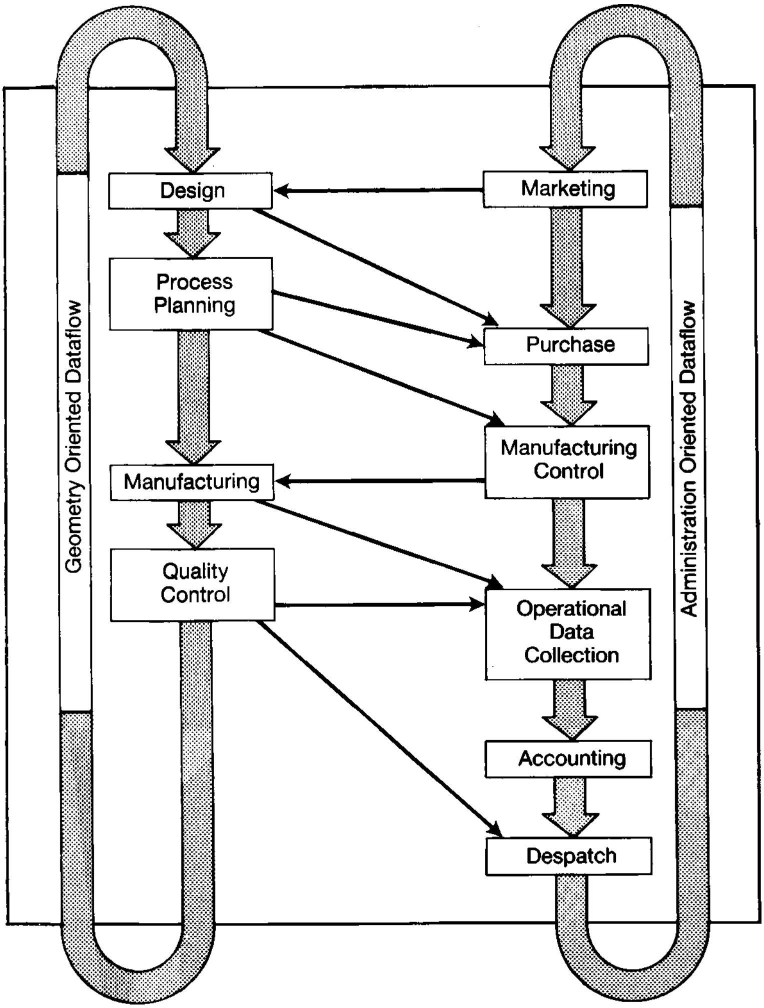

Fig. 2 Data flow in a CIM system

2.1.1 Applications in Computer Aided Engineering (CAE) Application of KBS here is a relatively new activity, largely confined to research institutes. Altan[5] outlines the current status of work in the metal forming area. He describes applications for designing for producibility by a given process and for the initial design of dies prior to process simulation. In this application, starting with the geometry of the finished part, a forging design is produced by an expert system in which the know-how is compiled in a structured fashion. This expert system also provides explanations of how it has selected and appplied the design guidelines.

Another example is PRIDE[6], which creates designs and analyses paper handling systems for copiers by representing knowledge of the design problems as a structured set of goals, in addition to the design methods, generators and rules.

2.1.2 Applications in Computer Aided Process Planning (CAPP) CAPP forms the vital link between CAD and CAM and has therefore received a great deal of attention from academic and applied research institutes. This is particularly noticeable in the metal working and electronics manufacturing industries, which are faced with converting geometry oriented data into finished products through a diverse range of manufacturing processes and methods.

To provide an effective CAD/CAM interface it is necessary to interpret the geometric and topological information that describes the part and apply manufacturability know-how to produce process plans prior to automatic communication for CAM. Early process planning systems relied on the Group Technology (GT) coding schemes for part descriptions; interpretation of the part was done manually and much detailed information was lost in the coding process.

Later generations of CAPP systems developed special descriptive languages to assist in describing parts, but this was still a manual process. An example is GARI[7], written in Mac LISP and consisting of a knowledge base and a general purpose problem solver. GARI produces a set of recommendations that define possible process plans; these plans are generated interactively by adding assertions to its database, which are then used to activate the rules. In this respect its behaviour is similar to a forward chaining inference engine. PROPEL[8] is another such development, inspired by GARI, and written in Common LISP.

The role of solid modellers in CAD for providing part descriptions is becoming established. Joshi & Chung[9] discuss the development of a CAD interface for automated process planning. The CAD model, containing a Boundary Representation (BREP) scheme, is used to make inferences about the part and to reason geometrically so as to extract information to drive the process planning system. In BREP features are represented implicitly and form the underlying structure for higher level features. One approach to recognising features is to use expert system rules, with a separate rule for each feature. For example, a rule to recognise a feature SLOT could be as follows:

IF face F1 is adjacent to face F2 and
face F2 is adjacent to face F3 and
angle between F1 and F2 $<$ 180 degrees and
angle between F2 and F3 $<$ 180 degrees
THEN faces F1, F2, F3 form a feature 'SLOT'

Recognition of features in such a case involves checking for the presence of each feature, one by one. The procedures use backward chaining and an exhaustive search strategy to match features in the part with the list of features being checked, and if used naively the computing time will grow exponentially with the number of features in the list. To avoid this a forward chaining procedure is used, in which topological information is represented by what are called Attributed Agency Graphs (AAGs) and recognition rules for generic features are written on the basis of the properties of these graphs.

Another knowledge based process planning system that uses a Boundary Representation (BREP) solid modeller is XPLANE (Expert Process Planning Environment)[10]. The development of this is part of a 50 man-year project at the University of Twente in Holland, aimed at delivering a working integrated system in 1990.

Two further systems of interest here are SIPS (Semi-Intelligent Process Selection) of Nau & Luce[11], and TURBO-CAPP of Wang & Wysk[12].

SIPS uses an approach to knowledge representation called *hierarchical knowledge clustering*. In this, knowledge (here about machining processes) is organised in a taxonomic hierarchy. Each process is represented by a frame rather than by rules of the 'IF conditions THEN actions' form, which are not suitable for process selection. It uses a branch-and-bound, least-cost-first search strategy rather than reasoning by forward or backward chaining. Knowledge is divided into two categories: static knowledge, internally stored as frames in a representation of 3-D objects; and problem solving knowledge, about operation selection, represented as hierarchical knowledge clusters in which archetype and item frames are found.

TURBO-CAPP is a knowledge based process planning system written in PROLOG. Problem solving knowledge is represented as frames or production rules, stored in three different planning layers of facts, of inference rules and of meta-knowledge respectively. The meta-knowledge is knowledge about rule manipulation.

2.2 KBS applications in the administration oriented domain

A manufacturing business, in common with other businesses, is subject to constant flux. Changes in the economies of nations, demand patterns, product mix, product designs, price of oil and raw materials – technological advances – competition – Acts of God – all kinds of events make the management of a manufacturing business a series of complex problems. Most of these problems are not amenable to traditional algorithmic solutions, and businesses continue to rely on human judgement and problem solving ability. Knowledge Based Systems are beginning to be useful in a growing number of these problem areas.

2.2.1 Application in Order Intake. When products are complex, matching a customer requirement needs the application of considerable expertise about how a combination of products can be configured, and such expertise is often scarce and not always available where it is needed – in the customer's office. In the computer manufacturing world both ICL and DEC have developed, and use routinely, expert systems to help: ICL's S39XC[13] to configure Series 39 mainframe systems to match customers' stated needs, DEC's XCON[14] to do the same for VAX systems. Corresponding expert systems are being developed by other engineering companies, using ICL's Advisor expert system shell.

Systems such as these provide the means for paperless order intake into CIM systems, and so contribute to reducing administrative delays and therefore overall lead times.

2.2.2 Applications in Manufacturing Planning. Manufacturing Planning consists of two major components, Materials Management and Distribution Management. Both are normally concerned with producing operational plans in weekly or monthly time slots for a one or two year time horizon. Larger strategic issues, like how many plants or warehouses should be maintained and where should they be located, are not the concern of this kind of planning, which aims to minimise inventory and cost and to maximise profits with given resources.

Support for materials management functions is provided by Materials Requirement Planning (MRP) systems and by related systems for controlling work in progress (WIP), inventory and production – as in ICL's OMAC (On-line Manufacturing Control), for example. Materials management starts with a Master Production Scheduler (MPS) which determines the product requirements for a one to two year period ahead; success here depends on how good the MPS is.

Distribution management is concerned with supplying customers with products through a specific distribution network, at minimum cost and to a given target of customer service level. Distribution planning systems help management to meet forecast demands and to overcome the lead time and capacity constraints of the supply chain – from vendors, production plants, distribution centres and warehouses to customers.

Manufacturing planning in CIM can involve many complex decision making processes that can have a significant impact on the competitiveness of the organisation. Decision support systems have been proposed to support a manager's needs for data and analysis, such as MADEMA[15]. Knowledge based systems can be applied here; Klingman & Phillips[16] describe an Intelligent Decision Support System (IDSS) that uses the knowledge of analysts, decision makers and experts in the relevant field to improve management support – this is shown in Fig. 3. The main functions of this are:

1 analysis of input data – to analyse, verify and modify the data that supports the system

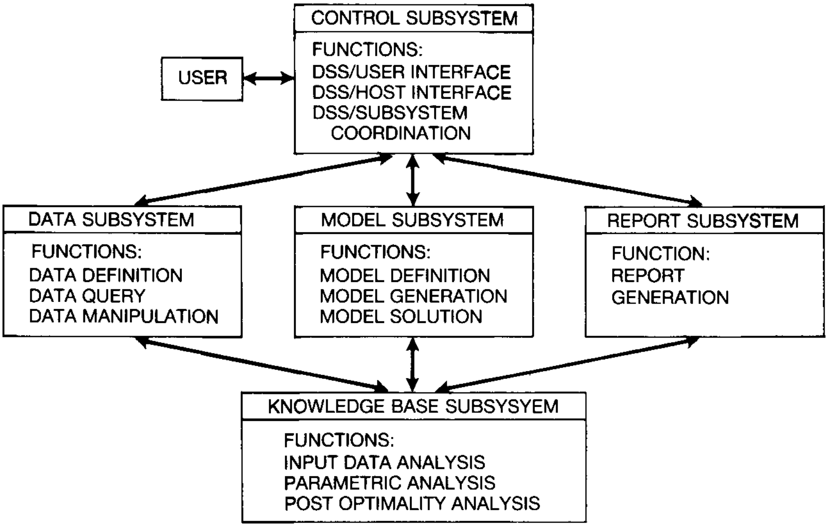

Fig. 3 Intelligent decision support system

2 parametric changes – to automate tactical 'what if' analysis by resetting certain parameters of the model, or to set parameters based on logical conditions
3 post-optimality analysis – to extract key information and various reports from the model solution, for evaluation of the model recommendation.

These functions of the knowledge based subsystem enable the system as a whole to overcome the limitations of data accuracy, by providing means for error checking, data validation, sensitivity analysis and exception reporting. IDSS used 'IF – THEN" rules for knowledge representation, rather than frames or semantic nets, to enable individual 'productions' in the rule base to be added, deleted or changed independently and to avoid cascading effects on other rules.

The following are further systems of interest in this domain.

SMS[16] is an IDSS for which the petrochemical company CITGO has reported multi-million dollar savings. This integrates an optimisation-based network model, a database management system, a fourth generation modelling language, flexible report generating capabilities and a knowledge base.

ESCORT (Expert System for Complex Operations in Real Time)[17], due to PA, was intended to complement the operations of existing process control hardware and software on a North Sea oil platform, to reduce the cognitive overload on the operators. Some 500 analogue and 2500 digital signals need to be monitored; ESCORT screens and interprets these signals and helps in exception management, providing advice and diagnosis in a crisis. Such time-critical operations require an efficient control regime, which in ESCORT is achieved by the use of a knowledge based scheduler.

Shop floor scheduling is a major problem that has been attacked by conventional algorithmic techniques. ISIS[18], applying KBS techniques, uses a constraint-directed heuristic search to explore alternative sets of resource assignments and execution intervals. Various alternatives are evaluated with respect to how well the decisions satisfy relevant preference constraints, as on work in progress, time objectives, machine preferences, personnel requirements.

ISIS is typical of predictive systems, whose effectiveness as a means of co-ordinating production is limited by the unpredictability of factory operations. Unanticipated events, like machine failures and part shortages, quickly invalidate predictive schedules, requiring reactive adjustments to be made. OPIS[19] – Opportunistic Intelligent Scheduler – extends ISIS by providing a framework for reaction. This is based on recognition of how a given status update affects the current predictive schedule, so as to determine what reactive action should be taken. OPIS's scheduling architecture has been designed to realise the integrated view of schedule generation as an opportunistic process that merges dynamic top-down problem decomposition with bottom-up reaction to problems encountered.

3 KBS developments in ICL Manufacturing and Logistics

The organisation of Manufacturing and Logistics is itself an example of an evolving CIM system. This section of the paper aims to give an overview of the KBS development activities there, the choice of application areas having been influenced directly by the perceived business needs.

3.1 Background

In common with most manufacturing enterprises, ICL's Manufacturing & Logistics strategy calls for an organisation that is not only cost-competitive but is also flexible and responsive. Flexibility and responsiveness can be gauged, relatively, in terms of how much more quickly the organisation can:

- introduce a new or changed product to meet changing market needs
- respond to a change in demand or product mix.

The costs and benefits of flexibility can be gauged in terms of the implications for revenue and market share, set against the cost of achieving this flexibility.

In high variety, low volume situations, as in ICL Manufacturing Operations, increased flexibility can best be achieved by investing in the reduction of the total manufacturing lead time from the concept of a product design to the delivery of that product to a customer. This has two components, as in Fig. 4.

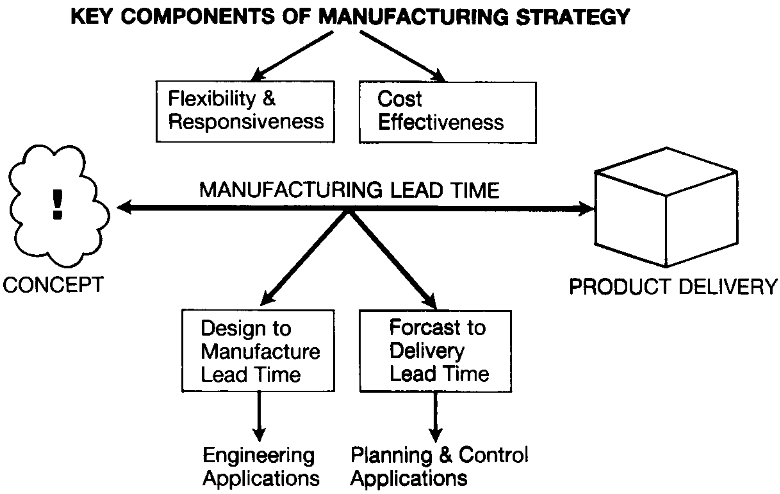

Fig. 4 Product lead times

1 the design-to-manufacture lead time: geometry oriented domain
2 the forecast-to-delivery lead time: administration oriented domain.

3.1 Applications in Design-to-Manufacture

The key projects in this area are aimed at applying KBS technology in the design-to-manufacture value chain shown in Fig. 5.

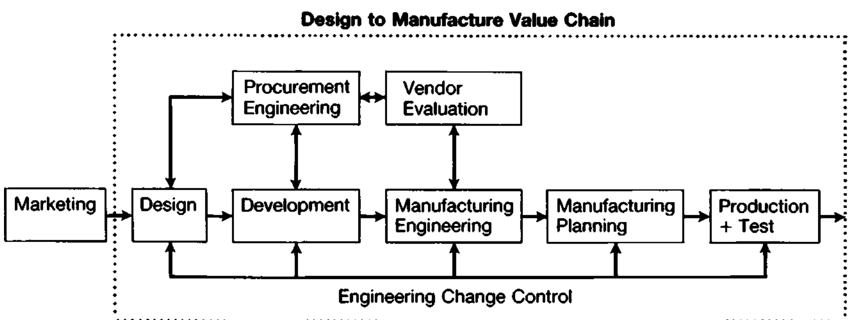

Fig. 5 Design-to-manufacture value chain

The purpose of this project is to develop a Knowledge Based Design Checker which can be integrated into a CAD system to enable designs to be produced for products that can be manufactured 'right first time'. Work is under way on developing a prototype design checker; this will include a Rule Acquisition Environment consisting of:

1 an Expert – Computer interface module
2 a rule induction engine
3 a validation/enquiry module.

The Rule Acquisition Environment will enable an expert to input expertise directly in the form that is most appropriate to the particular area – e.g. as question-and-answer, examples or templates.

The induction engine will convert example-based information into rules. The validation/enquiry module will enable designers to validate the rules provided by an expert against other external expertise; the validation tools used here will include simulation to provide 'what if' analyses.

3.2 Applications in Manufacturing Planning

Here, work to date has been focussed on the development of a Master Provisioning System[20]. KBS technology has been used in the design of two key prototype modules:

1 a Master Scheduler module
2 a Model Maintenance module.

The Master Scheduler module was aimed at enabling experienced planners to produce a top level manufacturing plan, taking into account forecast demand patterns and constraints of labour, machines, materials and money.

A prototype of this system has been developed in the KEE system from IntelliCorp, which provides the software infrastructures of AI/KBS techniques for the initial system. A KBS approach has been chosen because this is well suited to understanding the problem of a large amount of inter-related data where the relationships are often imprecise and are typically handled by humans, who make qualitative abstractions from the detail of the situation.

The features of KEE that are particularly valuable in supporting the initial system development are:

- the object-oriented programming style
- the representation of multiple worlds
- KEE connection for database access
- the wide range of predefined interface facilities, particularly in the human-computer interface (HCI)
- the rule system.

The proposed model maintenance module is concerned with the creation and maintenance of representative models of the manufacturing system. This can be in the form of an abstract Bill of Materials, capacity constraints and inventory and lead time constrains.

Further work is under way to define and develop applications to distribution logistics, to support strategic and operational distribution management.

Finally, there is MAES – MRP Actions Expert System – which is being implemented in ICL plants, to help in handling the large number of actions that result from the MRP process. This is described in the paper by Saxl, Phillips and Rudd in this issue.

3.3 Summary

The view taken in ICL's Manufacturing & Logistics organisation is that the applications of Knowledge Based Systems that will give the greatest benefits are those in the fields of product design and manufacture. Enormous competitive advantages can result from reductions in the product introduction and life cycle costs, and in the introduction lead times from the initial concept of a new product right through to 'right first time' production. The major effort is therefore being put into developing such applications; others are being developed, but it is recognised that their potential benefits are much smaller than those from applications that directly influence manufacturing costs and lead times.

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Open Systems Architecture for CIM

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Abstract

The goal of computer integrated manufacture (CIM) draws upon many of the traditional areas of manufacturing automation including CAD, CAM, MRP etc. ESPRIT Project 688, known as AMICE, has drawn upon the experience of 19 industrial and academic organisations to develop a European standard approach for the implementation of CIM systems known as the Open Systems Architecture for CIM (CIM-OSA). CIM-OSA is a modular framework for CIM development. The architecture is appropriate to a wide range of users who would select or reject components according to their need. Similarly, suppliers will have a free choice of which parts of the architecture they wish to specialise in and also the manner in which they wish to implement them. CIM-OSA supports the evolutionary approach. The total CIM-OSA model identifies a possible future manufacturing system towards which current systems can evolve, in discrete, manageable steps. This document describes the principal features of CIM-OSA and outlines the methodology used in identifying the system components that will be incorporated in future CIM systems.

1 Introduction

1.1 The Motivation for CIM

The need for improved automation in manufacturing industry is widely accepted, with considerable efforts being applied to achieve it throughout the industrial world. Improved methods for handling materials, processing them, mixing or assembling them into manufactured products have been developed over many years, indeed ever since the industrial revolutions of past centuries. In recent years computer technology has given impetus to the improvements in various ways, including

- online control of processes
- welding, painting and assembly by robots
- computer-aided process-planning
- computer-aided design and drafting
- computer-aided manufacture

More recently the scope of manufacturing automation has extended to include other aspects. Manufacturing, as a total business, is seen to include the marketing, selling and accounting aspects as well as the processes of design and manufacture.

Many areas of Information Technology (IT) have been applied to manufacturing automation, achieving appropriate benefits. However isolated areas of automation are occurring, the so called 'islands of automation', due to the use of incompatible products. Such 'islands of automation' are of considerable individual value but introduce problems because of the lack of communication between them. A typical example is found in an organisation where designs generated by a CAD system cannot be readily transferred to a production department using CAM because of data communication incompatibilities and the lack of a common database.

It is widely recognised that coordination and communication between separated areas of automation will bring additional benefits. The goal of computer integrated manufacture (CIM) is the appropriate integration of these 'islands of automation'. Integration at a basic level includes the physical and logical connection of processes by means of data communications technology operating to specified standards. At higher levels, integration implies:

- synchronisation of functions to ensure that tasks are carried out in the correct sequence
- the use of common data storage, in the form of databases accessed concurrently by a number of processes
- operating environments common to all processes
- activities subject to overall business objectives and able to react rapidly to changes in business objectives.

Economic pressures within industries and between individual companies are promoting competition on a global scale. Modern manufacturing is highly competitive and of necessity complex. Survival of an organisation depends on its ability to respond to the requirements of users, with business objectives focussing on the need for:

- products of good design and high quality
- variation and customising of products
- rapid response to changes in demand
- avoiding wastage of resources
- reduction of inventory and work in progress.

CIM with its exploitation of Information Technology is seen as a key factor in the development of industries capable of competing in world markets.

1.2 The Current Reality

Currently CIM means different things to different people. Ultimately it is to be considered as the complete integration of the components of the manufacturing enterprise. Few organisations have achieved even partial integration while many have no plans for implementing CIM and are unsure of how it may be approached. There is widespread misunderstanding of the nature of CIM which is often perceived as a dream, unattainable in the near future. Figure 1 shows the difference between this 'dream' and current reality.

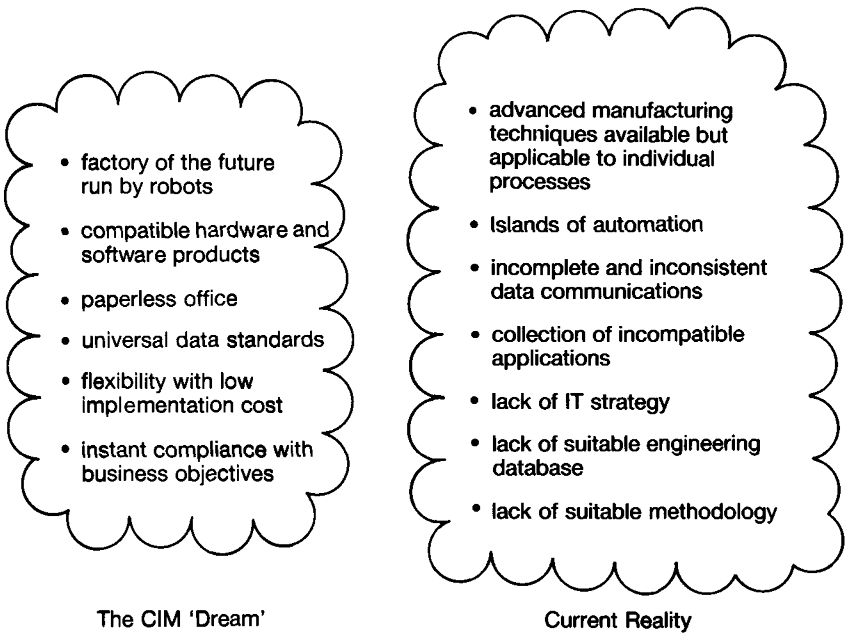

Fig. 1

It follows that there is no widespread agreement about the meaning of CIM and how it can be achieved. The complexity of the manufacturing enterprise itself is one of the reasons for this. Manufacturing is subject to a great range in type, scale and complexity and may be considered in many different segmentations, according to:

type of manufacture:	mass production, continuous flow, large batch, small batch, job shop
industry:	automotive, aerospace, clothing, pharmaceutical, food processing, electrical, microelectronics, etc.
scale:	large, medium, small
environment:	European, Japanese, third world etc.
production principles:	Just in Time, MRP etc.
objectives:	fast production, quality, variety, avoidance of waste material, etc.

Clearly there can be no single CIM solution, nor will CIM be applied to the same extent in all industries. The future needs of users and suppliers are summarised in Fig. 2.

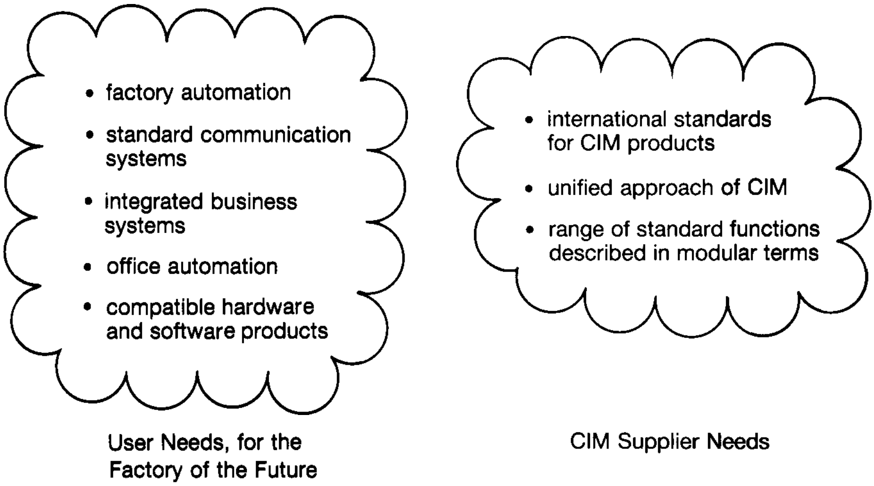

Fig. 2

To reduce the complexity to a manageable level a structuring concept has to be provided which will allow a common understanding of the subject. Generalised models are required to identify the principal components, processes, constraints and information sources used to describe a manufacturing business progressing towards CIM. The generalised models need then to be made specific by including aspects specific to particular manufacturing segmentations. Such a structured concept or architecture would be in the public domain and is therefore referred to as an 'Open System Architecture'.

Such an Open System Architecture must be described in terms of standard systems and subsystems in a modular manner. It would prescribe the basic building blocks of a working system for use by CIM designers and, in the process, provide an opportunity for CIM suppliers to specialise in selected areas of the structure without constraints on what must or must not be included.

There is a need for adherence to the developing international standards of OSI and MAP to enable communication and consistency between subsystems, but there is otherwise no constraint on how they are to be designed and implemented. The need for users to be able to select from a range of interfacing components available from a choice of suppliers will therefore be satisfied.

In summary there is a need for an Open System Architecture which provides:

- a general definition of the scope and nature of CIM
- guidelines for implementation
- a description of constituent systems and subsystems
- a modular framework complying with international standards.

1.3 Current Solutions

The majority of architectural system design methodologies relevant to standardisation bodies and/or to the work of ESPRIT (e.g. ICAM Project 1105; CAM-I DPMM; NBS AMRF; ESPRIT Pilot Project 34; ISO TC184/SC5/WG1 N15) address the main industrial environments of aerospace and mechanical engineering. None of these methodologies aim at addressing multiple environments by providing generalised concepts and solutions applicable across industry sectors. The wider context of the total enterprise as opposed to discrete parts manufacturing has only been partially addressed. Some attempts have been made to take into account complementary functions like Finance, Marketing, Strategic Planning, etc.

Furthermore methods for representing the dynamic behaviour of an enterprise, necessary to handle concurrent processes, is in general noticeable by its total absence from most of the current methodologies.

Currently the Business Environment is represented in a variety of (incompatible) ways depending on the particular design methodology adopted by a given user. Current methodologies all aim at creating particular models for a specific enterprise without providing finite restrictions on the types of functions that can be implemented. This makes it almost impossible for CIM component suppliers to provide readily available products since they do not have a stable broadly-based market place.

These methodologies tend to use graphical and/or verbal representations. This results in multiple diagrams if one attempts to define clearly alternative courses of action. The impreciseness of verbal descriptions makes it almost impossible to rationalise requirements and provide an optimal physical realisation. There is also a failure to distinguish between the tasks of creating a model and using that model to guide the implementation and operation of the resulting CIM system.

2 CIM in perspective

2.1 The Business Enterprise

A key concept of the Open Systems Architecture approach is the identification of a generalised 'business enterprise' and the separating of it from concepts of data processing, computer applications and manufacturing technology. The intention is that the manufacturing system is to be designed, modified and run under the control and motivation of the business enterprise. The technology is to be logically separate from the business but must respond to and serve the business objectives, whether static or changing.

'Islands of automation' referred to in the Introduction need to be joined and integrated into a responsive CIM system. The skill with which their functions are devised and integrated to serve the needs of the business will determine how much value will be added to the manufacturing process.

When designing a CIM system the business objectives can be assumed to be either dynamic or stable. In the former case the demands of the market, expressed as modified business objectives, are applied to the manufacturing operation to produce appropriate changes in response within very short timescales. As requirements change day by day, the manufacturing operation must adjust within the same timescales. This kind of CIM design and operation is sometimes referred to as 'pulling'.

Figure 3 shows this in diagrammatic form:

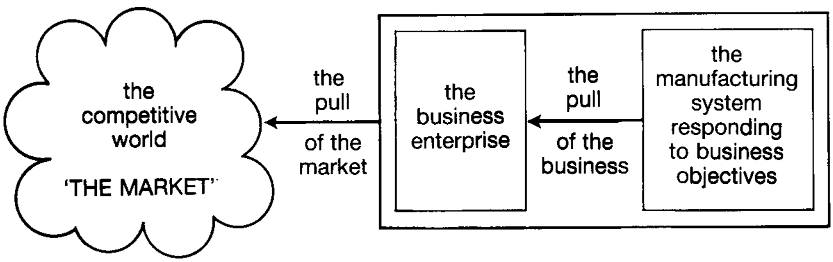

Fig. 3 The Market 'PULL' Determines both How the CIM System is Designed and How it Operates

Alternatively the current business objectives are assumed to be stable and are used to predict future requirements, resulting in a static design which cannot be modified as market pressures change. The design may provide short term efficiency but will reduce effectiveness as objectives change with time. This is referred to as a 'push' system.

In summary, the methodology provided by an Open Systems Architecture for CIM must cater for the identification of business objectives and the ability to configure and operate CIM systems in direct response to these objectives.

2.2 The Integration Problem

From the above description of the enterprise it would be logical to propose the development of CIM starting with the integration of business objectives and working towards the integration of applications, finally integrating the 'islands of automation'. Referring to Fig. 4 the steps would be:

(i) identify the business objectives
    e.g. strategic, tactical and operational plans
    market, product and production requirements
    scope and level of automation required
    cost and performance goals
    degree of flexibility in execution of operations

(ii) translate these into major, interacting business systems
e.g. decision support
business process monitoring BUSINESS
marketing feedback INTEGRATION
product/production simulation

(iii) support these business systems by identifying computer applications
e.g. decision support computing
marketing database management APPLICATION
order processing INTEGRATION
production control

(iv) design and connect manufacturing automation and data processing facilities
e.g. join CAD to CAM PHYSICAL
employ flexible manufacturing cells SYSTEM
computerised scheduling INTEGRATION

In practice integration has to begin from the existing situation of:

- manufacturing plant already installed
- already existing or planned 'islands of automation'
- communications standards and facilities still developing

Contrary to the supposed 'logical' order described above it has been necessary to integrate in the reverse order. That is:

(i) Join up the 'islands of automation' wherever potential benefit is identified and communication is possible
i.e. PHYSICAL SYSTEM INTEGRATION
(ii) Integrate subsystems using major computer application software
i.e. APPLICATION INTEGRATION
(iii) Hope that the applications can be eventually linked in order to support BUSINESS INTEGRATION.

Currently physical system integration has been achieved in many manufacturing enterprises and application integration is now under discussion. However the question of business integration has not been really addressed.

This is of course a typical example of the customary dilemma of whether to design from the top-down or the bottom-up. The major disadvantage of the bottom-up method is that due to lack of long term business objectives there is no guarantee that the process of integration at lower levels will eventually lead smoothly towards total business integration. Furthermore, it is found in practice that integration at lower levels has implications in the practical running of the enterprise at higher levels which have not been anticipated and may be in conflict with business principles and objectives.

While there is no simple solution to this dilemma, an Open System Architecture approach must propose a methodology which divides both the business and the manufacturing aspects of the enterprise into logical components. The resulting architecture would then allow implementation of

CIM to be carried out in an incremental manner starting with some area of the company and gradually evolving towards the final goal in accordance with identified long term business objectives.

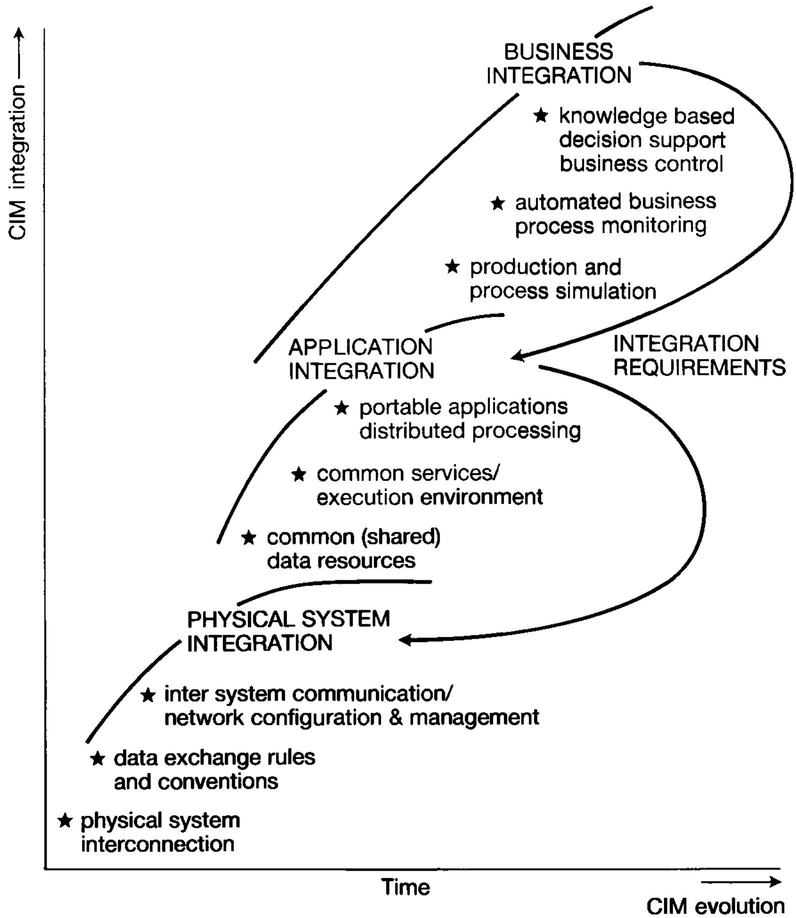

Fig. 4 The Integration Dilemma

3 The AMICE project

At this stage is it worth referring briefly to the origins of the AMICE project, set up to develop an Open Systems Architecture for CIM.

The name AMICE is based on the reversed acronym: European Computer Integrated Manufacturing Architecture.

The project is part of the European Strategic Programme for Research and Development in Information Technologies (ESPRIT) and is therefore a joint European initiative.

AMICE addresses the problem area of CIM systems design and implementation. It enjoys wide representative support with the participation of 19 industrial and academic organisations: CAP GEMINI SOGETI, Prime Contractor and AEG AKTIENGESELLSCHAFT, AEROSPATIALE, ALCATEL, AT&T EN PHILIPS TELECOMMUNICATIEBEDRIJVEN, BRITISH AEROSPACE, BULL, COMPUTER RESOURCES INTERNATIONAL A/S, DIGITAL EQUIPMENT G.m.b.H., DORNIER, GEC, IBM DEUTSCHLAND G.m.b.H., ICL, ITALSIEL, PHILIPS AND MBLE ASSOCIATED, SELENIA, SIEMENS, VOLKSWAGEN AG, WZL-AACHEN UNIVERSITY.

Its objectives are, broadly speaking, to devise and publicise a CIM Open Systems Architecture of the type described above. The main objectives of the project can be summarised as follows:

- to enable fast, economic utilisation of advanced technologies in industry
- to ensure long range, evolutionary CIM implementation and growth
- to enable and support independent development of CIM building blocks

It will meet these objectives by:

- establishing a common understanding and terminology for CIM
- providing models as a reference for CIM planning, design, implementation
- suggesting and promoting relevant standards in mature areas

4 The AMICE approach

4.1 The Use of Models

The broad objectives of the AMICE project, referred to above, are to provide a working description of CIM and its scope. CIM-OSA comprises a number of major components referred to as models, which themselves contain a number of interrelated components. The model is a description of a system which is used to illustrate selected characteristics. It enables discussion, and evaluation of the supporting system designs, of which there may be many possible.

It is worth noting the characteristics of such models:

- Models may be general (often referred to as generic), or specific.
- Models change with time.

General models do not refer to any particular industry or organisation. Specific models can be specific in various ways.

For example:

- by industry: specific to the electronics industry
- by manufacturing type: specific to mass production
- by organisation: specific to a particular organisation.

As the functioning of a business changes then it is appropriate to re-describe it as a different model. The 1989 enterprise model of an organisation may be distinct from the 1987 model.

4.2 CIM-OSA Goals

CIM-OSA has to solve all the above integration aspects of the manufacturing enterprise. However, it considers Physical System Integration to be addressed by the present efforts in OSI, MAP/CNMA and TOP. Therefore, CIM-OSA builds on OSI and focuses on Application Integration and on Business Integration. Especially for the business integration aspects CIM-OSA provides the methods and tools to employ information technology in the manufacturing industry.

CIM-OSA provides a reference architecture for CIM in all types of manufacturing industries. This architecture covers all internal functions of those enterprises as well as their relation to customers, vendors, general services, etc. This reference architecture serves the needs of CIM users and CIM vendors and fulfils their requirements.

- CIM-OSA guides CIM users and eases design, implementation and operation of CIM systems in their enterprises.
- CIM-OSA guides CIM vendors in the design, implementation and marketing of CIM systems and/or CIM system components. These CIM-OSA compliant components will support the CIM user and ease CIM system design, implementation and operation.
- CIM-OSA bases CIM system design on an evolving enterprise model: an enterprise model which is composed of business processes, each one designed independently but within defined architectural constraints to assure overall model consistency. Therefore, in CIM-OSA, enterprise analysis is not a thorough top down analysis of the total enterprise, but a series of definitions and analyses of particular parts of an enterprise (a set of business processes). For each Business Process all its required functions and their corresponding inputs and outputs are defined. A business process in the CIM-OSA context may be as small as the manufacturing of single parts in a Job Shop or it may be as large as the complete processing of a customer order, ranging from order entry to accounts receivable, including all required functions to complete this business process (e.g. product development, product engineering, production, customer billing and field maintenance). A hierarchy of business processes may be introduced to ease the business process design. However it is the user who defines the range and the content of the business processes rather than CIM-OSA. CIM-OSA only provides the

building blocks and the guidelines for the design, the implementation and the operation of such business processes.
- CIM-OSA supports the design of consistent CIM systems by relating new designs or modification of existing designs to the existing description of the enterprise's CIM system and by providing design choices for new parts.

The architecture could be seen as a description language for the manufacturing enterprise as well as a completely new method for application development in the CIM area, a method which allows the end user to define, to design, to implement and to execute the application programs according to his needs. The architecture also defines the necessary support environment for application program development and execution.

4.3 CIM-OSA Solutions

CIM-OSA is a completely general model. CIM-OSA has defined CIM as a structure or architecture comprising standard building blocks or system components.

The architecture is appropriate to a wide range of users who would select or reject components according to their need. Similarly, suppliers will have a free choice of which parts of the architecture they wish to specialise in and also the manner in which they wish to implement them.

CIM-OSA views the enterprise from two distinct viewpoints, that of the Business Environment as seen by the business user and that of the equivalent Physical Environment – the manufacturing and information technology implemented in the enterprise. These two descriptions are reflected in an Enterprise Model and an Implementation Model. A Translation Process connects the two parts and provides overall consistency during the design process of the enterprise model (see para. 5.2). Not all of the CIM-OSA parts listed are as yet defined.

- *Enterprise Viewpoint (Model)*
  - function viewpoint
  - information viewpoint
  - organisation viewpoint
- *Translation Process*
  - set of guidelines to generate intermediate models
  - set of intermediate models
    - information model
    - resource model
    - organisation model
  - set of guidelines to generate the implementation model from the intermediate models
- *Implementation Viewpoint (Model)*
  - CIM system description
    - specified components
    - implemented components

- CIM system support
  - build time support
    (Integrating Support Environment – ISE)
  - run time support
    (Integrated DP Environment – IDPE)

All of these parts may exist at the different architectural levels of CIM-OSA:

CIM-OSA Reference Level
CIM-OSA Shell Level
Particular Enterprise Level (implemented according to CIM-OSA)

CIM-OSA supports the evolutionary approach since such models may be created to reflect the enterprise at various stages of evolution (past, present, future1, future2, etc.). The total CIM-OSA model identifies a possible future manufacturing system towards which the current system can evolve, in discrete, manageable steps (see Fig. 5).

CIM-OSA is designed to provide visibility of the main characteristics of a manufacturing enterprise. An enterprise is a very complex system with many interwoven dependencies. CIM-OSA aims to separate out the various 'strands' that together make up the business environment.

It is important to recognise that, whilst CIM-OSA separates out such 'strands' it also sets them in a common (architectural) framework wherein internal interactions and the interfaces between 'strands' can be specified in a standard way. Without such a qualification the problem of coping with dynamic changes would simply be shifted to another place.

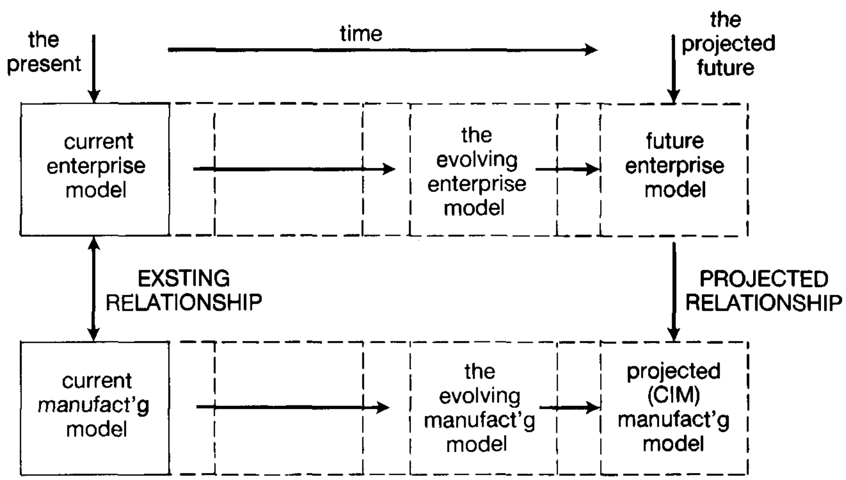

Fig. 5 The Total (Generalised) CIM-OSA Model

CIM-OSA provides a common language for describing all aspects of a complex entity like an enterprise. This language is made up of a finite set of building blocks precisely matched to describing each specific feature of the enterprise, and a set of guidelines for their use. Further because the set of building blocks is finite it is possible to provide a range of CIM-OSA compliant product offerings so easing the task of realising the desired system. At execution time control parameters will customise these generic product offerings to a specific task.

The basic set of CIM-OSA Building Blocks and Guidelines forms the reference base (reference architecture) from which to construct models of a particular enterprise. The reference base will also provide ready made design solutions (groups of CIM-OSA building blocks) for parts of particular types of enterprise according to the enterprise's size or industry sector.

CIM-OSA divides the problem of defining and implementing a CIM system into a number of major tasks:

Task 0 evaluate necessary changes to the Business Environment in response to changes in market conditions.

Task 1 describe what has to be done within the enterprise in terms that the business user can understand (this is a description of the Business Environment in the form of an Enterprise Model).

Task 2 logically structure that description and then translate it into a form that can be understood by the technology installed in the enterprise (this is a description of the Physical Environment in the form of an Implementation Model).
This translation must be exact so as not to distort the required functional or behavioural characteristics. The Translation Process also provides isolation between the Enterprise and Implementation viewpoints so that the Business User is totally unconcerned with implementation details. It is of no concern to him how the final system is implemented or indeed how that implementation may change during the lifetime of the system so long as it conforms to his requirement criteria.

Task 3 build, validate and install physical plant as per the Implementation Model.

Task 4 operate the upgraded system.

Each task is further subdivided into a number of discrete stages. In order to exclude extraneous detail which can obscure the essential processes CIM-OSA uses simple concepts. Each subsequent stage enhancing the level of detail already obtained.

5 CIM-OSA Model components

We now move on to discuss the individual components of the architecture, the Enterprise Viewpoint, the Translation Process and the Implementation Viewpoint.

5.1 The Enterprise Viewpoint

The enterprise viewpoint describes enterprises in terms of:

- the functions required to satisfy the objectives of the enterprise and the kind of resources required by each function.
- the control structure i.e. the rules which define the flow of action within the enterprise and the principles underlying the business process.
- the user's view of the information required by each function.

The enterprise viewpoint has a relationship with the outside world. It is a description of the enterprise system requirements, in terms of the Enterprise Model, but is not concerned with the detailed mechanism of how such requirements are fulfilled.

5.1.1 Function Viewpoint The three stages in developing the Function Viewpoint are (i) Identification of Tasks, (ii) Structural Description and (iii) Activity Description. Figure 6 shows the relationships between the various CIM-OSA Building Blocks used for each stage of enterprise modelling, as described below.

Identification of Tasks

The task of creating the Enterprise Model starts with the creation of a simple overall description of the total enterprise *identifying* what has to be done using the concept of the Business Process.

- *Business Process* is the business professional's[1] view of what tasks are required to achieve the objectives for the Business Process.
  Business Processes cluster Enterprise Activities according to the flow of control. The execution of Business Processes are triggered by Enterprise Events. Business Processes operate under the influence of external constraints (Declarative Rules) to produce a Business Result.
- *Enterprise Events* represent the 'relevant things that happen'. They trigger the execution of a Business Process by initiating the processing of the associated Procedural Rule Set and result in the activation of a cluster of Enterprise Activities which together comprise a Business Process.
- *Business Results* are generated at the completion or termination of a Business Process and describe the end product of each Business Process.
- *Declarative Rules* define the longer term strategic and tactical direction along which the enterprise has to operate, e.g. A policy decision to allow a wider choice of product customisation within the same delivery period would be a strategic change, resulting in a declarative rule.

It is usually necessary to describe a task by a series of sub-tasks. A business process can be expanded into a hierarchy of business processes which cooperate together to produce the desired result (see Fig. 7).

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[1] The person with responsibility for the process i.e. business manager, technical manager, supervisor, etc.

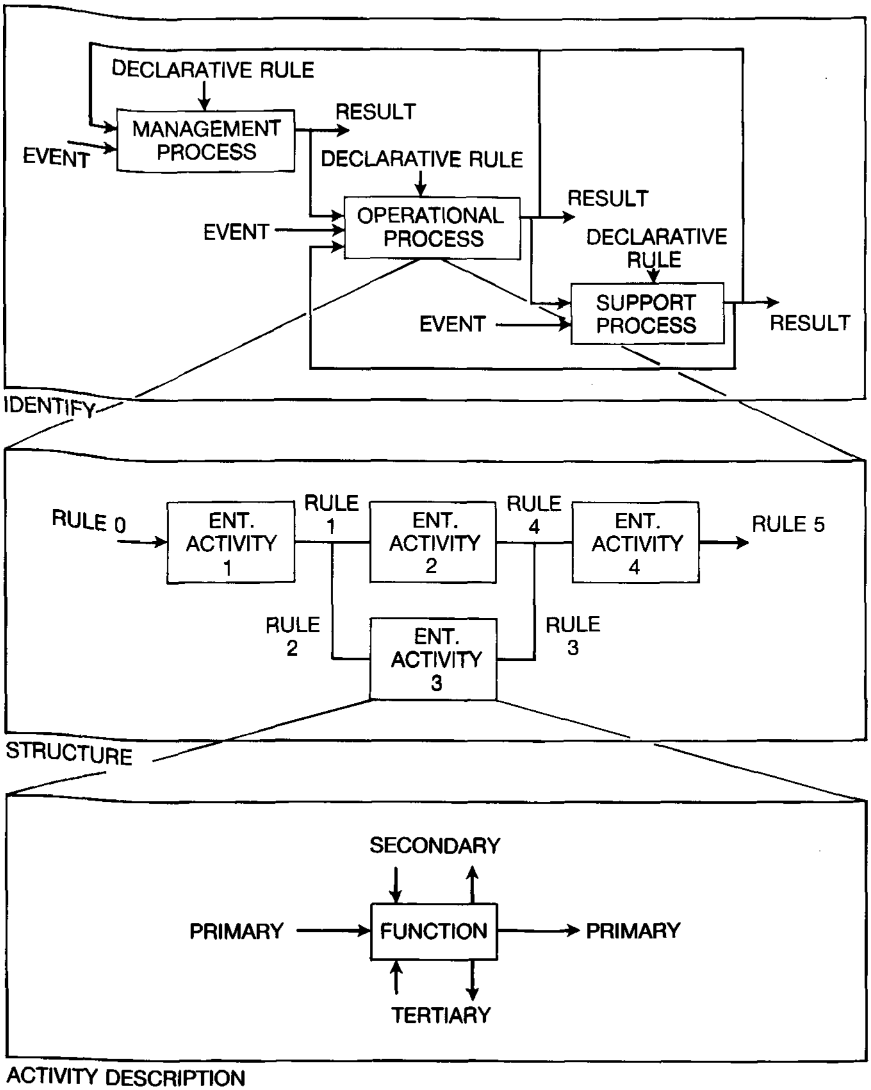


Fig. 6 Enterprise Building Blocks

Example The entire enterprise could be described by one single business process triggered by an event – *invest capital* – and producing a result – *profit*. This description may be adequate for an investor but it is not very useful for designing a CIM system for it tells us nothing about the internal workings of the enterprise. Consider a more CIM related Business Process 'Service Customer Order'. This could be broken down into three Business Processes 'Handle Customer Order; Make Product; Deliver Product' to describe the tasks necessary to service a Customer order.

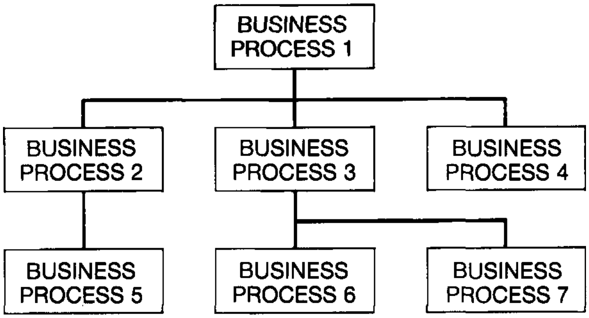


Fig. 7 Hierarchy of Business Processes

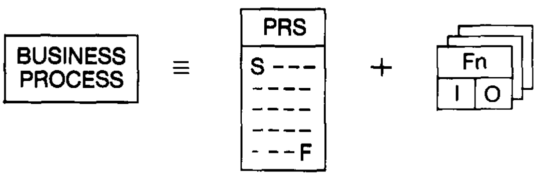
CIM-OSA categorises Business Processes according to their role within the enterprise. Each main category of Business Processes will be further subdivided according to the unique purpose of each Business Process. Currently we envisage three main categories of Business Processes based upon the role each plays within the enterprise:

- *Management Processes* are concerned with monitoring changes in the external environment (the market place) and defining corresponding adjustments to the Business Environment within which all enterprise tasks are performed. The results of Management Processes are plans and information used to manage and control other processes.
  Examples of Management Processes are:
  ○ Plan Enterprise Strategy
  ○ Plan Enterprise Operations
  ○ Monitor Enterprise Performance
  ○ Report Enterprise Condition
- *Operational Processes* are concerned with the creation of product items within the constraints of the Business Environment. They are usually triggered by external events like the receipt of a Customer Order and controlled by the outputs of one or more management processes. The results of Operational Processes are input to further operational processes while the resulting status can be fed back to Management Processes (like Monitor Enterprise Performance) for decision support, or fed forward to control Support Processes like Maintain/Repair Plant.
  Examples of Operational Processes are:
  ○ Develop Products
  ○ Produce Products
  ○ Market Products
- *Support Processes* are concerned with the setting up and maintaining of the Physical Environment required to host the Business Environment. The results of Support Processes can be fed back to operational processes to signal the availability of a resource following maintenance, or to a management process which monitors performance.
  Examples of Support Processes are:
  ○ Install Plant

- Maintain Plant
- Set-up Plant
- Repair Plant

Structural Description

The second stage in describing the enterprise system from the Enterprise Viewpoint uses the concepts of Enterprise Activity and Business Rules to provide a *structural description* of the enterprise. Each Business Process is formally defined by an associated Procedural Rule Set which describes the behaviour required from a defined set of Business Processes and/or Enterprise Activities.



PRS=Procedural Rule Set; S=Start; F=Finish,
Fn=Function; I=Input; O=Output

Fig. 8 Decomposition of Business Process

- *Procedural Rules* represent the flow of control between Business Processes. They define selection criteria for executing the cluster of Enterprise Activities required to produce the desired Business Result.
  There is one Procedural Rule Set for each Business Process. The rule set contains a series of statements, one for each Enterprise Activity or lower level Business Process in the cluster, to define what action is required upon completion/termination of each Enterprise Activity or lower level Business Process.
- *Enterprise Activities* define the functionality of the enterprise.

It should be noted that Enterprise Activities are not part of any given Business Process, but rather they belong to a central pool of activities upon which Business Processes draw in accordance with their associated Procedural Rule Sets. This relationship allows Enterprise Activities to be shared between different Business Processes and ensures a separation of functionality and behaviour making it possible to revise behaviour, in order to meet changing circumstances, without altering the installed functionality.

CIM-OSA categorises Enterprise Activities according to their primary purpose (function). Each main category of Enterprise Activities will be further subdivided according to the unique function of each Enterprise Activity. Currently we envisage three main categories of Enterprise Activities each associated with one of the main categories of Business Processes and each subdivided as shown:

- management orientated functions:
  Plan, Control, Monitor, Report.
- operational orientated functions:
  Develop, Product, Market.
- support orientated functions:
  Install, Set-up, Maintain, Repair.

Activity Description

The final stage is to expand each Enterprise Activity into its constituent parts (see Fig. 9). These are the inputs, outputs and the transfer function giving the relationship between the Inputs and Outputs. (Primary, Secondary and Tertiary).

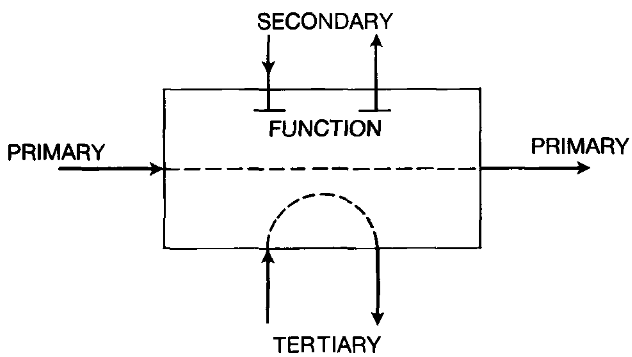


Fig. 9 Enterprise Activity

- Function – describes the required dependencies between the Inputs and the Outputs in order to produce the desired result. This is often referred to as a Transfer Function.

The following inputs and outputs exist each with a specific purpose:

- *Primary* – the object to be transferred (Information/Material)
- *Secondary* – constraints on the transformation
- *Tertiary* – the means required to execute the transformation
- *Primary Input* is the object whose property is changed by the execution of the function in order to create output. The complete primary input is contained within the output.
  We distinguish between Information and Material as primary input because of their different logistic properties (e.g. information can be easily replicated at several sites whilst material cannot) and the need to design different storage systems for them (e.g. databases and physical warehouses).
  Information covers information objects entering the primary output (e.g. a system design specification).

Material covers any physical objects entering the primary output (e.g. material, parts, sub assemblies).

- *Primary Output* is the object with changed properties i.e. the result of applying the transfer function to the Primary Input.
- *Secondary Inputs* are information objects which constrain the transformation (e.g. procedures, process definitions, work instructions, company policies, task completion criteria, etc.). They are used to determine how and what property is changed. They are NOT consumed by the function.
- *Secondary Output* is the status of function execution used as decision criteria to select next enterprise activity for execution. It is mandatory for all functions to create a status output even if that status is invariant (e.g. when monitoring is a separate activity).
- *Tertiary Inputs* are physical objects which facilitate changing the properties of a primary input but do NOT enter the primary output (e.g. people with specific skills or experience, capital equipment, machines, tools, etc.). They may be partially consumed when executing function.
- *Tertiary Outputs* are the unused part of resources returned to pool and status information on resource usage.

In order to guide the user each activity type will have associated with it one or more sets of Inputs and Outputs. The first level categories of Enterprise Activities are distinguished by the nature of their primary inputs and outputs:

Enterprise Activity Category	*Primary Input and Output*
management oriented	information
operation oriented	material
support oriented	resources

For all first level categories the secondary inputs and outputs are information, whilst the tertiary inputs and outputs are resources.

There will be specific unique sets of inputs and outputs associated with each 2nd level category of Enterprise Activity.

Inputs and outputs do not have separate existence apart from the Enterprise Activity they are associated with. They are classified according to Information Class as defined within the Information Viewpoint (Fig. 10) and not according to usage by any one specific function within the Enterprise Model.

The tables of Inputs and Outputs which are part of each Enterprise Activity form the basis of the Enterprise External Schemas for that Enterprise Activity which are developed during the Translation Process (see Information Model). Enterprise Activities include the presentation of information at the human and machine interfaces to the enterprise system so that the enterprise's information can be completely described from the user's point of view.

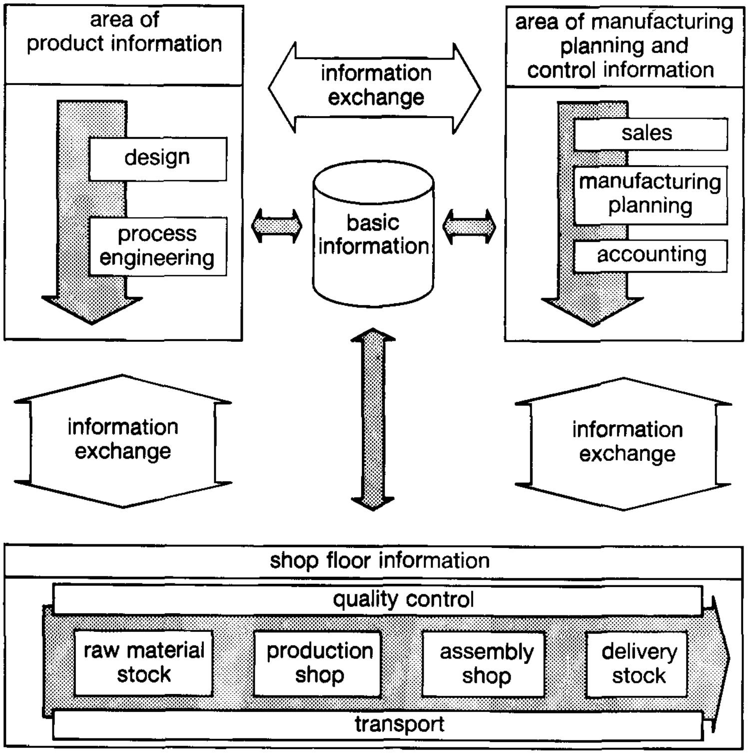


Fig. 10 Information Classes

5.1.2 The Information Viewpoint The classification of information has the objective of guiding the user in the design phase of using CIM-OSA. This is done by providing guidelines for building up structures of information and for identifying generic information types. Its impact on CIM-OSA implementations will permit easy adaptability to particular enterprises and to information organisations which offer qualified performance to users.

Although company activities range from management to research and from sales to quality assurance, presently AMICE has restricted its work to the manufacturing area. This area deals mainly with development/engineering, manufacturing planning and control, and the production and assembly shop. Concentrating our view on the information handled in these areas, we can define three classes of information from the users point of view – product information, manufacturing planning and control information and shop floor information.

As a fourth generic class from the users viewpoint – basic information – can be defined. This contains company wide guidelines and standards. This class of information supports the work to be done in different enterprise departments.

- *Product information* describes all the features of a product and its production processes. It comprises behavioural, functional and physical aspects such as the Bill of Material, product geometry, etc. Production process descriptions comprise process plans, CL-data, etc.
- *Manufacturing Planning and Control* information class contains all the information necessary to handle orders. Therefore the class contains information like customer or production orders, logistic information concerning raw materials or tool devices, current capacity constraints, etc. The required information of both the previous classes are accessed in the shop floor.
- *Shop Floor* information class handles the day-to-day operations in the production and assembly shops. Therefore we find process oriented information such as shop schedules translated from production orders, the actual use of resources, and technological oriented information such as work procedure descriptions for machine tools.
- *Basic* information is pertinent to all company departments. It contains the company standards and guidelines, and the equipment and organisation descriptions valid for the whole company.

The contents of the information classes is shown in Fig. 11.

Beneath these information classes defined from a users point of view, a fifth class called Context information is necessary. This information class describes the relationships which exist between the various items of user information and therefore support their use. The Context information is mainly handled by CIM-OSA services. It guides the provision of consistent data sets and the management of accessibility, exchange and distribution.

The definition of the classes supports the generation of particular internal and external schemas (see Section 5.2.2) because they are structured according user requirements and therefore supports all aspects of information organisation.

5.1.3 Summary of Key Concept Usage Thus the description of the enterprise from the business user's viewpoint describes:

- what has to be done within the enterprise in terms of Processes and Functions;
- what the enterprise uses in terms of Information and Resources;
- how the enterprise is organised in terms of Rules and Responsibilities.

The relationship between the results of each stage in the creation of an Enterprise Model is illustrated in Fig. 12.

5.2 Translation Process

The Translation Process creates an Implementation Model from an Enterprise Model.

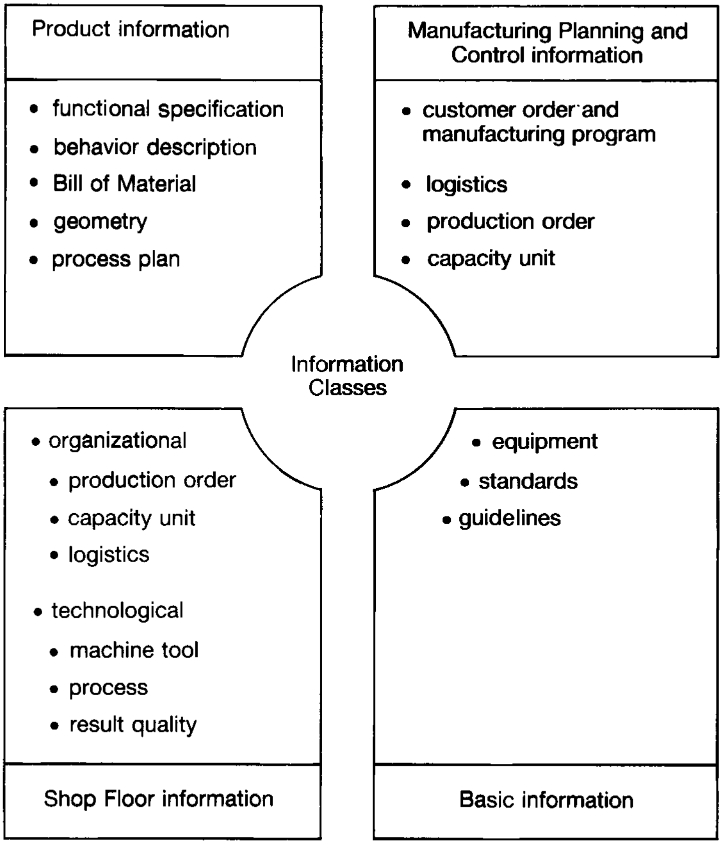


Fig. 11 Contents of the Information Classes

The Translation Process consists of a set of guidelines to generate three models (intermediate translation process results) from the enterprise model and another set of guidelines to derive from them the implementation model (the system descriptions required for the execution of the CIM system). Only one of the three intermediate models is presently developed. Work is currently proceeding on the Resource Model, on the Organisation Model and on the two sets of Guidelines required for the actual translation.

A number of fundamental aspects underlie the Enterprise Model (function, information, constraints, material, resources, rules and organisation). All of these aspects must be accurately reflected in the Implementation Model. Figure 13 shows how the Translation Process groups all of these aspects into three main subjects:

- *Information Model* – logical grouping of information
- *Resource Model* – logical grouping of resources
- *Organisation Model* – logical grouping of responsibilities.

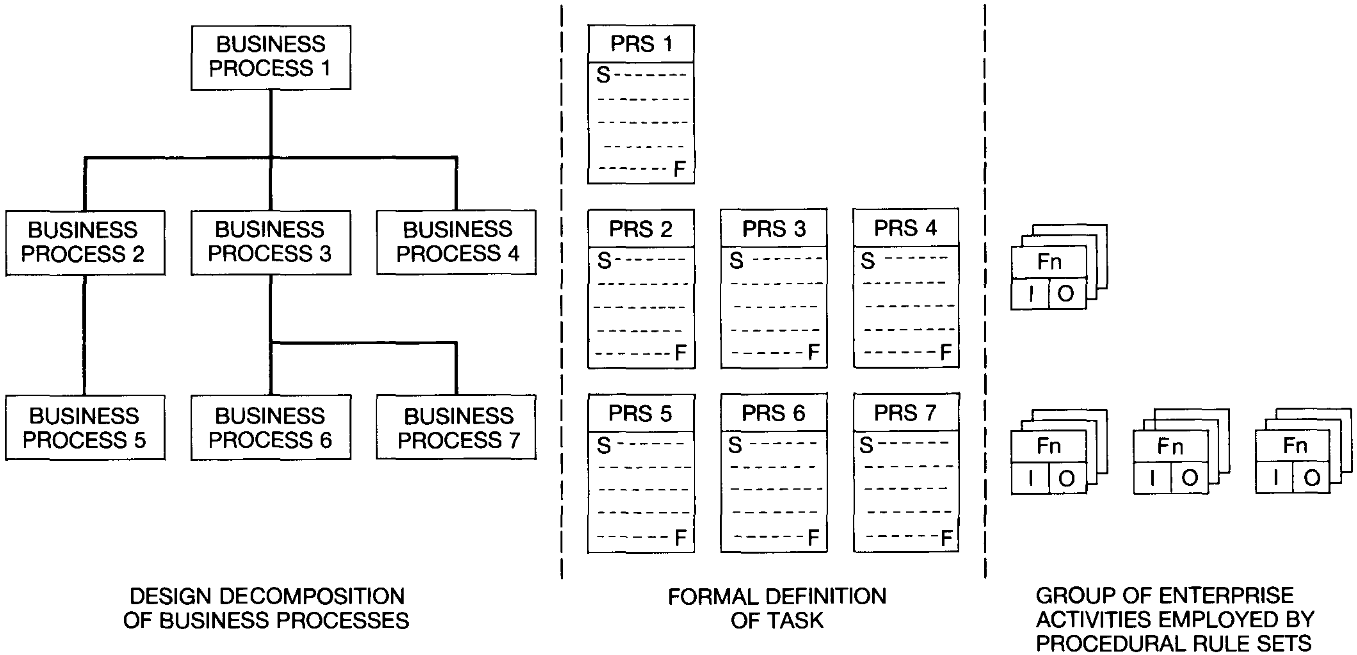


Fig. 12 Relationship between Stage Results

The most complex aspect is that of information for which CIM-OSA provides a number of unique building blocks for constructing an Information Model (see below).

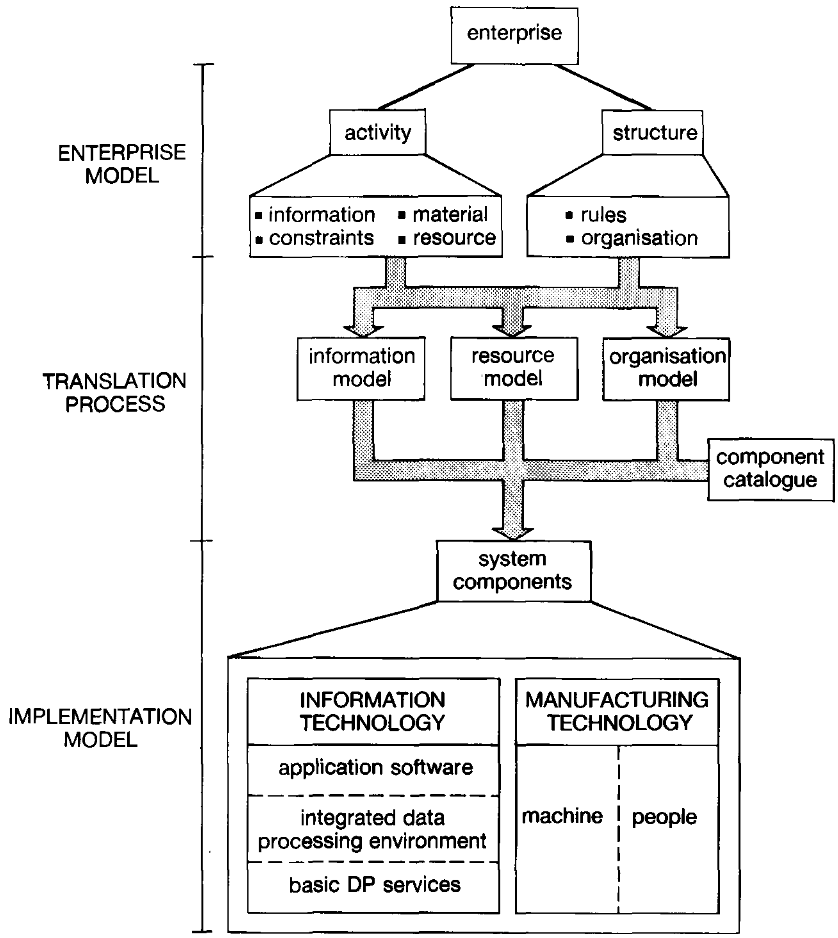


Fig. 13 Translation Process

5.2.1 Translation into the Implementation Model The Implementation Model is created by taking the outputs of the Enterprise Model and arranging them in a logically optimal way. This involves making organisational choices as to the grouping of Resources and Information, and assigning responsibilities for them. Technical choices are then made as to how these resources are to be provided, how and where data is to be stored and how the functionality will be provided using CIM-OSA compliant product offerings.

The CIM-OSA Implementation Model Building Blocks are directly related to those provided for the Enterprise Model. Thus there will be a fair chance that system components required will already exist in the market place, and for any that do not there will exist a CIM-OSA specification so that they can easily be implemented.

The translation (see Fig. 13) from the Enterprise Model into the Implementation Model starts with the organisational grouping of data (via Information Model), resources (via Resource Model) and responsibilities (via Organisational Model). These three models (see above) serve identical purposes but are appropriate to the specific aspects.

The second stage is to define the required CIM system components by choosing from standard CIM-OSA products those which meet or exceed the specifications for the required functionality and resources.

The Implementation Model is thus a description of the real world implementation of the Enterprise System.

5.2.2 Information Model Not only is it necessary to organise the memory of the enterprise in such a way that saving, retrieving and updating data, required to perform current enterprise operations and to plan future ones, will be conducted in an efficient and safe way. It is also necessary to address the problem of representing complex technical objects at various stages in their life cycles and administering their step by step growth.

The description of the data collected, produced and used by a particular enterprise is done using the ISO recommended three schema approach.

- *Schema* are building blocks for describing information. These cover the central rationalised description of all enterprise information (the conceptual schema), the description of the physical storage structure for the information (the internal schema) and the way information must be presented outside the storage system (the external schema). Such information includes the Business Rules, the Product Data and the Production Data as defined in the Enterprise Model as well as information about the physical environment.

In order that data on complex technical objects can be communicated throughout the enterprise a common CIM-OSA representation, the Enterprise Object View, will be used within the Conceptual Schema. Each Enterprise Object View will be described using the Entity Relationship Approach. This standardised representation will be converted in accordance with the relevant external schema for presentation to any enterprise subsystem requiring presentation according to a different standard (EDIF, IGES, SET, etc.).

- *Enterprise Object View* is a formalised way to describe each aspect of an enterprise object.

- In the *Entity Relationship Approach* simple objects are represented by Entities, whilst the various aspects of the object are described by sets of Attributes. The description of complex objects requires the use of several entities and sets of attributes so the Relationship between the various sets must also be defined.

5.2.3 Resource Model The Resource Model describes capacity, availability, organisation and physical location of resources. It structures the information defined in the Enterprise Activity Tertiary Inputs and Outputs of the Enterprise Model. The Resource Model is derived from the CIM-OSA Reference Model using CIM-OSA Resource Model Building Blocks and the relevant CIM-OSA Guidelines.

The Resource Model uses the basic construct of the Logical Cell to describe how resources should be provided in order to satisfy the needs of the Enterprise Activities.

- *Logical Cells* are building blocks for the definition of a group of resources required to support a set of related Enterprise Activities (and their required data and resources).

The primary purpose of Logical Cells is to identify collections of equipment and resources which are candidates for having a high degree of integration because they support groups of functions which require close or frequent interaction. They may be used to reflect a job-orientated structure, or a process-orientated one.

5.2.4 Organisation Model The Organisation Model describes the responsibilities within the enterprise for business processes (flow oriented organisation) and for resources (function oriented organisation). The Organisation Model uses the basic construct of the Organisational Cell to describe how the responsibility for resources and processes should be organised in order to satisfy the needs of the Enterprise Activities.

- *Organisational Cells* are building blocks for assigning responsibilities within an enterprise, providing a basis from which the timely provision of resources and information needed for the execution of actitivities can be enabled.

5.3 The Implementation Viewpoint

The implementation viewpoint (Fig. 14) produces a description of all the tangible components used in the manufacturing process. These are divided into two groups:

(i) Manufacturing Technology required to process materials, assemble articles, pack and move them. They include both machines and people.
(ii) Information Technology required to process and distribute data for all applications of the enterprise. The information technology therefore

includes the application programs plus the CIM-OSA Integrated Data Processing Environment which consists of all the CIM-OSA Services that support the application programs and allow them to run on the selected hardware, while keeping programs and hardware independent of each other.

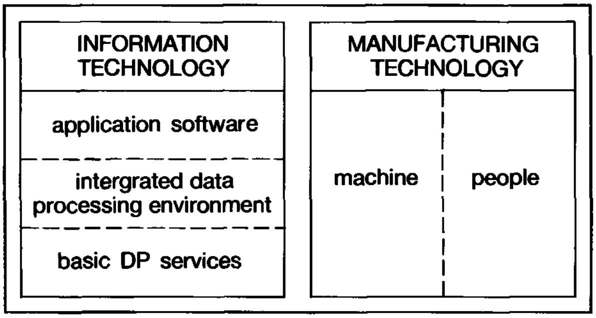


Fig. 14 The Implementation Viewpoint

5.3.1 Integrated Data Processing Environment Applications are software packages which execute the functions defined in the model of the enterprise. In order to simplify the task of providing application packages CIM-OSA seeks to make them independent of their environment by transferring all environment dependent concerns to a set of CIM-OSA services common to all application packages. CIM-OSA calls this group of services the Integrated Data Processing Environment (IDPE). These services can be installed in an incremental manner to reflect the bottom-up approach to integration previously described (see Fig. 15).

The first set of services (i) is associated with Physical System Integration. Physical System Integration is the realm of enterprise-wide homogeneous data communications. It involves isolating application packages from the physical environment and providing logical communications and location independent data access to permit the merging of 'islands of automation'. It makes use of the Information Interchange, Communications Management and Data Management services.

- *Information Interchange* provides a service to control the CIM system-wide exchange of information. This service will interact with peer counterparts, via the Communication Management service, in order to obtain information from another node, and via the Data Management service to obtain information from the local database system. When communicating with external devices Information Interchange will also provide any data conversions required by the device.
- *Communication Management* provides a location-independent system-wide addressing facility. It handles data communications within a network, identifying users and locations by name and handling the

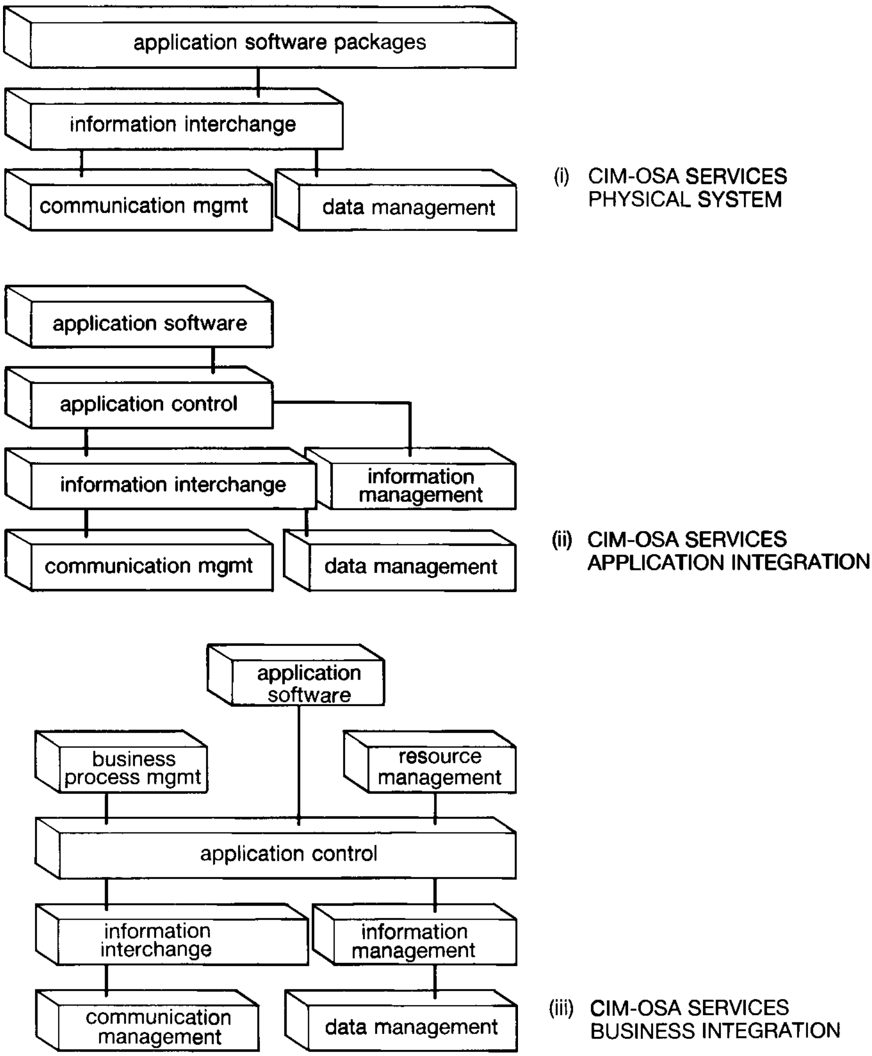


Fig. 15 Incremental Evolution of the Integrated Data Processing Environment

underlying physical connections. The objective is to relieve the user of the need to understand the network and follow its changing configuration.

- *Data Management* provides local address conversion. It handles named data items and is able to identify their physical location on computer storage media, and relocate them when necessary. It is envisaged that most of these services will be provided by OSI networked facilities in the Transport, Session, and Application Layers.

The second set of services (ii) is associated with Application Integration. Application Integration is the realm of enterprise wide shared data resources and view independent data access. It involves portable applications, distributed processing, common services/execution environments. It makes use of the Information Management and Application Control services.

- *Information Management* controls the exchange of information between applications, and between applications and enterprise storage systems. In order to present data to the appropriate application in the form required it will perform system wide view conversions in accordance with each application's requirements. It also provides system-wide information version management and control in order to maintain consistency between the many sets of information (view editions) existing within the enterprise.

  It is envisaged that parts of this service will be provided by the OSI Presentation Level, though it is foreseen that some CIM dependent enhancements may be needed.

- *Application Control* service looks after the run-time execution of Applications and provides them access to Information Management and the Physical Integration services.

The final stage in simplifying application packages (iii) is associated with Business Integration. Business Integration is the realm of enterprise wide monitoring and control of operational and financial aspects. It involves knowledge based decision support, automated business process monitoring, and production and process simulation. It makes use of the Business Process Management and Resource Management services.

- *Business Process Management* controls the sequencing and the synchronisation of activities by invoking the rules specifying the flow of action. Business Process Management must have access to the Implementation Model for the current operational system so that it can find out where, when and how the processes or applications can be activated on the correct node(s).
- *Resource Management* looks after the maintenance and allocation of resources to ensure that the necessary resources are available when required for the execution of particular activities.

At this final stage application packages are only concerned with functionality by providing generic functions that are parameterised by input/output tables defined by the business user via the Enterprise Model.

6 The use of CIM-OSA

6.1 Multiple Models

CIM-OSA provides a methodology for designing and operating CIM systems rather than a prescriptive method. The basic CIM-OSA building blocks can be used to create a wide range of consistent models to suit the needs of each particular enterprise. Thus models can be created for the current and proposed future systems. Models may be strategic, tactical or operational depending on the time horizon. Again they may be structured according to some particular design hierarchy or according to an existing enterprise structure. Again the degree of automation can be controlled so that it is possible to introduce CIM in a limited way in some area of the enterprise and gradually evolve towards the final goal.

No matter how many sets of models are created CIM-OSA will ensure consistency between them. It does this by providing a finite set of Building Blocks, Guidelines for their use and a set of customisable constraints to control the development of models.

6.2 Model Creation

We now turn to the process of designing a specific CIM configuration for an enterprise. This involves the analysis and projection into the future of the proposed enterprise. Using the CIM-OSA building blocks and guidelines the user will be able to identify the components of the CIM implementation.

The initial design activity is done by the Business User carrying out an online interactive dialogue with the CIM-OSA knowledge base. In response to the Business User's replies appropriate CIM-OSA building blocks will be proposed and the user prompted to complete the relevant details for each. The interaction continues until all the stages outlined above have been completed and the Enterprise Model is to the satisfaction of the Business User.

The CIM-OSA Translation Process now converts these details into the Implementation Model. The process is controlled by the CIM-OSA Guidelines which can be customised by the Business User to reflect his own enterprise strategies. Thus it would be possible, for instance, to define the degree of interaction/autonomy and type of automation to be applied to any specific area of the enterprise. Implementation choices are resolved by a Systems Designer who will be asked to choose between possible organisational choices (e.g. job shop versus FMS cells) and technical solutions (e.g. numerically controlled machines versus capstan lathes) at various stages in the Translation Process.

6.3 Use of Model

The physical implementation of the required system is created by assembling the CIM-OSA compliant components defined in the particular enterprise's Implementation Model.

During run-time the CIM-OSA Business Process Management service will be activated by the occurrence of each Enterprise Event (such as the receipt of a customer order). Business Process Management then selects the appropriate rule(s), requests assignment of necessary resources, gets required information, passes control to and from the activity and checks status of the result. Business Process Management refers to the Implementation Model in order to establish where, when and how the processes or applications can be activated on the correct node(s).

7 Benefits of CIM-OSA

The purpose of the AMICE project is to encourage order and bring structure to a situation where the need for CIM is recognised but the means for achieving it are only partially defined. The primary objective is to provide a well understood mechanism for analysing the evolving requirements of an enterprise and translating these into an enterprise specific CIM architecture which enables and integrates the functions which support the requirements.

CIM-OSA is therefore a methodology rather than a prescriptive method. A major benefit is that it provides a frame of reference for CIM users to strategise, plan, implement, maintain and involve their manufacturing enterprise.

CIM-OSA will in due course result in well understood and accepted standards adhered to by vendors and users, making available standard Information Technology modules and tools which can be readily assembled to build unique CIM systems.

CIM-OSA provides a solution which allows the business user himself to express his needs for information processing and thereby to generate executable application programs (CIM-OSA Business Processes). This solution can be seen as a Business Description Language (containing a set of building blocks) which covers all the internal functions of the enterprise as well as its relationships to customers, suppliers, general services, etc.

The CIM-OSA solution is an enterprise-wide supplier-independent Information Technology support for Business Process (application program) development and execution. For this CIM-OSA defines two sets of support: for development the CIM-OSA Integrated Support Environment and for execution the CIM-OSA Integrated Data Processing Environment. The isolation of application software packages from their physical environment by a standardised environment (the Integrated Data Processing Environment) means that new applications can easily be created and integrated into the overall system. This ease of integration will reduce overall costs and elapsed time scales so that medium and small companies will be able to justify the necessary expense of CIM.

Again the division of the enterprise system into a set of installed functions and a set of easily modified rules for combining them towards a specific objective leads to flexibility in operation so that a rapid response to market changes can be made resulting in a more competitive enterprise. A reduction in manufacturing costs, development and production time, inventory lead time, order and delivery times will also result.

An open system will allow integration with foreign (non CIM-OSA) components, and intercommunication with other systems. It also means that CIM-OSA will be tolerant to future technological evolution.

CIM-OSA will promote the realisation of CIM systems which are flexible in structure leading to supplier independence. The ability to integrate information across a company makes information available as and when required and in the exact form required by the end user. It will also be possible to design more autonomous enterprise structures in which decision making can be postponed until enough information is available. We call this decision postponement by constraint propagation using 'least commitment principle'. Thus each sub-system will be able to autonomously control its own region of responsibility by reacting to events according to rules that encapsulate the experience and knowledge of the enterprise (decentralised decision making).

8 Some conclusions

The results shown here should be considered as provisional since a lot of detailing, verifying and integrating is still required.

Defining, developing and validating a CIM Architecture involves a huge effort. This endeavour requires close collaboration and support not only from the partner companies in the AMICE Consortium, but also from future users and the concerned European Organisations since it has extremely important consequences, both for users and for Information Technology suppliers and even more for European industry.

An architecture with adequate characteristics, supported by industry and by standardisation efforts, constitutes the enabling integration technology for CIM.

9 Acknowledgements

The author would like to thank Mr Anthony Lucas-Smith for his help in creating the general sections on CIM, the members of the AMICE Consortium for permission to publish this paper and also all those who have contributed to the concepts contained in this paper.

MAES – an expert system applied to the planning of material supply in computer manufacture

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Abstract

This paper is about planning and controlling the supply of materials to a manufacturing plant. The specific application described is to ICL's own manufacture of computers, but the principles and methods apply to any manufacturing process.

The ICL software product MAES (MRP Actions Expert System) is an expert system that helps the (human) materials controllers at a plant to carry out the actions generated by the module MRP (Materials Requirement Planning) which is itself an optional component of ICL's general program suite OMAC (On-line Manufacturing Planning and Control) for managing a manufacturing process. MAES was built with the help of the ICL expert system shell REVEAL. Within ICL it is already in use in the Kidsgrove plant and its use is being extended to the other plants.

Introduction

Manufacturing and Logistics controls a supply chain which extends from components and peripheral suppliers in Europe, America and the Far East, through Manufacturing in the UK and to eventual customers worldwide.

Manufacturing and Logistics is responsible for controlling the total inventory in this chain and each plant is therefore responsible for optimising its own inventory and simultaneously achieving the difficult balance of minimum inventory and maximum service to the next customer in the chain. The normal measure of stock level is inventory turns, i.e. cost of goods sold divided by inventory. ICL's worldwide performance of approximately 4·5 inventory turns puts it ahead of its competitors even though it also offers exceptionally high levels of customer service, measured in terms of the lead time from receipt of order to despatch of goods.

The principal computer system which plans the material to be bought and the machines to be built throughout ICL's four Manufacturing plants is

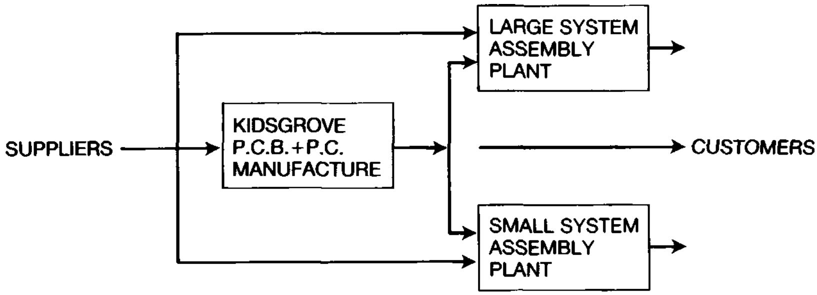

Fig. 1 Simplified supply chain

OMAC Material Requirements Planning (MRP). OMAC works in a similar way to other MRP systems in that it calculates the actions to be taken, based on a top level plan called a Master Schedule, and by referring to existing stocks and orders. This has become the industry standard way of controlling inventory, replacing the previous technique of re-order level control in which an order is placed for a part whenever the stock of the part falls below a certain pre-determined re-order level which is based on past experience rather than future anticipated requirements. Within Manufacturing and Logistics each plant operates its own MRP system and the requirements of the assembly plants become the orders on the feeder plants.

OMAC MRP is described in more detail in later sections of this paper, but for the sake of clarity an overview is provided here.

The core of OMAC is the bill of material which expresses the relationships between the component parts of a product in the form of a family tree (see Fig. 2). OMAC uses the bill of material to determine which dependent

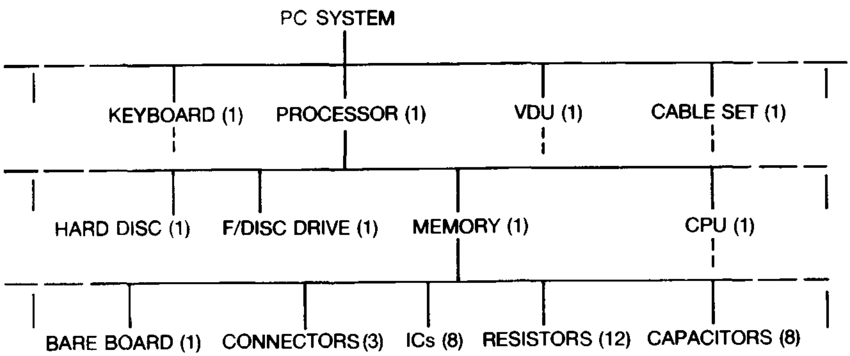

Fig. 2 Simplified bill of material

components are required, and when they are required, in order to build the final product. These requirements are then compared with any existing stocks of these components and any orders already placed. This then serves as a basis for recommending the user to raise new orders or to adjust existing orders. These adjustments might involve expediting existing orders, deferring them, adjusting the quantity on order or cancelling the order altogether.

The user (Material Controller) examines MRP's recommendations and takes the appropriate action. He may decide that the change recommended by MRP is not actually necessary and should be ignored. Alternatively, he may decide to take action, either exactly as recommended or in a modified form.

In taking these decisions, the Material Controller will be using knowledge which is not available to the MRP system itself. Some of this knowledge will be the same from week to week, for instance it may cost more to defer an imminent, low value delivery than it will cost to hold the stock. Other knowledge will vary from week to week, for instance it may be necessary to give close attention to the parts for one product line because of instability in the demand forecast.

The need for the Material Controllers to examine and act upon the output of MRP raises a number of issues:

- The number of actions suggested by MRP should not exceed the capacity of the Material Controllers.
- Too many actions mean that more Material Controllers will be required, or not all actions will be dealt with by the next run of MRP, or insufficient attention will be given to each action.
- Material Controllers dealing with large volumes of data find it hard to remember and implement management instructions (short term knowledge).

The key issue which affects the performance of MRP is the amount of change in the Master Schedule which is the original basis for calculation of the demand. For a company like ICL the total procurement time (the time to procure the component and to build the item assuming that nothing is in stock) is greater than the customer order leadtime. As a result a large part of the Master Schedule must be based on forecast sales which will inevitably be subject to amendment. The changing view of the future results in changes to the Master Schedule which MRP then translates into adjustments to orders already placed. OMAC contains various features for ensuring that the user is not asked to make trivial changes to existing orders. Any change ignored by the system or by the user, however, implies something other than the theoretical minimum possible stock and therefore has a cost in terms of excess stock held within the plants.

The normal solution to this uncertain demand is to increase buffer stock to absorb the changes without having to go through the administrative cost of amending orders on suppliers. This may, however, result in an unacceptable level of inventory.

ICL wished to further reduce inventory and to be even more responsive to changing customer demand. This meant reducing the time spent dealing with the output of MRP and reducing the interval between MRP runs.

The demands on each Material Controller needed to be reduced in order to achieve this objective, and MAES was designed in response to this need.

MAES (MRP Actions Expert System) is an expert system which contains the knowledge of the Material Controllers and their manager in the form of rules which are applied to the output of MRP. The rules are used to identify the cases where the Material Controllers can be expected to either ignore or completely agree with the recommendations of MRP. Other software then executes the recommendations, simulating the action of the Material Controllers. The result is fewer actions for the Controllers to deal with and more time spent on the ones which are important and difficult.

The relationship between MAES and OMAC MRP is shown in Fig. 3 (System Overview); the following sections describe in more detail OMAC, MAES and the REVEAL software upon which MAES is based.

OMAC

OMAC (On-line Manufacturing planning and Control) is a modular product aimed at providing production management with a central database of information required to run a manufacturing organisation. Modules of OMAC are aimed at a range of areas within the manufacturing environment, including Materials Requirements Planning as mentioned earlier in the paper. The product, as used by ICL Manufacturing and Logistics, is written in Cobol, and utilises the Integrated Database Management System, IDMSX. This ensures that each module of the product is able to access the data within the database which it requires to process TP transactions (via the Transaction Processing Management System, TPMS).

Within OMAC, the MRP module contains both the MRP processor program and a complementary suite of reports and TP transactions. The MRP processor 'recommends' actions to take to ensure that the order pattern for components and assembled items meets demand. These recommendations, to either confirm new orders or change or cancel existing orders, are represented physically within records of the OMAC database.

New orders to be placed are represented by 'tentative' orders, placed by MRP, which act to propagate requirements for materials down the Bill of Materials levels. The tentative orders provide measurement of potential useage of stock where commitment to product build has not been confirmed. They may have recommendations attached to confirm the order if they

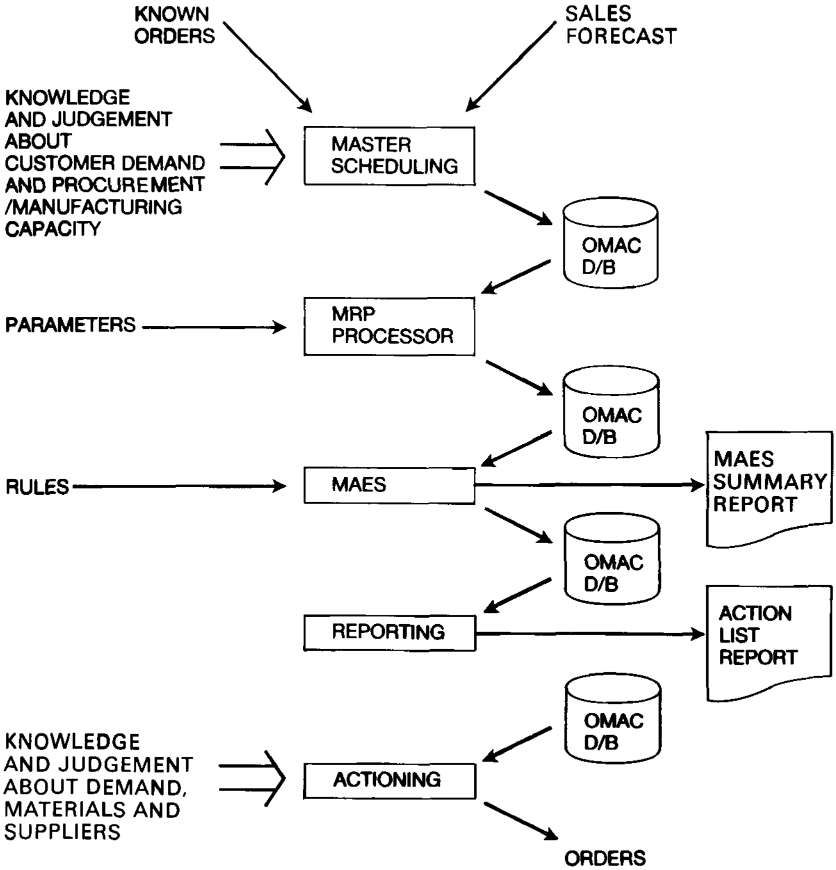

Fig. 3 System overview

fall within the documentation period as defined, at MRP run time, by the user.

This means that recommendations, or 'actions', can be accessed in a useful manner. Transactions are provided within the MRP module, which access the set of actions for a specified part, and perform the necessary amendments to the database relating to the type of action (e.g. confirm or change order) as directed by the user. Replacement of tentative orders with firm orders and order cancellation or amendment are all functions of these transactions.

Other modules of OMAC provide Stock control, Work In Progress control, Costing and many other facilities. The product is used in its VME 1.00 version by ICL Manufacturing and Logistics, but is also available in a range of QuickBuild options, and runs on 2900 and Series 39 mainframes.

MRP ACTIONS EXPERT SYSTEM (MAES)

As described above, a changing environment means that materials management needs flexible systems to help in quickening the turnround of MRP actions. This requirement had previously been tackled by conventional systems development. These systems included 'Message Suppression' software which allowed the user to specify a set of order date and value parameters for actions which would be deleted from the database prior to MRP reporting. This meant that some less critical actions could be ignored until the next MRP run highlighted them again. Other software facilitated the automatic confirmation of tentative orders suggested by MRP, permitting MRP recommendations to place new orders to be performed without the manual intervention of Material Control staff.

This type of software, although extremely useful, did not give the flexibility which the current environment demanded from computer systems. This led to the idea of MAES to provide these and further automatic action processing facilities.

The MAES system now operational within ICL Manufacturing & Logistics was originally built as a prototype, mimicking the previous Message Suppression system. The prototype acted on a filestore copy of the MRP Action List (a report of all actions on the database), and deleted from that report all actions which corresponded to the parameters input by the user. The prototype was then given an interface, written in Cobol, which enabled the software to process and update the database directly. This meant that the system could not only emulate the facilities of Message Suppression, but could also support more parameters than those provided by the Cobol program.

This development process was useful in proving that the product, REVEAL, was capable of doing the job required, whilst also building up the confidence of the users in expert systems concepts. Further benefits of this development cycle came later, in the testing phase of implementation – these will be discussed later.

Having developed an emulation of the Message Suppression software it was necessary to improve the facilities offered to incorporate the flexibility of action filtering which the user required. This meant providing a facility to increase the scope of the criteria by which actions were chosen to be deleted, plus facilities to perform actions, based on criteria similar to that for action suppression.

To do this a method of representing the knowledge which a Material Controller uses in processing MRP actions was required. This knowledge, within MAES, takes the form of rules within REVEAL file structures, which are of the form IF-----THEN DO. Attributes of the actions along with their values are specified within the IF part of the statement, and a procedure is attached to those attributes, the DO part of the statement. This procedure dictates the process to be performed when an action has attributes corresponding to those values within the selection criteria. Each action which MAES processes is presented to these rules, and those actions whose attributes conform to the selection criteria for any rule, are subjected to the procedure attached to that rule.

Elements of the knowledge which is used within MAES will be constantly changing according to the business environment at the time MRP is run. This means that the user must have access to, and control over, the knowledge up until the point at which the software is run. Since this scenario implies that the system's users, members of the Material Control department, would have access to update the knowledge within the system, a sophisticated user interface was developed.

The requirements of this user interface were to allow the input, update and control of the knowledge, or rules, within the system, to be carried out by users with the minimum possible amount of risk. These objectives are met by the use of menus and templates at all stages, in conjunction with the REVEAL facility of field level help. The system is essentially menu driven, and the input, amendment and deletion of rules or sets of rules are all available via the menu system. This means that the user is prompted at all stages of rule input or amendment and novice users can enter rules with the minimum of guidance.

The user may recall existing rules into the system or may enter new rules. This involves calling a list of fields available for use as attributes within selection criteria. The user chooses a subset of these and is then presented with an input template to provide values for these attributes. This provides great flexibility in rule specification whilst complete validation of field names and operators is provided with a minimum of processing. The rule input is formed in logical English type statements, and is thus easy to read, and the mechanism for rule input is either via menu or template, a similar concept to the OMAC user interface (see Fig. 4).

The user-defined rules can be stored away in files, the names of which are user defined, so that they can be called, merged or deleted by the user at a later stage. These facilities are provided by menu driven rule maintenance procedures completely under the user's control.

The above describes the input and maintenance of user defined rules. However, as a result of the development history, there is a further facility to include fixed format rules of the form used by the previous Message Suppression system. These rules are specified via a predefined template, and can be included or excluded during any run of the software.

Because of the high level of flexibility provided by the user interface there could be a risk of rules affecting the database in unexpected ways. The system

```
SELECT RULE FIELDS                                   screen 1

You may use any character to select the appropriate fields.
select screen _ _ (E to end field selction, Q to Quit).

 1) Action type          _ Y _      2) Part number              _ _
 3) Description          _ _        4) Normal Store             _ Y _
 5) Normal Bin           _ _        6) Product Group            _ Y _
 7) ABC classification   _ Y _      8) Normal order type        _ _
 9) Unit of measure      _ _       10) Responsibility code      _ _
11) Order method         _ _       12) Auto order marker        _ _
13) Bulk issue marker    _ _       14) Stock account            _ _
```

Fig. 4 (a) Selecting fields to construct a rule

```
INPUT RULE MENU

PLEASE ENTER RULE 5 AND PRESS SEND.
OR ENTER 'Q' TO QUIT _ _

Action Type _LT_ _9_
Normal Store _STARTSWITH_ _ P _
Product Group _ CONTAINS _ _ P2 _
ABC Classification _ EQ          _ _C0_

ACTION FOR RULE _CO_
```

Fig. 4 (b) Constructing a rule

```
ICL MANUFACTURING OPERATIONS                                              PAGE    1
                                                                          DATE    24/08/88

              MRP ACTIONS EXPERT SYSTEM - CURRENT RULES
RULE NUMBER  <- - - - - - - - - - - - - - - - RULE - - - - - - - - - - - - - - - ->   ACTION

     1       IF    Action Type IS NOT 1,
             AND   Part Number EQ        5108603
             AND   Product Group STARTS WITH P      THEN: '. . . . . . . . . . . . . . . . PERFORM THE ACTION

     2       IF    Action Type IS 7 ,
             AND   Part Number CONTAINS 5108069
             AND   Product Group EQ         P4BG    THEN: '. . . . . . . . . . . . . . . . PERFORM THE ACTION

     3       IF    Action Type IS GREATER THAN 6 ,
             AND   Part Number STARTS WITH 80070653
             AND   Product Group CONTAINS  P4A      THEN: '. . . . . . . . . . . . . . . . PERFORM THE ACTION

     4       IF    Action Type IS 7 ,
             AND   Normal Store EQ       PAC ,
             AND   Product Group ENDS WITH 6GA ,
             AND   ABC Classification STARTS WITH C ' THEN: . . . . . . . . . . . . . . . SUPPRESS THE ACTION

     5       IF    Action Type IS LESS THAN 9 ,
             AND   Normal Store STARTS WITH P ,
             AND   Product Group CONTAINS P2 ,
             AND   ABC Clasification EQ      CO'    THEN:. . . . . . . . . . . . . . . . PERFORM THE ACTION
```

Fig. 4 (c) Report of current rule

therefore requires facilities for security and user input validation. Some validation mechanisms operate at rule input time; operand validation, the use of predefined OMAC field names and the provision of field level help for instance. There is also an inbuilt mechanism to allow the user to run the system, in 'Non-update Mode'. This makes possible prediction of the overall effect of the rules within the system before they are used to update the database. This facility gives both detailed and summary reports to aid in the analysis of the updates to be expected from the rules.

After rule input and an MRP processor run, the software needs to be run against the OMAC database in update mode. The logic which controls the use of the rules within the system is kept separate from the rule input part of the system. This means that the programmers and support staff can have control over the processing logic and the users control over the knowledge. The system is usually scheduled to run immediately after the MRP processors before any reports are produced.

The access and extraction of data from the database and any updates required are performed by the Cobol interface software. The REVEAL part of the system accepts the data for each action and compares this against the rules within its knowledge base. Any activities which are required are then indicated to the Cobol interface for database update. The database is analysed part by part which ensures restartability if the process is interrupted at any point.

Updates to the database may be performed either directly, in the case of deleting actions, or via batch update. The system will create batch update files for use in order confirmation, cancellation etc. These amendments may then be performed within the run of MAES or may be postponed until after the output is validated by the users. This facility has proved particularly useful in testing of the software initially, and in the introduction of the software into the user environment.

After processing, detail and/or summary reports are produced to give information on the actions which MAES has processed and performed or deleted. These reports (see Fig. 5) are used for analysing the effect of the rules, which can then be refined for future runs of the system.

The summary reports also provide valuable management information on the results of the MRP run itself and the way it affects the financial aspects of the order pattern.

REVEAL

REVEAL is ICL's Fortran based Expert System tool; it is marketed by Knowledge Engineering Business Centre and is the base tool for the VME Computer Management System.

The product is essentially a modelling package, incorporating facilities to perform approximate reasoning on its model. It is aimed at all levels of user but it is a programming language and thus requires some degree of training and/or familiarisation before more extensive models can be produced.

REVEAL uses a relational database along with constants and variables to contain and maintain its data with the usual arithmetic and string functions for data manipulation. There are also some specific financial functions available.

Declarative programming is catered for within REVEAL policy statements, where English-like statements can be made containing variables (like 'product cost' or 'order due date'), qualifiers (like 'good' or 'early') and noise words (like 'should be' or 'his'). All these words are user defined but some defaults are provided and hedge words are also given (like 'quite' or 'almost') to complement the qualifiers.

Approximation within the package is represented by a truth value associated with any statement. This value is determined using the principles of Fuzzy Set Theory. Reasoning based on these values allows for the representation of vagueness in the knowledge within the model on which decisions are based.

Output from REVEAL can be in either report or graphical format. The package has its own report and graph generating facilities, which provide all the usual facilities. Report layouts can be defined in terms of page length, margin sizes, column and row titles plus further text and many others.

ICL MANUFACTURING OPERATIONS — PAGE: 1

SITE: XXXX — DATED: dd/mm/yy

MRP ACTIONS EXPERT SYSTEM-SUMMARY REPORT (BY ACTION).

	TOTALS		SUPPRESSED				ACTIONED				REMAINING			
	NO.	VALUE	ACTUAL NO.	%	ACTUAL VALUE	%	ACTUAL NO.	%	ACTUAL VALUE	%	ACTUAL NO.	%	ACTUAL VALUE	%
CANCELS	nnnn	nnnnnnnnnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn
DEFERS	nnnn	nnnnnnnnnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn
EXPEDITES	nnnn	nnnnnnnnnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn
CONFIRMS	nnnn	nnnnnnnnnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn
TOTALS	nnn	nnnnnnnnnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn	nnnn	nnn	nnnnnnnnnn	nnn

ICL MANUFACTURING OPERATIONS — PAGE: 1

SITE: XXXX — DATED: dd/mm/yy

MRP ACTIONS EXPERT SYSTEM-SUMMARY REPORT (BY RULE)

RULE NO.	SUPPRESSED		PERFORMED	
	TOTAL NO.	TOTAL VALUE	TOTAL NO.	TOTAL VALUE
nnn	nnnn	nnnnnnnnnn		
nnn	nnnn	nnnnnnnnnn		
nnn	nnnn	nnnnnnnnnn		
nnn	nnnn	nnnnnnnnnn		

ICL MANUFACTURING OPERATIONS — PAGE: nnn

SITE: XXXX — DATED: dd/mm/yy

MRP ACTIONS EXPERT SYSTEM-SUMMARY REPORT (BY RULE)

RULE NO.	SUPPRESSED		PERFORMED	
	TOTAL NO.	TOTAL VALUE	TOTAL NO.	TOTAL VALUE
nnn			nnnn	nnnnnnnnnn
nnn			nnnn	nnnnnnnnnn
nnn			nnnn	nnnnnnnnnn
nnn			nnnn	nnnnnnnnnn

Fig. 5 Summary reports

Graphs are character based, and the format of the graph can be defined by the axis scale and labelling, density of character plotting etc.

The package runs under VME on ICL's 2900 and Series 39 mainframes. Interfaces are provided to allow for integration with Fortran, Algol or Cobol procedures and for calling SCL procedures.

Implementation

The implementation of MAES presented a number of issues especially in relation to rule input validation and testing.

Because the MRP system is of critical importance to Manufacturing and Logistics, and because the effect of any problem is seen very quickly, the users and the development team needed to have great confidence in the quality of the MAES system.

The fact that the rules within the system would be changing frequently, and at any time up until the run of the MAES software, meant that a certain amount of control over batch work moved out of the hands of the support team and into the hands of the user. The software support team therefore needed a great deal of confidence in the rule validation mechanisms within MAES.

Confidence was achieved by stringent testing before the system was accepted as a 'live' program. The testing involved the running of MAES with Message Suppression parameters, alongside the original Message Suppression system itself, followed by bit-for-bit comparisons of both outputs. The software was then run on a copy database in parallel with Message Suppression and extra rules were introduced in a careful and controlled manner whilst further integrity and run time testing was performed.

The successful introduction of REVEAL and expert system concepts into the user environment has taken some time but should provide a secure base for future implementations of expert systems within Manufacturing and Logistics.

MAES has also started to encourage a different attitude in the user community because, by increasing the extent to which users can influence MRP processing, it has increased the users' feeling of ownership of the MRP process and may in time lead to greater independence from their MIS department.

The implementation is also helping to identify other possible uses of expert systems in the materials planning area. One possibility of current interest is the detailed planning of engineering change implementation.

MAES in Manufacturing and Logistics

MAES can be seen as an important component of the material planning process.

All manufacturing areas within ICL are implementing the 'Just in Time' or JIT philosophy which revolves round the elimination of every form of waste from the manufacturing process. By eliminating the waste of time in the

Material Control function, MAES supports the philosophy of JIT. The inventory reduction aspects of JIT demand rapid and frequent communication of requirement information to our suppliers and MAES is an essential part of this activity.

MAES is particularly appropriate in ICL's Kidsgrove plant where there is an increasing trend toward product line focus. MAES is therefore able to enforce different component procurement policies according to the product group within which the component falls.

To date, the system has only been used to deal with the bottom, or component, level of the Bill of Materials. This is quite acceptable within Manufacturing and Logistics where the product structures are of the shallow pyramid type. It also avoids any issue arising from changing the assembly level plan without modifying the plan for dependent components.

Enhancement

Now that the system is installed in its current form it is time to look to further development and to the introduction of its concepts into other areas. The current plans are to develop the system to allow it to identify where small amendments to the MRP output can be made before the actions are performed. The system will then make those alterations and update the database.

In addition to providing the ability to specialise MRP by product groups, MAES may also be used to provide vertical integration of the MRPs within the supply chain. This would be achieved by using MAES to validate the printed circuit board requirements generated by the assembly plants before transmitting these requirements to the Kidsgrove feeder plant. In order to achieve the full linking of MRPs it will still be necessary to ensure that the plan loaded on to the feeder plant MRP system is achievable, and will not generate impossible demands. This is the responsibility of a master scheduling system: there is an existing project in Manufacturing and Logistics to develop a new and sophisticated Master Scheduler for use throughout the organisation.

Future developments

Although MAES has been presented here as an addition to MRP, it can also be viewed as a step in its replacement.

As explained earlier, the central problem arises from the need to carry out detail planning on uncertain and changing data. In the long term, the likely solution to this problem is an MRP system based on the use of artificial intelligence techniques. Such a system would take into account the uncertainty which always exists in the top level Master Schedule, and plans generated for lower levels would therefore cope with a range of possibilities which would not only reflect the degree of uncertainty in the original schedule, but also balance against the cost and difficulty of changing the existing plan.

This more sophisticated calculation is based on a much richer view of the data and it is this which will differentiate our future systems from our present ones. The need is to carry more data through the planning process so that it is available to support better decision making. Current systems force the user to ignore a great proportion of the information because the system cannot use or even store it (see Fig. 6).

Within ICL Manufacturing and Logistics this final step of replacing MRP is being defined. In the meantime, there are two main initiatives moving Manufacturing & Logistics towards this goal.

One is the development of the Master Scheduler which will increase the sophistication of the master scheduling process and provide better schedules for use by subsequent systems. The other is the MAES system which is the subject of this paper (see Fig. 7).

Master Scheduler can be thought of as replacing some of the initial functions of MRP in that it fits within the original master scheduling phase of the MRP process, whereas MAES can be thought of as replacing some of the later functions in that it fits within the order raising and amendment phase of the process. MRP is thus being replaced from the outside but the actual core process of MRP is likely to exist within Manufacturing & Logistics for many years to come.

In the meantime, systems running before and after MRP, like Master Scheduler and MAES, will be given the capability to handle this breadth of data so that they can support this new MRP when it is actually implemented (see Fig. 8).

At a detail level, while there is some advantage in keeping MAES separate from MRP as it is at present, in the long term the integration of REVEAL type rules within MRP provides a more elegant solution. This could be achieved by providing user hooks within the MRP system which would be able to call special REVEAL rules at the end of processing for each part.

MAES may not be suitable for use at high levels in a contract bill of material. Possibly it should not be used to control the plans for made-in items which in turn have many sub-assemblies. For these items the future may lie in a form of interruptable MRP which can be halted at the end of processing for a level, in order to assess the plan generated, before passing the information down to lower levels for component evaluation.

Fig. 6 Existing systems discard information in master scheduling process

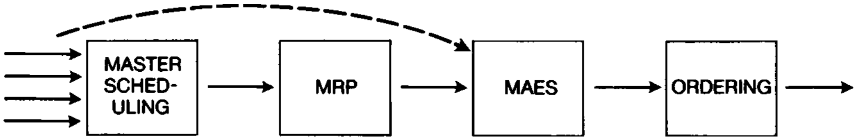

Fig. 7 MAES allows information to be used after MRP

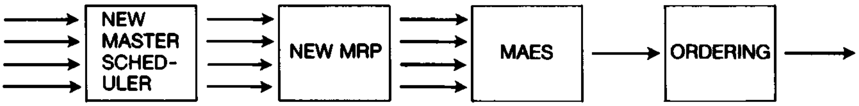

Fig. 8 The ultimate goal is to use all the information. MAES and the new Master Scheduler can be seen as an interim stage

Conclusions

MAES has proved to be a valuable tool that enables materials management to give increased flexibility, reduced inventory and improved customer service. Its successful implementation in Manufacturing and Logistics will lead to continuing enhancement of the system and introduction of expert systems into new areas.

Following the success of MAES within its own plants, ICL is now planning to make the system available to its customers.

Acknowledgements

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JIT and IT

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Abstract

This article will attempt to do three things: describe Just-in-Time techniques as seen by the author in Japan; and consider the limitations and breadth of applicability of those techniques; consider the role of MIS and IT in JIT systems, and describe one application where information technology was enlisted to enhance an essentially manual production control system.

Just-in-Timep: the principles

Just-in-Time is not a system but a philosophy of manufacturing management involving a variety of techniques, some new and some old. Its essence is a determination to maintain materials flow, receiving small and frequent deliveries from suppliers, straight to the first process (not via a goods inwards store), and pulling small quantities of parts and components through the manufacturing sequence to final assembly – not pushing them through to replenish safety stock or in response to a shortage list. Machine set-up times are reduced to a level (less than ten minutes) where these small batches are still economic, because changeovers are not a significant loss of productive time. Factory floor layouts are organised to follow the manufacturing sequence and machines are placed close together – space alongside machines is not needed when there is very little inventory to store there. Very low scrap rates are essential – with so little material in the system, defective components mean stopping production. Some spare production capacity, of machines rather more than of labour, is usually kept available. There are many other aspects to JIT, the most important being associated with the flexibility and responsibility of the worker, who will operate several machines, reset and maintain them himself, halt production if a problem occurs, and ensure the quality of his own output. The Japanese worker is exceptionally well educated in quality control techniques, as can be seen from Table 1. JIT in its most complete form, as it may be seen in Toyota and other Japanese automotive and electronics companies, is beyond doubt the most important development in the manufacture of complex assembled products since Ford perfected the assembly line itself. But in that "pure" form it is not widely employed, even in Japan.

Table 1 Quality training programme of a Japanese automotive company

	EMPLOYEE	COURSE	CONTENT
ENGINEER	NEW EMPLOYEE	INTRODUCTORY COURSE	·CONCEPT OF QC ·DISTRIBUTION OF STATISTICS ·DATA ANALYSIS
	GENERAL	QC BASIC COURSE	·STATISTIC METHOD ·BASICS OF DESIGN OF EXPERIMENTS ·BASICS OF RELIABILITY ENGINEERING
		DESIGN OF EXPERIMENTS COURSE	·FACTORIAL DESIGN ·ORTHOGONAL ARRAY ·S/N RATIO (PARAMETER DESIGN. TOLERANCE DESIGN)
		RELIABILITY ENGINEERING COURSE	·RELIABILITY DATA ANALYSIS ·CONCEPTS OF RELIABILITY DESIGN ·FUEL FTA ·FAILURE ANALYSIS
	ASSIST. MANAGER	QC SEMINAR FOR ASSIST. MANAGER	.TAGUCHI METHOD
	MANAGER	RELIABILITY ENGINERING COURSE	·RELIABILITY CONTROL FOR MANAGER
WORKER	NEW EMPLOYEE	INTRODUCTORY COURSE	·QUALITY CONSCIOUSNESS, 5S* ·POCA CYCLE ·QC CIRCLE ACTIVITY
	GENERAL	SKILLED WORKER TRAINING COURSE	·7 TOOLS FOR QC CAUSE AND EFFECT DIAGRAM PARETO DIAGRAM CONTROL CHART. HISTOGRAM SCATTER DIAGRAM STRATIFICATION CHECK SHEET
	FOREMAN	QC TRAINING FOR FOREMAN	·INSTRUMENT OF 7 TOOLS FOR QC ·PROCESS CAPABILITY STUDY METHOD ·PROBLEM SOLVING PROCEDURES
	ASSIST. MANAGER	QC CIRCLE FACILITATOR COURSE	·METHOD TO FACILITATE QC CIRCLE ACTIVITES ·GROUP DISCUSSION

The JIT approach was developed in one company, Toyota Motor Company, over a period of nearly twenty years, and in Japan managers usually refer not to 'Just-in-Time', but to the 'Toyota Production System'.

Toyota holds equity in its major suppliers, which are located close to Toyota's own plant, and which themselves have been encouraged and assisted to adopt elements of the JIT system. The Japanese consider JIT to be a war on waste, the waste of space, and the waste represented by defective work and idle inventory. But strictly what they have done is to demonstrate that the waste most abhorred by conventional Western attitudes, which is the waste of capacity ('keep the machines running and the workers working, even to build unwanted stock') is far less costly than the problems it creates. Inventory is used in the west to buffer us against problems of quality, supplier delivery, unstable lead times and demand instability. Plenty of (the right) stock will cover companies against these difficulties. The Japanese view is precisely the opposite – stocks must be reduced to the level where these problems would halt production, and so the problems *must* be solved. Hence the emphasis on close supplier relations, comprehensive quality assurance, and – to avoid demand instabilities disrupting production – a fixed and levelled final assembly schedule. These are the principles of JIT as they have been explained by most Western writers (e.g. ref. 1).

Just-in-Time in practice

The author attended a "JIT study tour" of ten factories in Japan in June 1987. Our host at our very first visit began by announcing, "I'm not sure why we have been included in your tour, since we do not practice Just-in-Time, and could never hope to do so." This company, Ishida, manufactures retail and agricultural weighing and sorting equipment. The product variety is very high, small batches are designed and made often to an exclusive customer specification. The manufacturing system they employ is that which could be seen in any batch engineering company in the United Kingdom. They had a large inventory store, shortage lists to drive production, and a loading board to sequence activities. Our first visit was a small shock, and (we confessed) a relief. They had considered JIT, but rejected it as inapplicable to a high variety manufacturer with a substantial element of customisation. Did JIT apply only to assembly operations?

Certainly that was where we saw something close to the ideal described in the literature. Figure 1 shows the classic "pull" method as it is applied in another company we visited, one of Toyota's principal suppliers. The key element is that the authorisation to manufacture parts flows backwards from the succeeding stage to the preceding one – a stage cannot make anything without receiving a "kanban" (card) from the next process requesting it. Nothing is made which is not needed for that shift (sometimes for that hour) and inventory is kept low and material kept moving. JIT is not a myth and it is impressive to observe. But it is not comprehensive and not without problems. Even in this automotive component manufacturer, there are stocks to be seen – and not only in the warehouses shown in Figure 1. We saw an automated line making car radiators, and spoiling what seemed a large number of them. It was explained to us (ref. 2) that they currently had a 0·5% scrap rate (hardly the 'parts per million' or PPM quality we had been led to expect), and kept emergency stock to ensure each small container (a box of ten) was able to be filled before the Toyota delivery truck arrived with another kanban (an hourly event). Nor does Figure 1 illustrate the system used for all the company's products. They manufacture a wide range of components for all of Japan's nine car makers, and other vehicle assemblers of different types. Where a product has an especially large number of variants the JIT system is relaxed, and batch flow rather than single piece flow is employed, although the Japanese ability to achieve rapid machine change-

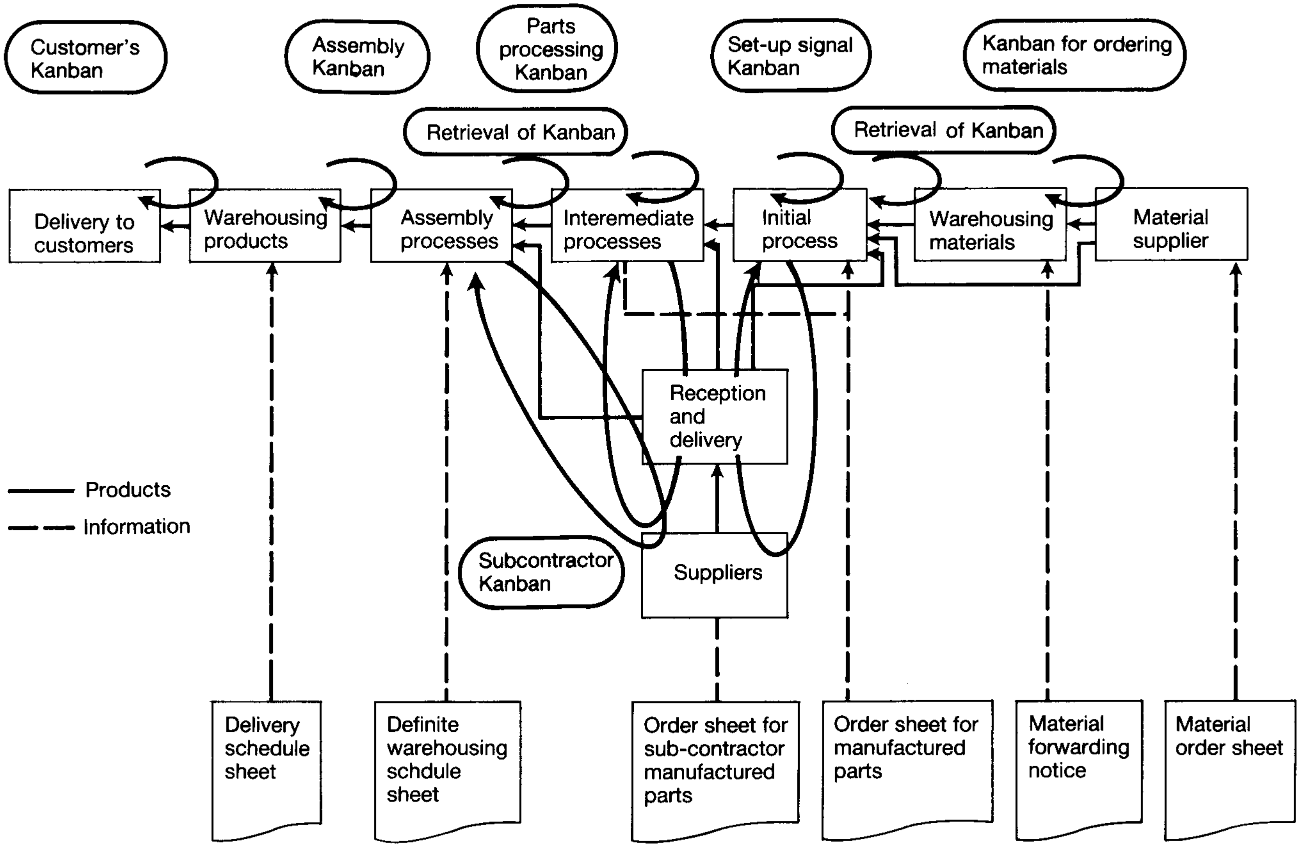


Fig. 1 JIT/Kanban materials and information flow

overs means that batches can still be kept quite small because more frequent changes are still economic.

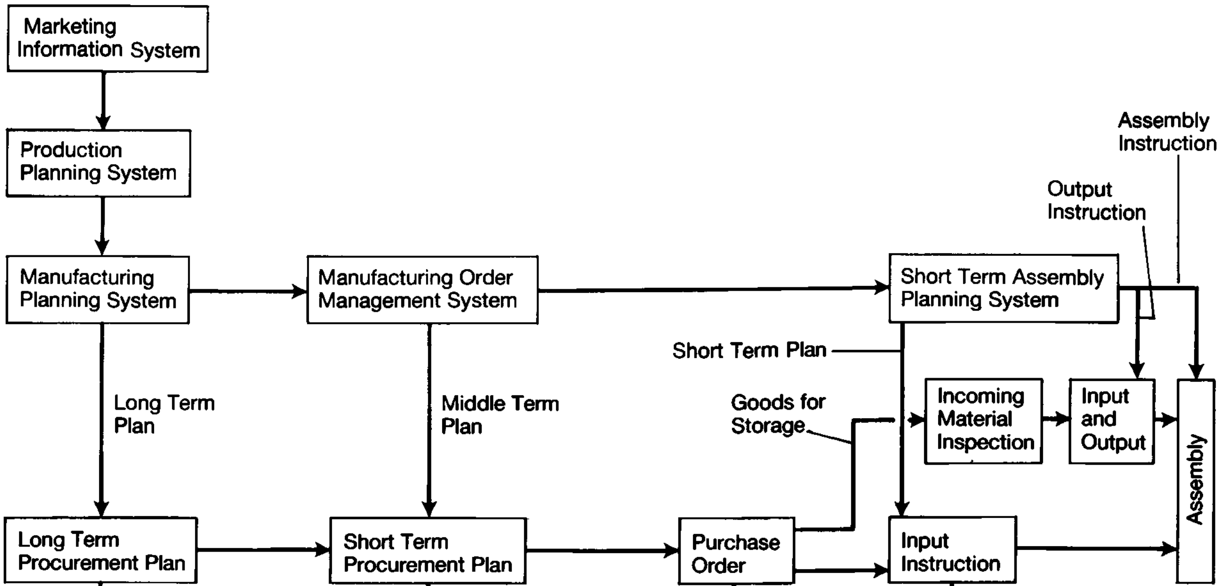
Similarly, a manufacturer of word processors, facsimile machines, point-of-sale terminals, and automatic teller machines has a wide product range, an ever decreasing product life cycle and a large customer base. Electronics assembly operations (of which Japan has over six hundred) are principal users of JIT. Figure 2 shows how this company plans JIT supplies by collaborating with vendors and informing them of needs 3–4 months before assembly, and continues to refine this information right up to a fortnight before assembly. Delivering just-in-time means planning in plenty of time, and working closely with a few suppliers over a long period – the western practice of switching purchase arrangements around in pursuit of cost goals is inimical to JIT. But this company explained that not all suppliers received the degree of trust that permitted them to deliver directly to the assembly line, bypassing any quality checks or goods inwards control.

Thus Fig. 2 shows two routes for incoming goods; one directly input to final assembly, the other via an incoming material inspection stage. This company's management told us they could not envisage a time when all suppliers supply just-in-time. The brief (and shortening) product life cycle and the demands of the market for new products and features implies new component needs, perhaps from new suppliers. Thus the split of JIT to non-JIT supplies is likely to remain at its current 50–50 ratio. They do not use kanban ("our lines are too varied") and the warehouse for finished goods typically held 5–10 days stock. Like most of the Japanese managers we spoke to, they regard the American crusades for "Zero Inventory" (ref. 3) and "Zero Defects" (ref. 4) as unrealistic, slogans which were hardly helpful even as ideals.

Information needs for JIT systems

In the west, (and, as we have seen, to some degree, even in the east), inventory is needed to cope with uncertainty, or accumulates because we pursue process economics as one of the many goals of a manufacturing system. Japanese marketing, industrial engineering, and supplies management have combined to remove these uncertainties and invalidate this conventional view of process economics as essentially long runs and the avoidance of any idle capacity. JIT and new manufacturing technologies such as FMS and CIM have put pressure on conventional cost accounting methods, which so strongly influence western manufacturing management. (Indeed, some accounting literature is beginning to respond positively to this challenge – see ref 5).

The contrast between JIT and buffer stock systems is summarised in Table 2 below. The middle block of this table illustrates that buffers are basically justified by uncertainty – the absence of sufficiently precise information. From this viewpoint, it can be seen that JIT in some ways replaces inventory

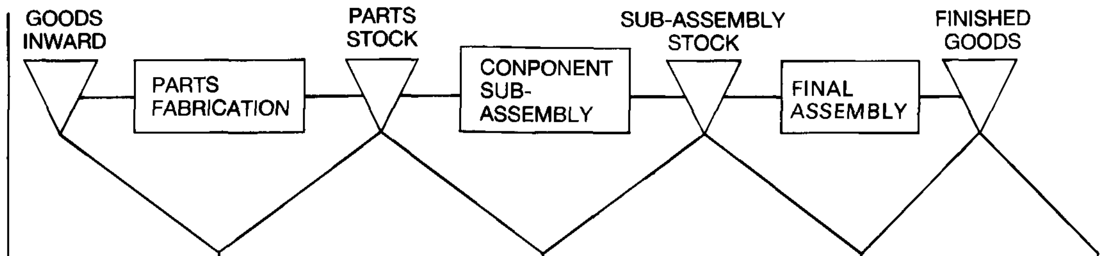


Timing	3~4 months before assembly	2~months before assembly	1~2 months before assembly	10~20 days before assembly
Term	for 3 months	for 1 month	for 10 days	for 10 days
Vendor's Reaction	Scheduling of employees and facility	Parts procurement	Start of Production	Input Control Reponse of Delivery Date

Fig. 2 JIT planning system and supplier involvement

Table 2 Contrasting approaches/attitudes of buffer stock and JIT assembly operations

STOCK POINTS
PROCESSES



ROLE OF INVENTORY UNCERTAINTY/ PROCESS ECONOMICS	Buffer against: variable supplies quality; unstable supply lead time; Take advantage of quantity discounts	Long set-up times need long runs for economic production. High parts variety produced from restricted capacity. Cover against defects. Engineering change leads to obsolescence.	Cover for frequently altered final assembly schedule. Costing methods encourage high capacity utilisation at all times	Market demands lead times shorter than manufacturing lead time
JIT APPROACH TO INVENTORY REDUCTION	Work with suppliers on quality and delivery. Holding of large quantities cost more than discount value	Design to reduce components variety & number Reduce set-up times Train operator in quality control Subcontract items which might impede flow.	Level production, fix schedule, no alteration within manufacturing lead time. View costs to encourage through put, not local utilisation. Kanban prevents unwanted production, tolerates some idle capacity	By removing buffers throughput time greatly reduced. *Variety* and *delivery* can then be offered to the market

with information. If the Japanese company is not sure of supplier lead time or quality, it will work with suppliers to make these elements of service which can be completely relied upon. Internal processes cannot produce, 'just-in-case' items may be needed. Information on what to produce when is provided by the subsequent process submitting a kanban. (In practice these are moved at fixed intervals, and may be no more than an empty pallet, but the principle still holds). And the entire system is driven from a final assembly schedule which is fixed for sufficient time to protect supplying processes from disruptive variation. The reduced manufacturing lead, time that results permits the producer to offer both competitive variety and delivery to the customer. Thus JIT can be interpreted as a manufacturing method which replaces inventory with information.

Information, but hardly information technology or what we mean by a management information system. Information in the form of computer driven schedules provided by materials requirements planning systems, is needed more for the western rather than the eastern model, at least at the operating level of daily schedules, stock status reports, and shortage lists. JIT is not a paperless system, but as can be seen from Fig. 1, the key documents listed relate to external events, while the internal processes are driven by the movement of kanban cards. 'Information' in a JIT system is often no more than the data provided by the workers' eyes. Machines are close together in product flow sequence, so it is clear what the situation is in adjacent processes – 'management by sight' is a term rightly used of various Japanese techniques such as the "andon" or warning lights prominent in most factories. Management information is of course still crucial above the operational level, and the various planning stages illustrated in Fig. 2 are reliant on computer-driven forecasting, bills-of-materials, and MRP-type explosions. The conflict often perceived between MRP (characterised as a "push" system) and JIT-style pull systems does not apply above the level of shop floor activity. Japanese companies use MRP as a planning tool (often developing their own systems in-house), and JIT is highly dependent on a widely credible master production schedule. But for materials movement and daily processing activity, the systems (and not only kanban is used) are largely manual.

Kanban, POP, and Bar Codes

Just to demonstrate how in a Japanese JIT environment very few generalisations remain true for long, one company at least has employed information technology to enhance its kanban system. This is another automotive components manufacturer which has been using JIT or 'TPS' (Toyota Production System) since 1961, and has since 1983 worked on what it calls 'POP' – 'point of production' control system. This company, like those we visited who do not use kanban because, as they explained, it was too difficult to implement, regards kanban as a very demanding technique to operate successfully. Because the kanban cards generate work, decide sequences, indicate quantities and type of operation required, they need very tight control. The number of kanban in a system, their times and points of collection, and the detailed information they contain are all prone to error – and in such highly responsive systems as those described errors in kanban control are rapidly converted into costly production mistakes. This is summarised in Table 3.

Table 3 Human Errors in Management of Kanban System

Work	Possible	Results
Making Kanbans	Content error (item number, quantity contained, deliverer, or receiver)	Wrong items Wrong acceptance check Wrong destination
Kanban maintenance (control of no. of Kanbans in rotation)	Timing error in increase or decrease of quantity Excessive or insufficient no. of Kanbans Lost Kanbans	Insufficient parts Increase inventory Unbalanced production
Collection of Kanban	Uncoordinated collection time	Insufficient parts Increased inventory (Uncoordinated nos. of Kanbans)
Issuance Kanban	Uncoordinated nos. issued Classification error on issuance shelves	Insufficiant parts Supplier (previous process) confusion
Receiving according to Kanbans	Uncoordinated receiving time	Insufficient parts Increase inventory (Uncoordinated nos. of Kanbans)
Collection of old Kanbans	Collection error	Supplier confusion Production confusion Creation of long-stored parts
Exchanging Kanbans	Exchange error	Wrong items
Counting nos. of Kanbans	Counting error	Wrong acceptance check Wrong totaling (in items and quantities)

To solve these problems, and to enhance the kanban system to provide comprehensive knowledge of production status online, it was decided to develop a kanban with a bar code on it, which could fulfil its current role of pulling material through successive processes, and by being read into a computer each time it was moved, serve as the control information source also. The equipment necessary to do this, and even the type of bar code, were not available at the time and had to be developed by the company itself. Table 4 illustrates the features of the system they developed contrasted with other methods available in 1983.

The system thus developed has considerable ramifications not only for internal control ('point of production') but for parts ordering control also. For parts purchased from outside, it is necessary to issue various vouchers for received goods, and to check delivery status. If the kanban carries this

Table 4 Features of Bar Code Reader System

	Other methods	ND method
Codes		
No. of digits (within Kanban width)	Max 30	63 (standard) 80 (max) (many digits possible as necessary)
Division within Kanban	All codes in one string	1–3 divisions possible in one Kanban without change in codes (Various combinations possible)
Reading direction	Lateral to Kanban →	Lateral to Kanban (Electronic crosswise scanning made automatically) →
Reading in reverse-direction	Yes/No depending on bar code locations	Yes (Central position makes it possible to read bi-directionally)
Dislocation of codes in any directions	Not read due to fixed position (may also depending on code size)	Automatic correction of position within electronic range
Reading speed	1–2 sec/sheet (may require several readings at this speed due to high rejection rate)	0.5 sec/sheet (usually only one within required due to low rejection rate)
Reading accuracy	Mis-reading possible due to long,one-string information without diversions, making sections of information unclear	Since codes are divided into blocks, and checked block by block, reading accuracy is secured. In addition, more digits can be expended for checking information, due to a large no.of digits available leading to further reliability (no wrong reading discovered so far)
Rejection rate (rate of information not properly read)	Rejection rate high since it is read only once and codes are in a long string. Small dust pieces may cause rejection	Minimum, since information is read many times electronically
Dirt risistance	Low, since reading position is fixed, it cannot read information if that location is dirty.	High, since information is read many times electronically with slight changes in reading positions each time at high speed
	Since codes are in a long string, information is not read if they are of differential darkness due to spot dirt.	Reading is automatically adjusted depending on color (dark/light) of information codes block by block making it possible to read partially dirty Kanban
Legibility through vinyl case	Many of them required contact reading method, decreasing their reading rate through vinyl.	Non-contact method making it possible to read information through any transparent material.

information the issue of vouchers and recording of checked delivery can be carried out by transferring information from kanbans. This type of office work normally requires a large number of processes, particularly if work at the customers' end is included, and therefore the possibility of error is great.

To overcome this, the company has developed a system in which supplier kanbans are read at the time of their issue. Issue certificates are automatically generated, and the number of kanbans issued kept in memory; vouchers for delivery and reception are issued at the same time, and delivery vouchers which have been issued before are read (via OCR) at the point of receiving the delivery; and the check for confirmation of delivery and reception procedures are carried out. In this system, issue (placing orders), delivery (receiving delivered goods) and counting of delivered and undelivered items are easily confirmed. At the same time delivery certificates and receipts necessary for transactions with other companies are automatically drawn up. Figure 3 illustrates the flow in this system.

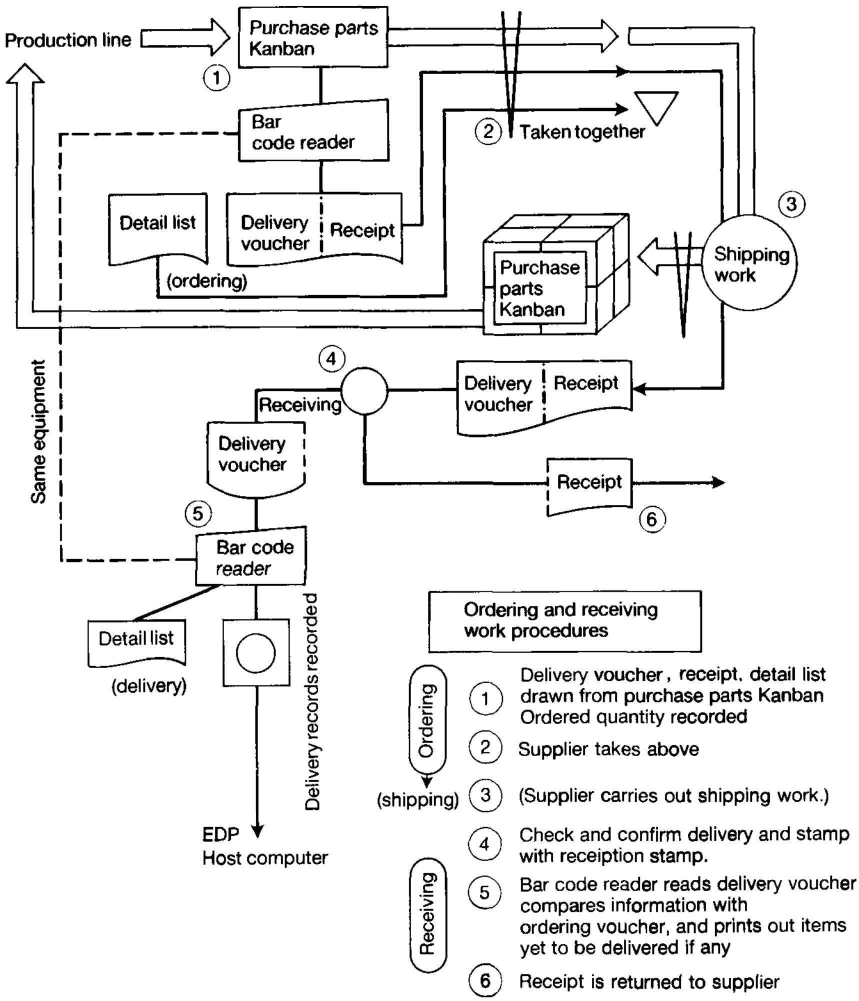


Fig. 3 Control System of Ordering and Receiving Purchase Parts using Bar Coded Kanbans

So the description given earlier, of kanban control schemes being essentially manual and replacing inventory with information but not information technology, may soon cease to be a tenable generalisation. A key point in the understanding of Japanese manufacturing systems is the constant search for improvements. Production is never, as it has been seen formerly in the West, a "solved problem".

Conclusion

This article has attempted to show that JIT is an approach of major importance for enhancing competitiveness in the manufacture of assembled products within certain variety constraints. The classic description of JIT is partly an idealisation of the actual practice to be seen even in major Japanese companies. Although many kinds of western companies are now adopting what they call Just-in-Time manufacture, the fully fledged Japanese approach appears formidably demanding even to sophisticated Japanese managers who understand Toyota's example completely. They would not endorse the claim made by Ingersoll Engineers (and most other manufacturing consulting firms), that JIT is "an essentially simple philosophy ... equally applicable to manufacturing which is not high volume and low variety". (Ref. 6). Doubtless these consulting firms can demonstrate impressive improvements in client companies, and have learned from many Japanese techniques. But to call this Just-in-Time and claim its widespread relevance to non-repetitive manufacture is to call into question not only how thoroughly JIT has been understood in the West, but whether 'Just-in-Time' continues to be a useful term.

It is this writer's conviction that the Japanese example will continue to influence western practice, causing managers to emulate, as far as their individual contexts allow, low inventory, high quality (reliability), manufacture, carried out by an increasingly flexible workforce. But for many managers the context will be too intractable for radical change, and they will look not to information to replace inventory, but to MIS and IT to help them manage the stocks which they see – rightly – as essential to the delivery of good customer service in the face of uncertainty and variation. In some respects it is a challenge which information systems have yet fully to respond to.

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Computer Aided Process Planning (CAPP): experience at Dowty Fuel Systems

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Abstract

The paper shows how computer software can perform tasks involved in process planning a manufacturing operation, giving benefits of accuracy, consistency and efficiency and, by making more and better information available quickly, can help the management in making the important decisions. The system C-PLAN, designed for this purpose by CADCentre Ltd and marketed by ICL, is described, and as a case study the use of this in the Fuel Systems Division of Dowty Defence and Air Systems Ltd.

Part I: THE C-PLAN SYSTEM

1 Process planning and estimating

The term is used to cover the activity of deciding how to turn raw material into a final product, including planning sequences of machining and inspection operations and – most important to the financial health of the company – costing and estimating.

All this, of course, has been done manually, with greater or less formality, ever since manufacturing has been undertaken on any but the smallest scale; but with the present levels of scale and complexity of manufacturing, the demands made on the quality and reliability of its products and the intensity of competitive pressures, it has become a very demanding task indeed – a heavy burden for the enterprise to carry, in fact. Since all this is, in the end, essentially a matter of handling large volumes of information, the computer should at least be able to help. However, the information is very diverse, some of it may be expressed rather informally, much of it may change, perhaps quickly, and it has to be combined and used in many different ways. It is only quite recently that advances in hardware technology – for example, in making very large capacity, fast access information storage an economic possibility – in database management techniques and in the understanding of the properties of information – for example, the formal representation and manipulation of knowledge – have made it possible to build systems that can be of real, practical help to a large scale manufacturing operation.

The main benefits one would expect from a computer based system are these:

Capture of experience. Good human planners have usually spent a long time with their employer and have built up a considerable knowledge of the operation – often almost subconsciously; and much of this is likely to be lost to the company when they retire or leave for any other reason. Once captured in a computer system, this knowledge is there for all time and for all to use, and can be kept up to date as new knowledge is gained.

Consistency. Once a plan has been agreed on and input to a computer system the system will execute it whenever required without error or variation; only changes made deliberately will cause changes in execution.

Avoiding duplication. It becomes much easier to search for previously constructed plans that, perhaps modified, will meet new needs; and to build a new plan from appropriate parts of old ones.

Lightening the load. A large amount of the work of even the most skilled planners is sheer tedium, like filling in forms and writing out instructions to machine operators – and it just has to be done. Such documents can be produced automatically, quickly and very accurately by a computer system.

And of course:

Speed, which cuts leads times, reduces backlogs and makes frequent changes possible.

A further feature of a computer system is the control it allows over access to information. If it is to be of real use in a factory then almost everyone will need to make some use of it; but the kind of access each individual is allowed can be controlled as rigidly as is desired by a password system, supplemented if necessary by control of users' powers. Even a knowledge of the existence of certain information can be concealed from all but a specified set of individuals, as can the power to change certain items – for example, standard times for basic machining operations, or unit costs.

2 The C-PLAN system

CADCentre has developed a large scale CAPP system, C-PLAN (Ref. 1). Its core is a database of effectively unlimited capacity, with a very sophisticated management system. The essential structure is shown in Fig. 1. It provides these main functions, all with many possibilities for variants:

Planning: conversion of designs to complete production plans, with all details given.

Reporting: automated production of all necessary information and paperwork, including that needed for a production control system such as MRP. Costs and estimates are included here.

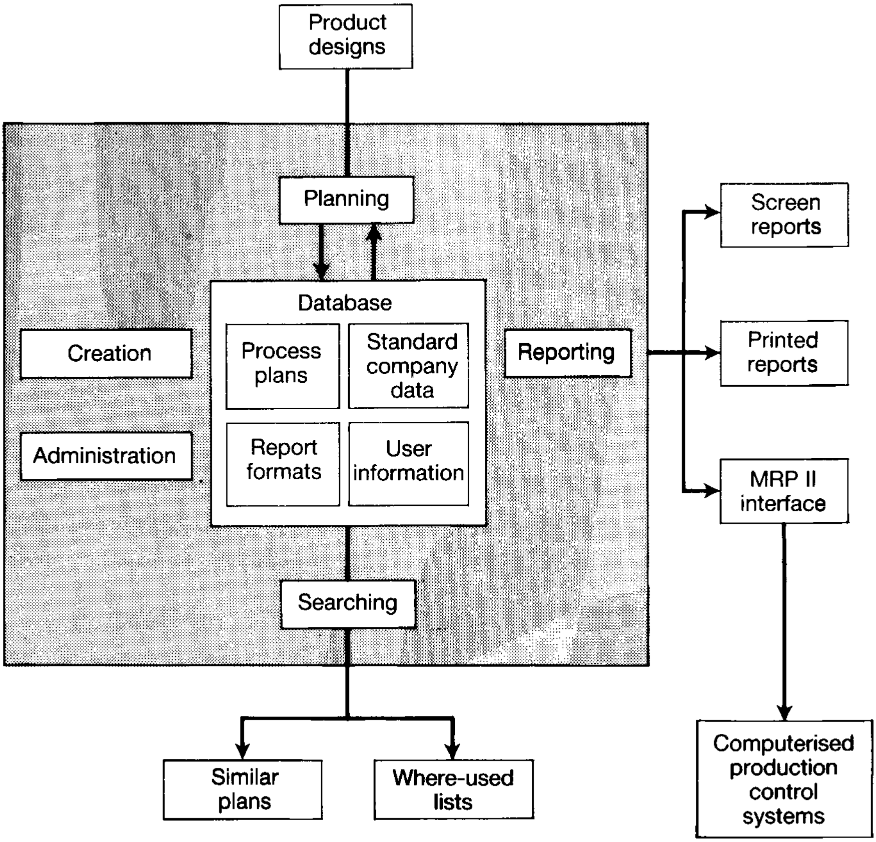

Fig. 1 Components of the C-PLAN system

Searching: as the name implies, searching the records for previous plans or parts of plans that could be useful in the current situation.

Data creation: storing, in the form or forms required for the various uses, all the factual information relevant to the company's operations.

Access control: as described above; with continuous control of all use made of the system.

It will be clear that such a system must allow many relations of dependency to be specified among the data items, and to be changed easily and quickly when necessary. This is achieved in C-PLAN by means of modified data structures which permit relational-like flexibility without the usual penalties in response time and processor demand.

In the interests of portability the system is written mainly in Fortran.

So comprehensive a system is obviously complex, and anything like a full description would need many more pages that a journal paper could reasonably allow. The following simple illustration should give an idea of how it looks to an end user, in this case a planner building an entirely new plan.

The plan is constructed by a dialogue between the engineer and the system, in which the latter either prompts the user or asks for information. The system is menu-driven and assumes no knowledge of computers. For example, having selected a particular turning machine tool the user may be presented with the options displayed as in Fig. 2.

Option Key	Abbrev	– 15 entries in menu OPERATOR INSTRUCTIONS
1	CLDC	LOAD TO COLLET
2	FDST	FEED TO STOP
3	RFFN	ROUGH AND FINISH TURN_MM DIA X_MM LONG
4	THRD	TURN THREAD DIA_MMX MM DEEP
5	CDRL	DRILL_MM DIA X_MM DEEP
6	CTAP	TAP_MM DIA X_MM X_MM DEEP
7	RFBR	ROUGH AND FINISH BORE_MM X_MM DEEP
8	CLFC	FACE_MM DIA
9	CLPO	PART OFF_MM LONG
10	CHAM	CHAMFER EDGE_
11	CLPD	PACK TO AVOID DAMAGE
12	UNLO	UNLOAD
13	DRLH	DRILL_HOLE X_DEPTH
14	RTRN	ROUGH TURN_X_LENGTH

Fig. 2 Example Turning Operation Details

Any of these options can be selected either by entering with the key or by pointing with the cursor. Some of these details (e.g. 1 and 2) do not contain any parameters, so the system will ask the planner to supply a time estimate if a standard does not exist. If however an option is selected that involves parameters, the system will prompt for these and for any other data that has been specified as compulsory. In this way a complete operation is built up, as shown in Fig. 3.

OP	COST CODE	LOCATION	OPERATOR INSTRUCTIONS	SET	RUN
	203	CAPSTAN		20	3.072
		LATHE	–1 FEED TO STOP		0.150
			–2 ROUGH TURN 25.5 × 30.5 LENGTH		0.459
			–3 FINISH TURN 24.5 × 30.5 LENGTH		0.253
			–4 DRILL 15.0 HOLE × 67 DEPTH		2.010
			–5 PART OFF 59mm LONG		0.200

Fig. 3 A Complete Machine Operation

3 Areas of application

C-PLAN is currently being used for process planning products as diverse as printed circuit boards, machined components and highly complex assemblies. A recent timed analysis of the direct productivity showed a gain of 2·34:1 for C-PLAN over alternative methods.

C-PLAN has now been sold into more than a dozen manufacturing sites, with a total of over 60 concurrent users.

Part II: IMPLEMENTATION IN DOWTY FUEL SYSTEMS

The Dowty Group is a large engineering organisation that operates at a high level of technological sophistication. One of its constituent companies is Dowty Defence and Air Systems Ltd, within which is the Fuel System Division, referred to here as Dowty Fuel Systems, DFS.

DFS designs, develops and manufactures advanced products concerned with the use of fluid fuels for motive power, such as pumps and controls for gas turbines and the main- and after-burner systems for jet engines. It has factories in Cheltenham and Staverton in Gloucestershire and at Atworth in Wiltshire, totalling over 1000 employees; the implementation described here was at the Cheltenham plant, where the main test facilities are located. The company as a whole has had long experience of computer aids to engineering design and production.

In early 1987 DFS, after much study of the possibilities of CAPP, issued a specification for the system it was prepared to consider. This was a very detailed document which started by setting these objectives:

Overall

- to improve the efficiency of operation, storage, retrieval and modification of process plans
- to create a medium for capturing and storing Production Engineering knowledge in a structured and accessible format
- to integrate the production of process plans into the Dowty Fuel Systems CIM system
- to improve the clarity and consistency of presentation of process plans.

Details

- to reduce the time taken to produce process plans
- to eliminate duplication of effort when preparing process plans
- to standardise the text used within process plans
- to minimise the volume of clerical work undertaken by skilled engineers during process plan preparation and to enable them to allocate more time to improving manufacturing methods
- to utilise an Information Classification system as the main driver for the process planning function

- to provide a rationalised company-wide database of Production Engineering data (e.g. feeds, speeds, times, materials etc.)
- to shorten the learning cycle of new Methods Engineers
- to provide links between the process planning and manufacturing systems for transfer of routing, tooling and all other associated information
- to provide links between the process planning and CAD systems, enabling the viewing of CAD data during the process of process plan creation.

An interesting point of industrial psychology was that these were displayed on a large sheet on the wall of the office in which the implementation team worked.

CADCentre responded with an equally detailed document proposing C-PLAN, were invited to perform a benchmark test and were awarded the contract. The software and hardware were delivered in September 1987; as shown in Fig. 4 the system administrators were trained in September and then spent 3 months setting the system up. Training of end users began in January 1988, the system went live in February 1988 and extensions were ordered in March 1988. The effort required for this implementation was 9 man-days of CADCentre support (Dowty had estimated 20, but the 9 proved sufficient) and 154 days of their own staff. The timetable of the operation is given in Fig. 4.

ACTIVITY	CALENDER					
	SEPT	OCT	NOV	DEC	JAN	FEB
Delivery Software	§§					
Administrator Course	§§§					
Build Database		§§§§§§§§§	§§§§§§§§§§	§§§§§§§§		
Test Database				§§§§		
Planner Training				§§§		
Initial Problem Solving					§§§§	
Produce Plans						§§§§§§§§§

Fig. 4 Dowty Fuels Implementation Plan August 1987

Considering the scale and complexity of the operation the implementation went very smoothly. Dowty had decided on a 'Big Bang' policy: the old manual system was to be closed down one day and C-PLAN taken up the next, with no overlap. This certainly concentrated the minds of the people responsible for the change, and whilst the experience was traumatic the change was made with no real hitches.

C-PLAN now produces all the process plans and shop-floor documents at the Cheltenham plant, just as was required of it by DFS; and the generation of output to link to the company's production control system is being considered. To give a simple example of the paperwork now being produced Fig. 5a is a typical hand-written instruction sheet for a machine operator and Fig. 5b that produced by the system.

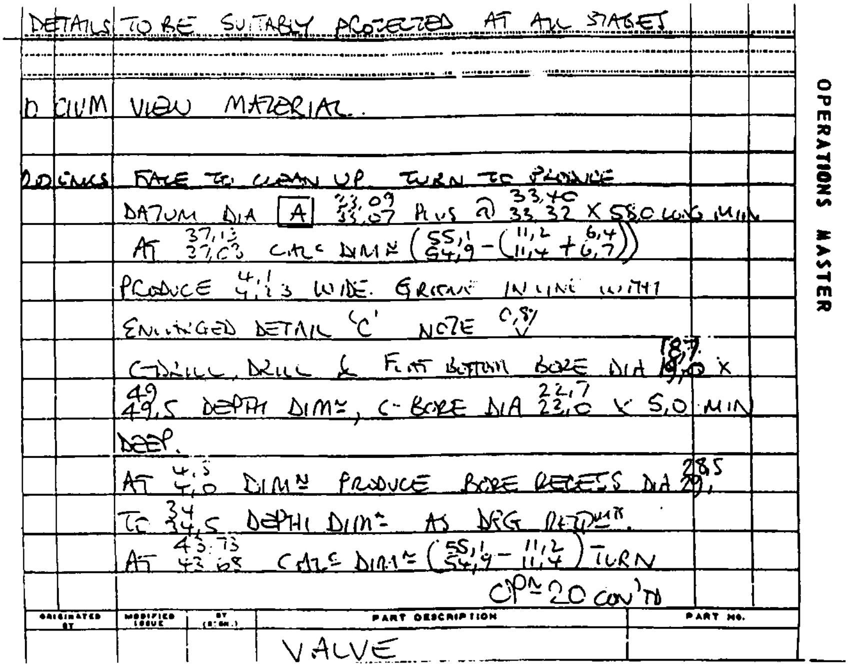
DETAILS TO BE SUITABLY PROTECTED AT ALL STAGES
10 CIUM VIEW MATERIAL.
20 CMCS FACE TO CLEAN UP. TURN TO PRODUCE
DATUM DIA $\boxed{A}$ 33,09/33,07 PLUS @ 33,40/33,32 X 55,0 LONG MIN
AT 37,13/37,03 CALC DIMN (55,1/54,9 − (11,2/11,4 + 6,4/6,7))
PRODUCE 4,1/4,13 WIDE. GROOVE IN LINE WITH
ENLARGED DETAIL 'C' NOTE 0,8/
CENTRE, DRILL & FLAT BOTTOM BORE DIA 18,7/19,0 X
49/49,5 DEPTH DIMN, C-BORE DIA 22,7/22,0 X 5,0 MIN
DEEP.
AT 4,5/4,0 DIMN PRODUCE BORE RECESS DIA 28,5/29,
TO 34/34,5 DEPTH DIMN AS DRG REQUIREMENT.
AT 43,73/43,68 CALC DIMN (55,1/54,9 − 11,2/11,4) TURN
OPN 20 CON'TD
ORIGINATED BY | MODIFIED ISSUE | BY (S.OH.) | PART DESCRIPTION | PART NO.
VALVE
OPERATIONS MASTER

Fig. 5a

DFS reckon that they have achieved all their objectives with the system; they value it particularly for:

- increased productivity
- the taking of the load of paperwork off the engineers' backs
- the feeling of greater control of the plant that it has given them.

The system has in fact become indispensible to the running of the plant; and the users are enthusiastic – very much because they were thoroughly involved in the implementation. DFS have now ordered further extensions to serve the other two factories.

Reference

1 C-PLAN – Computer Aided Process Planning.

Descriptive brochure available from CADCentre Ltd, High Cross, Cambridge CB3 0HB.

Fig. 5b

SUITABLY PROTECT COMPONENTS AT ALL STAGES

Header Notes

Op No		M/C Code	Operation Description
10		CIVM	VIEW MATERIALS
20		CNKS	NAKAMURA TMC 2
-	1		FACE TO CLEAN UP
-	2		TURN OVERSIZE 33.400 / 33.320 DIA X 58.000 / 58.100 LONG
-	3		PRODUCE FOR GROOVE 27.000 / 26.950 DIA X 4.100 / 4.230 DIMENSION
-	4		PRODUCING SURFACE FINISH TO 0.80 MICRO METERS AS DRAWING REQUIREMENTS
-	5		CENTRE DRILL
-	6		DRILL TO PRODUCE 18.700 / 19.000 DIA X 49.00 / 49.500 DEEP
-	7		FLAT BOTTOM DRILL TO PRODUCE 18.700 / 19.000 DIA X 49.000 / 49.500 DEEP
-	8		C/BORE TO PRODUCE 22.700 / 23.000 DIA X 5.000 / 5.100 DEEP
-	9		BORE TO PRODUCE 28.500 / 29.000 DIA X 34.000 / 34.500 DEEP
-	10		TURN FOR 24.800 / 24.750 DIA X 58.000 / 58.100 LONG
-	11		R.S.E
-	12		PART OFF 56.00 DIMENSION, MIN OVERALL LENGTH

Use of Integrated Electronic Mail within Databases to Control Processes

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Abstract

This paper describes how the use of an integrated mail facility has been developed by Manufacturing Operations within its Engineering databases. This facility enables 'processes' to be defined, controlled and driven by electronic mail. The facility was introduced in October 1985 on the PPCC database which controls Engineering Changes.

1 The creation of the concept

During the early part of 1985 the paperless change control system (PPCC) was being developed. Engineering Change Control is an extremely complex and costly part of ICL's business. The basic logistics are:

4000–4500 changes per year.
Estimated total cost in excess of £20 million.
An active community of 1000 users.
Total community of 3500–4000 users.
The active involvement of 15–20 ICL locations.
A worldwide requirement for the latest information.

It was quite easy to see how most of the data related to change control could be held on a conventional database, but two problems emerged which had to be addressed to produce a successful system, namely:

(i) How to achieve the multiple signatures required by the change control process.
(ii) How to give visibility to the Engineering, Manufacturing and Customer Services community of the status of a particular Engineering Change Proposal, i.e. where it is, where it had been and where it was going.

Fortunately the solution to both problems came from the introduction of an Integrated Electronic Mail facility: that is, not a separate system requiring LOG OUT and LOG IN, but a facility that was available alongside the normal database transactions.

2 How the concept developed

It was noticed that the process of Engineering Change Control contained many different stages, each one involving an actionee and invariably a signature. The signatures related directly to each of the stages in the process. The requirement of control, monitoring and visibility would require the ability to automatically:

1 List all the actions of a process
2 List all the actionnees of a process
3 Record each time an action was placed
4 Record each time an action was accepted
5 Record a target for action completion
6 Record each time a signature was added
7 Record each time an action was completed
8 List all completed actions
9 List all current actions
10 List all outstanding actions

3 Implementation of Integrated Mail

The first step was to identify the stages in the process. This screen template became known as the status screen 40. The stages in the Change Control Process are identified on a single screen display and became known as the 'STATUS' of a change.

Example (see Fig. 1).

Each line of the screen represents an action in the process of change control. The actions can run consecutively or concurrently as required by the process.

Each time an action is placed a date appears under the column 'Memo date' and a prompt appears on the mail box of the 'actionee'. When the actionee acknowledges the mail prompt a date appears under the 'In work' column.

The 'Target date' is input automatically by calculating the appropriate number of working days from the 'Memo date'. When the actionee has completed the database input and signed off the appropriate screen the next memo in the process is automatically sent to the next actionee and a date appears under the 'Completed' column. Consequently this status screen automatically monitors the precise state of the change proposal as it passes through the process.

The memos which drive the process can have considerable functionality but each individual memo is always consistent. For example in the change control system memo type 3 is always sent to raise an Engineering Change Proposal. Memo type 5 always actions design services and Memo type 6 always actions the design authority after the Design Services input. Because of this consistency in memo functionality, the sending of memos can be directly related to the actions contained within the process.

```
40EM08300                   ENDB Service ECP STATUS   for VDB3 on 22 FEB 88 at 09:28
PPCC No:   M08300           Issue: 02        Received: 080288        Status: ####5
Title   :  K400 CHANGE PAL AND LOGIC
Product Group : 116         Actionee         Memo date  In-work  Target  Completed
----------------------------------------------------------------------------------
1 PIF Raised
  ECP Raised                HEATH J           080288    080288           080288
----------------------------------------------------------------------------------
2 Design Investigation      HODGKINSON W      080288    080288   180288  090288
  Design Services Auth      HUGHES J          090288    090288   240288  090288
  Design Authority          HODGKINSON W      090288    090288   190288  090288
  System / Quality          WARD B            090288    090288   140288  090288
----------------------------------------------------------------------------------
3 Manf Appraisal 1          PASS R            090288    110288   190288  150288
  Manf Appraisal 2          HAYWARD D         090288    110288   190288  110288
  Tech Lit Appraisal
  WSD 'Appraisal            MILLER G          090288    110288   190288  110288
----------------------------------------------------------------------------------
4 ECP Authorised            HEATH J           190288    190288   190288  190288
  ECP Rejected
  FCA Authorised
----------------------------------------------------------------------------------
5 NCD Issued                HUGHES J          150288    150288   060388
                            TRANSACTION COMPLETED
```

Fig 1

The process can be represented; in terms of its memos, as in Fig. 2. The diagram shows how each of the memos actions the various participants in the process.

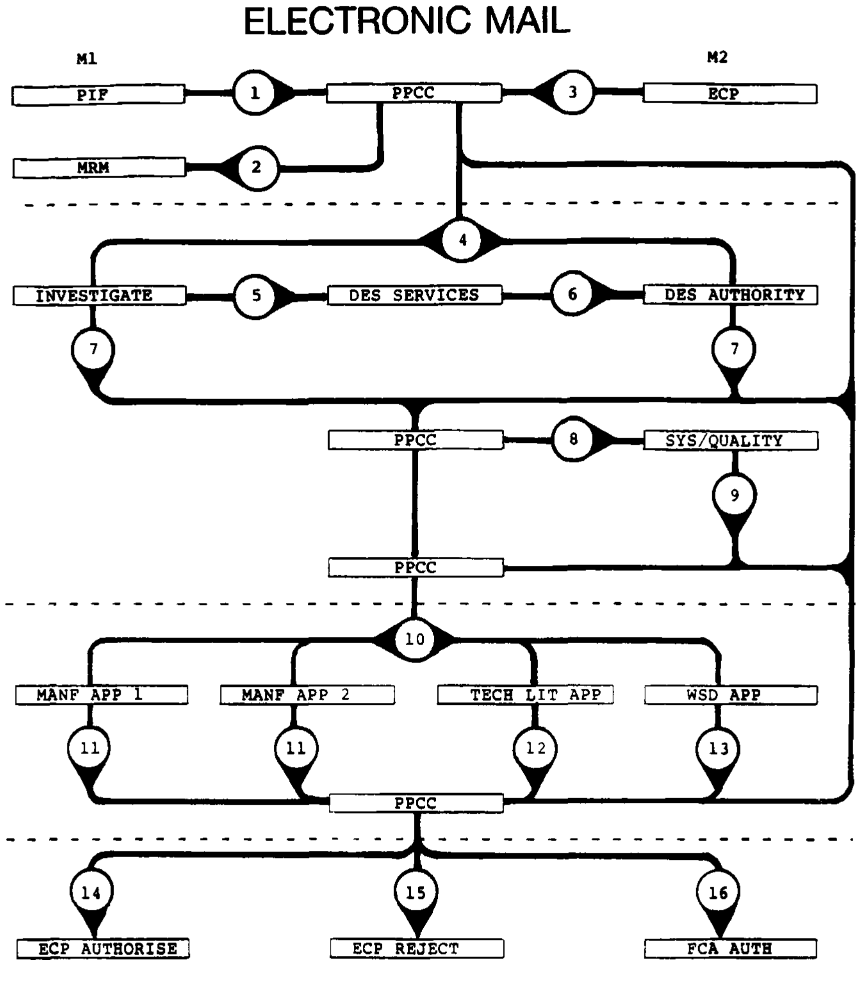

Fig. 2

The PPCC system was developed during 1985 and went live on 7th October 1985.

Soon after the system introduction it became apparent that the mail facility coupled with the signature integrity were the features which ensured success. At last a MAIL system had been developed which actually made life easier for the users: instead of forcing users to record their progress on a database, the very act of 'doing the job' automatically maintained the progress.

4 Exploitation of Integrated Mail

With the benefit of hindsight it was realised that database integrated mail was an extremely powerful tool that could be adopted on any other system.

Unfortunately the PPCC mail was 'hard coded' into the database and could not be extracted for use elsewhere. Therefore the decision was made in 1986 to produce a flexible, stand-alone version of the mail which could be 'tailored' or 'parameterised' to control any process. The parameterised mail system was produced during 1986 and was launched in 1987.

5 The PASS System

The system is called PASS, standing for Prompts, Actions and Status Summaries. The following block diagram shows the basic PASS functionality.

Figure 3 shows the 'STATUS', which is the process definition. Against this are held:

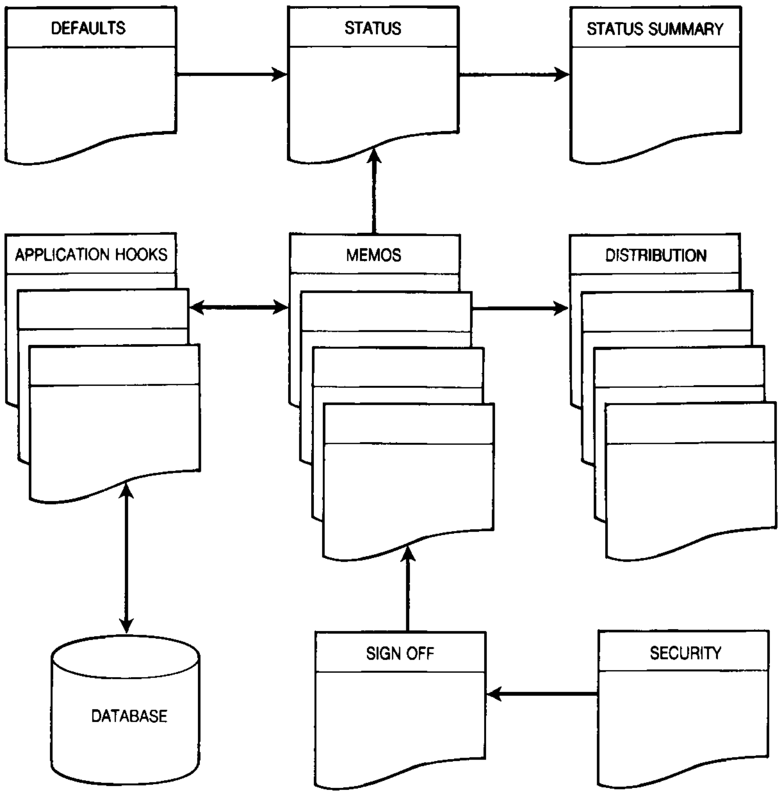

Fig. 3

- The 'DEFAULTS' of actionee.
- The 'STATUS SUMMARY' which enables the status of multiple examples of a process to be viewed.

The 'MEMOs' drive the 'STATUS' and 'DISTRIBUTION'.
The 'SECURITY' determines who has the authority for 'SIGN OFF' which in turn can drive 'MEMOs'.
'MEMOs' can be linked with 'DATABASE' transactions via 'APPLICATION HOOKS' such that a memo may be driven automatically by completion of a 'DATABASE' transaction, directly from a translation or may be conditional on the sending or receipt of another 'MEMO'.

To enable an implementation of PASS to be defined several transactions are required to input the parameters and view the resultant mail and status.

These transactions can be diagrammatically represented as in Fig. 4.

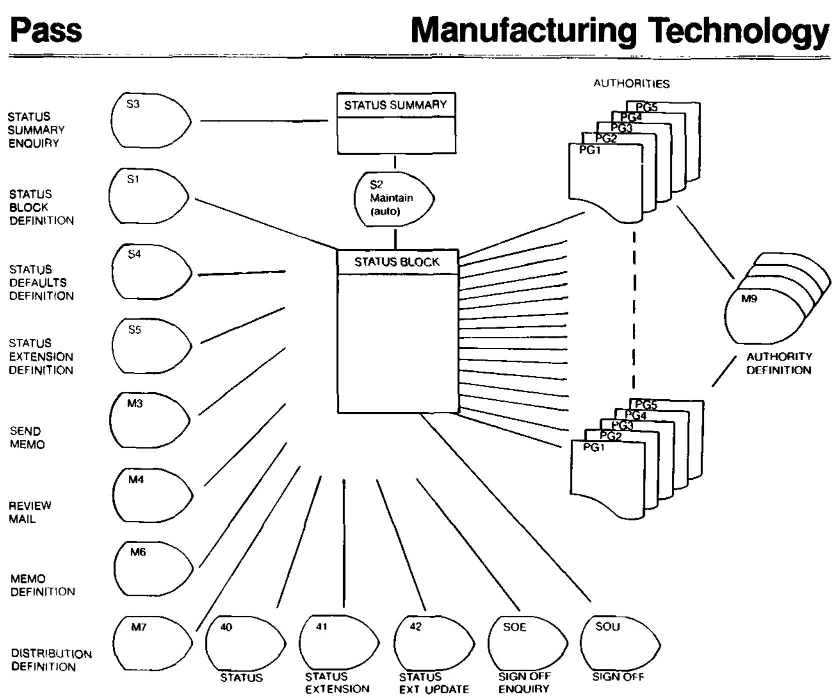

Fig. 4

6 PASS system definition

6.1 Data types

PASS is capable of handling over 50 000 different process types. Each process type is known as a data type (i.e. any combination of 3 alphanumeric characters). Each data type is created and maintained by the following transactions.

6.1.1 Status blocks (S1 transaction). Each process type is defined by the number of 'Status Levels' that may exist. These 'status levels' may relate to serial or concurrent steps which take place to complete the process.

These status levels form what is known as the 'STATUS BLOCK'. Therefore the 'STATUS BLOCK' defines all the possible steps in a particular process.

6.1.2 Status summary (S3 transaction). The 'STATUS BLOCK' is divided into 5 sections to enable a simple 'STATUS SUMMARY' to be produced showing the status of a number of processes.

This 'STATUS SUMMARY' takes the form ⟨12345⟩ representing the 5 sections of the 'STATUS BLOCK' (see Fig. 1). Where a section has outstanding actions the section number is displayed and where the section is complete an '*' is displayed. Therefore **34* indicates STATUS BLOCK sections 3 & 4 are incomplete and sections 1 2 & 5 are complete or unnecessary.

Each of the 5 sections of the 'STATUS BLOCK' can be subdivided into 9 status levels dependent on the requirements of the process; therefore there are a possible 45 (5×9) status levels or steps in any process.

6.1.3 Status defaults (S4 transaction). The status block indicates all the actionees of a process. The list of actionees is defaulted for each data type, and within each data type different lists of actionees can be handled by use of 'PRODUCT GROUPS' (or security groups); thus each data type could have over 50 000 actionee lists.

In addition to PRODUCT GROUPS there is a further variant of 'SITE' (5 chars) where the actionees can vary dependent on physical location. This makes the combination of 'DATA TYPE', 'PRODUCT GROUP' and 'SITE' effectively unlimited. The default lists are provided to save user input time. It is quicker and easier to amend a list of actionees to suit a particular instance of a data type than to create a new list each time.

6.1.4 Status extension (S5 transaction). As each status level may have other dependencies, each of these levels is capable of extending to a further 14 actionees by use of the status extension facility; therefore any process could have up to 630 ($5 \times 9 \times 14$) actionees.

6.1.5 Security (M9 transaction). To enable security to be applied to PASS, each status level can have any number of authorities appended to it; and these authorities can be held by any combination of 'DATA TYPE' 'PRODUCT GROUP' & 'SITE'.

6.1.6 Sign off (SOU & SOE transaction). The 'signing off' of each status level is achieved by reference to the Security and a check as to the user who has 'logged in'. SOU provides data input and SOE provides an enquiry.

6.1.7 Status summary creation/maintenance (S2 & S8 transactions). Once a status summary has been created it will be maintained each time the status block is amended by the S2 transaction (NB: this transaction is invisible to PASS users). The S8 transaction has been produced specifically for the change control environment and produces a status summary for an NCD (Notification of Change to Documentation).

6.1.8 Product Groups (P1 transaction). Many of the PASS transactions utilise the facility of 'PRODUCT GROUPS'. This facility enables the division of a data type into groups which have the same 'SECURITY, STATUS DEFAULTS, STATUS EXTENSIONS and DISTRIBUTION LISTS'.

6.2 PASS prompts and actions

The mail system is created maintained and viewed by following transactions.

6.2.1 Memo Definition (M6 transaction). The prompts and actions in PASS are called 'MEMOS' and have predefined functionality input by the M6 transaction.

Each PASS installation can have in excess of 50 000 defined memos.

The memo definition includes many details i.e. description, who sends, who receives, what checks are required, what distribution, what happens to other memos or what happens if it is rejected plus the facility to react to, or cause a reaction in, a remote database via a facility called 'APPLICATION HOOK'.

6.2.2 Memo Sending (M3 transaction). Memos can be sent automatically by interaction with 'SIGN OFF' transactions or 'APPLICATION HOOKS' dependent on how they are specified by the M6 transaction. Memos can also be invoked manually by direct use of the M3 command.

6.2.3 Mail Viewing (M4 transaction). Mail boxes can be viewed by use of the M4 transaction. When the user views their own mail it will be displayed in update mode, all other mail boxes will be display only. To view 'own mail' M4 only is required, otherwise the precise name of the mail box is required.

6.2.4 Distribution (M7 transaction). Distribution of prompts and actions is defined by the M7 transaction. M7 can define an unlimited number of distribution lists, related to product group or independent of these. Lists can be manipulated as they are invoked and combined if required.

6.3 PASS viewing transactions

The user of PASS will view the system using the following transactions:

6.3.1 STATUS BLOCK Views (40, 41 & 42 transactions). The 'STATUS BLOCK' produced by PASS for a particular process can be amended or viewed by these transactions.

The 40 transaction displays the STATUS BLOCK: any ability of amendment will generally be restricted to a high level of authority.

The status block transaction can be used to reiterate a process. At any stage in a process's progression, the process can be halted and reiterated back to any previous status level. When this occurs the status block will be cleared between the 'current status level' and the 'proposed status level' and the memo actioning the 'proposed status level' will be re-sent.

The 41 transaction creates and displays the STATUS BLOCK EXTENSION.

The 42 transaction permits the completion of status block extension actions by the addition of a date.

7 PASS system implementation

The implementation must follow a predefined path, as follows:

STEP 1 BUSINESS ANALYSIS

The process to be controlled needs to be analysed to establish the stages in the process and the function of each stage. It is then necessary to establish how each of the stages is started and completed; this will provide the 'memos' or 'prompts and actions' necessary to drive the process.

At any stage of the process there may be a requirement for 'application hooks' to the database or distribution lists.

STEP 2 STATUS BLOCK DEFINITION (S1)

The status block definition defines the stages in the process (e.g. raised, approved, appraised, authorised, completed).

Each stage is allocated a number (NN). In a simple 5 stage process, the status block would be:

11, 21, 31, 41, 51.

Each stage has a description which describes the functionality. The sub-section of each stage can now be defined (up to 9 for each stage).

STEP 3 MEMO DEFINITION (M6)

Having defined the stages in the process in step 2 it is necessary to define the memos (prompts and actions) which will drive the process using the M6 transaction.

STEP 4 STATUS BLOCK DEFINITION (S1)

The memos created in STEP 3 can now be added to the status block. Each level of status can be opened, accepted into work or closed by the action of sending, accepting or receiving any of the memos.

Memos may be grouped together if required.

STEP 5 PRODUCT GROUPS (P1)

Where multiple security is required the product group or security groups must be specified.

STEP 6 SECURITY (M9)

Each level of status can now be given security by the M9 transaction. Multiples of authorities can be held by product group.

STEP 7 STATUS BLOCK DEFAULT (S4)

Each level of status for each product group can now be given an actionee (or default). This is not essential, but when the actionee list is fairly consistent it will avoid unnecessary input to the 40 screens when status blocks are created.

STEP 8 STATUS BLOCK EXTENSION DEFAULTS (S5)

Where a level of status has a consistent list of 'EXTENSION ACTIONEES' these lists can be input by the S5 transaction by product group and status level.

STEP 9 DISTRIBUTION LISTS (M7)

Whenever distribution lists are required these are input by the M7 transaction.

STEP 10 COMPLETION

The basic PASS system has now been input. It is a dynamic system, and all the stages can be amended 'on the fly' – as Transaction Processing interactions; but great care must be taken if any deletion is involved, as this could affect other users. Any amended definitions will come into force after a database recycle or at the next reload.

8 Summary

8.1 Product Performance and Change Control (PPCC)

The first use of an integrated mail facility was implemented in the Change Control System (PPCC) in October 1985.

The introduction of PPCC to the Engineering Database service (ENDB) resulted in the worldwide use of a system which had previously been confined mainly to drawing offices and production engineers and controllers.

At the time of going to press the following statistics are relevant: they will give an idea of the scale of the activity:

Number of world wide users		3000–4000
Number of mail users	approx	1000
Current live memos	approx	12000
Reduction in number of changes		20%
Annual savings to M & L		£750K
Daily transaction rate	approx	15000
Number of terminals logged in	approx	130–150

8.2 Prompt Actions and Status Summary (PASS)

PASS has been implemented into the Issue and Archive Database (IADB) to control the flow of manufacturing data into the Kidsgrove plant. Each type of data has its own process requirements and lists of actionees; to date the following have been defined in the system:

1 The issue, validation and release of PCB drilling data.
2 The issue of drill instructions.
3 The issue, processing, validation and release of PCB artwork data.
4 The issue, processing, validation and release of automatic insertion data for PCBs.

Several other types of data are under investigation, including graphical and test data.

The PASS system, integrating electronic mail with databases, has already proved its value in ICL. Now that the stand-alone system is available and proven its use is being considered for other databases where complex combinations of controls and signatures are required.

Value engineering – A tool for product cost reduction

Sarah Lynn
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Abstract

The paper reviews some of the well-established Value Engineering techniques used to effect product cost reductions. It outlines what ICL does to ensure that the underlying concepts are taken fully into account in the company's approach to manufacturing. It also aims to illustrate how cost reduction must be strategically focussed with the emphasis on competitiveness rather than on quick savings.

A summary is given of a study made in collaboration with Salford University in which a proprietary software package was used to analyse the design of a particular ICL product. This study identified certain problem areas and led to a new and more satisfactory design.

1 Introduction

It goes without saying that value is distinguished from cost, in that the value of a product or service is the value to the purchaser or customer whilst the cost is borne by the manufacturer or supplier. The manufacturer's aim is of course to maintain value while reducing cost.

The general term Value Engineering covers traditional Value Analysis/Value Engineering (VA/VE), Design for Assembly and Design for Manufacture; here we shall consider only the first two, in that order, and as a case study for the second we describe some work done by ICL and Salford University in collaboration.

Total costs can be reduced in two main ways: by avoiding altogether some of the individual elements of cost, or by reducing elementary costs inherent in the design or in the assembly process used.

The principle of *cost avoidance*, associated with Value Engineering, Design for Assembly and Design for Manufacture, means essentially that the methods should be used early enough so that unnecessary costs and/or problems are not built into the design of the product: cost *reduction* as such then becomes less important. There is a close relation between these principles and the approach underlying the ICL Quality Education System – Prevention, not Appraisal.

1.1 Background

The principles of VA/VE were enunciated many years ago; they originated in a lean period just after World War II, and there is plenty of evidence for their effectiveness. This paper argues that a manufacturer should not simply use the methods to gain, say, a 10% reduction in the cost of a particular product, looking at his own products in isolation. He should incorporate into his study a deep knowledge of those of his competitors in his attempt to gain a competitive advantage in cost or technology. With this approach VA/VE and Design for Assembly can be transformed from merely tactical to strategic activities.

1.2 The ICL position

The view just advocated is that taken in ICL. The problem, common to all manufacturers, is that certain products cost too much to make and therefore lose their potential competitive edge. This is attacked by two routes:

- applying Value Engineering to find ways of reducing the production costs of the existing designs, taking account of everything that can be learned about competing products
- designing for cost avoidance in the early stages of development of all new products.

2 Value analysis/value engineering

The ultimate aim of VA/VE is to eliminate all those activities and features associated with a product that add no value.

It may be helpful at this stage to distinguish between VA and VE. The objective of VA is to reduce the direct cost of a product without reducing its value, whilst VE concerns designing a new product with regard to both cost and value. Both involve studying the costs that follow from compliance with the requirements of the market (the prospective customers) so as to give a competitive product at the lowest possible cost; the study will also provide guidelines for the allocation of resources according to function.

An important part of VA is *function cost analysis*, the identification of the production costs associated with the provision of functions given specifically in the statement of market requirements. Such analyses require information on the costs of components, the manufacturing processes and design data, at the very least. The analysis will often reveal that some function, though said to be necessary, in fact adds little to the value of the product but a great deal to its cost.

ICL held a Value Analysis Workshop in March 1987 at which a function cost analysis was carried out on a particular printed circuit board (code K400, although the name is immaterial here). This gave the following allocation of production costs to functions:

provision of	processing power	29% of total
	floating point	20
	local store	15
	mass store	11
	communications interface	10
	video interface	8
	user interface	4
	enhancements	4

The approach to VA/VE can be quite structured and can be helped by answering a set of standard questions, such as:

- can a cheaper material be specified for a part?
- can less material be used?
- can the required material/part be produced more cheaply?
- can limits/tolerances be eased?
- can the risk of error in manufacturing or elsewhere be reduced?
- can anything else be done to reduce costs or to increase value?

ICL is heavily committed to VA/VE and has instituted training programmes to forge closer links between designers, engineers (both in Manufacturing and in Customer Service) and marketing specialists: in fact, over 140 engineers from manufacturing, service and business areas of the company attended relevant training Workshops during 1987. Function cost analysis will be integrated into the standard review process in the company's product development cycle.

An example of the application of these methods is to the design of the ICL Office Systems Video Workstation. A cost reduction study of this was made at another Workshop, in November 1987; this was before it had gone into volume production, so any possibilities for cost avoidance that were found could be realised in full. The original marketing requirement asked for two communication interfaces, Microlan-2 and RS232; the analysis led to the decision, approved by Marketing, not to provide the combined version but to offer the option of one or the other. This reduced the production cost per unit by about 10% of the total.

3 Design for assembly

This differs from VA/VE in that the focus of interest here is the process of manufacture of the product rather than the separate costs of the various functions and parts; it is clearly related closely to Design for Manufacture. There is general agreement that some 75% of a product's manufacturing costs are determined at the design stage.

Identification of inefficiencies associated with the assembly of a product can lead to direct labour savings, but in general the cost saving here will be modest; the most significant savings result from:

- shortening the design cycle
- identifying possibilities for automation
- standardising of parts
- improved quality
- improved serviceability
- optimal use of equipment and services in production

As stated in the Introduction, the important concept, accepted universally in manufacturing, is cost avoidance rather than cost reduction.

For any manufactured product 'Conformance to Requirements' is vital. The requirements of any product can be split, broadly, into two: the functional criteria relating to customers' needs and the production criteria of those who manufacture it. Design for Assembly implies a formalised, assembly-oriented consideration of the design process; it makes possible the satisfying of these production requirements at an early stage of design.

The basic rules for Design for Assembly can be stated very simply:

- reduce the number of parts
- ensure quick, straightforward assembly

A study made by ICL of the methods of a number of major companies, in the IT and other industries, showed that the approach varies widely. In effect, Design for Assembly may employ any combination of the following:

- Systematic techniques of part classification – e.g. that of the software product marketed by Boothroyd & Dewhurst Inc. in the USA, referred to below.
- Awareness-creating techniques: if people are educated in the principles of Design for Assembly and become convinced of its importance, this becomes an integral part of their professional standards and they build 'assemblability' into their designs from the start.
- Close liaison of designers with production staff: this is vital to the effectiveness of the two preceding activities.
- Learning from one's own mistakes.
- Learning from the mistakes and achievements of one's competitors.

This last point is very important. Through in-depth studies of the methods and products of competitors a manufacturer can gain invaluable information on the trends in technologies, processes and production methods, and can discover how particular difficulties that he meets have been overcome in competing products. Such study has been undertaken regularly in ICL Manufacturing Operations, as indeed it has been throughout the IT industry.

Two views on which there is general agreement are, first, that whilst the most critical period for the application of Design for Assembly principles is that between the conceptual and the detailing phases of a design, they must be applied throughout the project if maximum effectiveness is to be achieved; and second, that the educational activity, to which a wide range of staff must be subjected, must have the enthusiastic and visible backing of top management.

3.1 The collaborative study between ICL and Salford University

This had two aims: to review ICL's needs with respect to Design for Assembly and to evaluate Boothroyd & Dewhurst's software by applying it to an ICL product.

Using this package, a product is divided into sub-assemblies, with the recommendation that each of these is constructed from a maximum of about a dozen parts. Each sub-assembly is examined in turn by responding to a question and answer routine: each part is described in terms of its envelope and geometrical symmetries, weight, magnetic properties and other relevant characteristics including, for example, some indication of the ease with which it can be grasped, manipulated and aligned during assembly. Inter-part relations are considered during this process, such as the fastening methods. Input of all this information takes less time than one might think, and at the end the program has a comprehensive part-by-part description of the sub-assembly, in a standard form. It then works out the times for handling, inserting and other operations on each part, using a built-in database of standard times derived from very carefully conducted observations. It also uses built-in information to make possible the identification of potentially redundant parts.

Another output from the program is what is called the *assembly efficiency*, a measure based on standard times and the number of potentially redundant parts; this is used only for purposes of comparison.

In general, this package helps in the following tasks:

- identification of areas for redesign
- production of new designs
- achievement of standardisation
- identification of redundant parts
- reduction of assembly time (savings of 20–30% have been achieved)

For this study the Salford group suggested the A2 processor module of the ICL DRS 300, for these reasons:

- it was difficult to assemble
- it is one of a family of products
- there were plans to redesign it at the time of the study.

The constraints imposed were that neither the envelope nor the functionality of the module could be changed.

For the purposes of the study the A2 processor was considered to consist of 12 sub-assemblies. Appendix 1 gives the results for one of these, the 'ejector mechanism' – the function of this is immaterial to the present argument; being difficult to assemble, it was a good subject for the analysis. The Appendix gives the separation of this sub-assembly into parts. The program rated the assembly efficiency of the original design as 12%, a value that may seem low, but one that is not unusual; and as stated above, the numbers are for use for comparison only and do not have an absolute significance. The analysis led the Salford group to suggest a redesign for which the efficiency was rated as 45%.

The result for the complete A2 module was to indicate a possible saving of 21% in the overall assembly time. The next task, as in any study of this kind, was to investigate the technical feasibility of the proposal and the development effort that would be needed to implement it.

The final outcome of this study was the replacement of the A2 module by a new module, called A4, with a completely redesigned chassis. This is much easier to assemble than the A2 and gives better protection to its printed circuit board. The redesign also enabled a different ejector mechanism to be incorporated that has fewer screws and, more important, replaces an expensive special component by cheaper but equally satisfactory standard ones.

The savings in labour costs that result from this redesign are not of great significance, but the implications for serviceability are important: if the business centre wished the new module could be serviced by the customers themselves.

This study showed that appropriate software can identify problems and can provide valuable aid in Design for Assembly. As a result, ICL made an evaluation of the packages that are now available and has decided to buy the Boothroyd & Dewhurst system, for implementation in September 1988.

4 Conclusion

The study has shown that a proper approach to the use of Value Engineering methods can give significant benefits in manufacturing; and that proprietary software is already available that can aid their application. By adopting a strategic approach to the use of these methods, and taking account of all the information he can gather about competing products, a manufacturer can reduce the cost and improve the quality of his products and shorten the time to delivery of new products.

Appendix 1

Results of cost function analysis of ejector mechanism sub-assembly in Module A2 of ICL DRS 300.

Table 1 Summary

	Original design	Post-analysis redesign
Assembly efficiency (%)	12	45
Total assembly time (secs.)	121	39
Number of different operations	7	5
Total number of parts	16	6
Theoretical minimum number of parts	5	6

Table 2a Manual assembly analysis of original ejector mechanism

Part number Part name No. of repeats	Operation times/part (secs) Handling	 Insertion	 Extra opns.	 Total	Candidates for elimination
2 TAPTITE SCREWS 4	1·80	8·0	0	39·2	4
3 WASHER 4	2·18	6·5	0	34·72	4
4 FLEXIBLE PCB 1	3·00	6·5	0	9·5	0
5 SLIDE 2	1·95	5·0	0	13·9	2
6 SPRING PIN 2	1·69	5·0	0	13·4	1
7 BRACKET ASSEMBLY 1	1·95	1·5	0	3·5	0
8 PCB EXTRACTOR 2	1·95	1·5	0	6·9	0

Table 2b Manual assembly analysis of redesigned ejector mechanism

Part number Part name No. of repeats	Operation times/part (secs) Handling	 Insertion	 Extra opns.	 Total	Candidates for elimination
2 TAPTITE SCREWS 2	1·80	8·0	0	19·6	0
3 FLEXIBLE PCB 1	3·00	6·5	0	9·5	0
4 SLIDE 1	1·95	1·5	0	3·5	0
5 PCB EXTRACTOR 1 (redesigned)	1·95	2·0	0	4·0	0
6 BRACKET ASSEMBLY 1	1·95	1·5	0	3·5	0

DESIGN AND MANUFACTURE OF PRINTED CIRCUIT BOARDS

ASP: Artwork specifications in Prolog

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Abstract

The artworks used in the making of printed circuit boards are currently specified on a pragmatic basis. This paper reports an attempt to put the writing of artwork specifications on a sound theoretical basis by identifying the rules which lie behind specifications, and, more importantly, to identify what information is required in order to apply the rules.

The method used a modern rule-based programming language (Prolog) of the kind used by the Advanced Engineering Applications team within Manufacturing and Logistics and by those who provide an Artificial Intelligence consultancy to the rest of Manufacturing.

The results show that the technology rules for this aspect of printed circuit board design depend upon which processes are used to make the board and also which aspect of the board has been designed.

The rules found have been incorporated into a computer program which writes artwork specifications in an interactive, question and answer, session.

So as to show just how the problem arises the paper starts with a simplified account of the relevant processes in p.c.b. design and manufacture.

1 Background: how Printed Circuit Boards are manufactured

This paper is about how I used a modern computer language as a prototyping tool to identify the information required to specify the photo-tooling needs of P.C.B. manufacture.

The following is a much simplified account of p.c.b. design and manufacture which covers the background necessary to understand the problem tackled by the program.

Most Printed Circuit Boards (P.C.B.s) are made from woven glass fibre cloth which is impregnated with an epoxy resin, on both sides of which are attached copper foils. The whole three layer unit (sandwich) is known as a laminate. The required printed circuit patterns are etched out of the copper foils. For a double sided board, just one laminate is needed and this requires two interconnect patterns, one for each side. One side is known as the solder side and the other side is known as the component side. The electrical devices (components) are mounted on one side and soldered on the other, the component legs pass through holes drilled for the purpose. There is usually a circle of copper round each component hole for a component leg and the inside of the hole is usually coated with copper.

The patterns of the required tracks and pads (the copper circles round each hole) are etched out of the copper by putting a patterned mask over the copper surface and then spraying it with a solution which dissolves copper. The copper will then be etched away except where the mask is. When the mask is removed it reveals the required pattern in copper.

The mask, known as an etch resist, starts out as a continuous sheet of very thin material which sticks to the copper surface (see Fig. 1b). The etch resist is sensitive to ultra violet (u.v.) light and, by exposing some parts to u.v. light and keeping it off other parts, the etch resist is hardened in places and adheres firmly to the copper while the other parts can be washed away. The hardened parts constitute the pattern for resisting the etchant (see Fig. 1c).

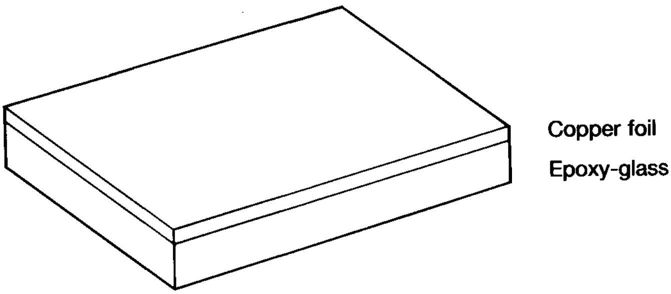

Fig. 1a Base Laminate. Epoxy-glass with copper foil

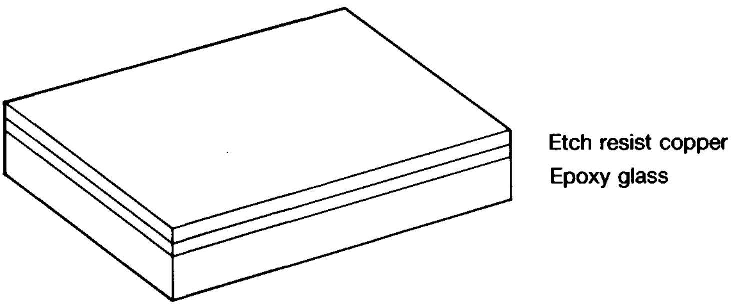

Fig. 1b Base laminate with added etch resist

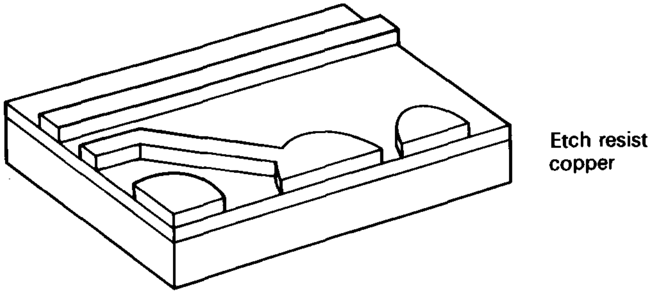

Fig. 1c Etch resist exposed and developed

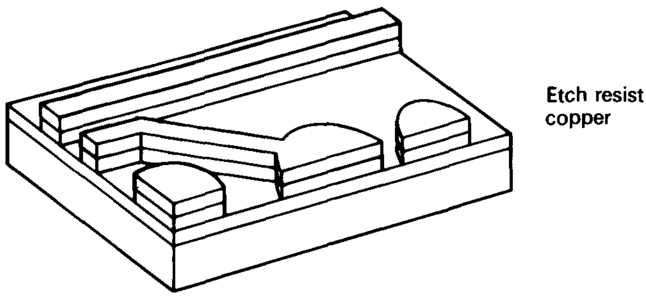

Fig. 1d Copper etched where exposed

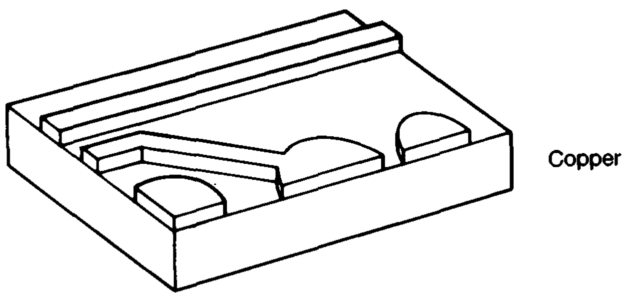

Fig. 1e Resist removed, leaving the required copper pattern on the base laminate

The pattern of ultra violet light is created by a film known as a *phototool*. This is held in intimate contact with the (unexposed) etch resist when the whole is illuminated with ultra violet light. The phototool has to be clear where we ultimately want copper on the finished article: that is, the resist is removed from the unexposed parts and then the copper is etched away (see Fig. 1d). Finally the resist is removed, leaving the finished copper circuits (see Fig. 1e). If the etch resist were softened by light then the phototool would have to be produced with opaque (black) where copper is required.

The patterns, etched out of the copper, connect the required component legs together, and avoid all other legs. The list of required interconnections is known as a net list and achieving this interconnection using copper tracks is known as tracking the board. In general, in order to simplify this task, the tracks on one side of the board run parallel to each other and the tracks on the other side of the board run at right angles to them. If a track has to change from one side to another, that is it has to pass through the board, this is done by the use of a hole, known as a via hole; it is usually smaller than a component hole and must be copper plated (lined) to be of any use.

For multi-layer boards a similar process is used but a number of laminates are bonded together by layers known as *pre-preg*, our old friend glass cloth impregnated with epoxy resin. These act as an insulator or dielectric and stop the two adjacent copper layers from touching.

In order to simplify the problem of tracking a multi layer board (but also for electrical reasons) certain layers within the board are treated as a sheet of copper and used to get power to the components (+ 5 volts) or away from the components (0 volts or ground plane). For the purposes of this paper I will call them both power planes. When the laminate containing the power plane has been bonded into the final multi layer board, been drilled, and the holes have been plated with copper the plating down each hole makes electrical contact with any copper surface (edge on) which it meets in the middle. By this means power is delivered to those component legs which need it.

With the explanation given above it is also delivered to all other component legs as well. Thus a phototool is needed for power planes which contains patterns of pads to isolate those component legs which must not be connected to this power layer (see Fig. 2).

If a component with a leg connected directly to a power plane has to be removed (de-soldered) each leg, including the ones connected to power planes, must be raised to the temperature of molten solder. For a directly connected leg this implies that some part of the power plane must be at that same temperature. In order to limit the extent of this hot part, that is to stop the heat from running to legs which are not to be desoldered, each component leg which is connected to a power layer is surrounded by a thermal barrier. The thermal barrier consists of a pattern of lines where there is no copper, the electrical connection being the copper between the lines, and is a compromise between electrical and thermal conductivity. The phototool for power layers thus contains pads and thermal barriers (see Fig. 2). These features represent places from which copper is to be removed.

In addition to the copper layers described above, most P.C.B.s have other layers which require phototools in order to be made. An obvious one is the legend, most often seen as white ink, and is used to identify the components. There are also solder resist patterns, which avoid the pads, so that the component may be firmly soldered in, but cover the tracks so that any odd

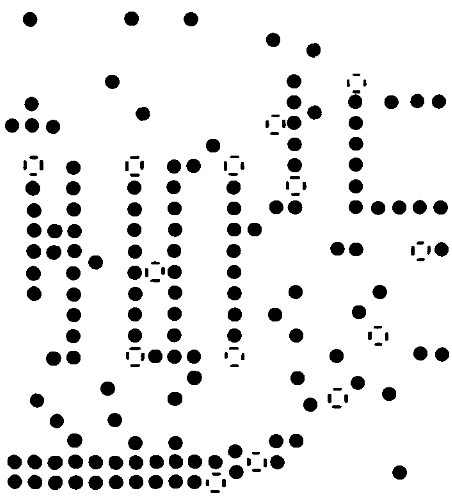

Fig. 2 Phototool pattern for a power layer showing thermal barriers and isolation pads. The black areas are where copper will be etched away. When a hole is drilled through the solid black circles and then plated, the plating will not contact the copper plane – an isolation pad. When a hole is drilled through the pattern of four short lines, the plating will contact the copper and make electrical contact with it, but the pattern of four lines, from which the copper will be etched, act as thermal barriers permitting the inside piece of copper to be heated to the temperature of molten solder without having to heat the whole of the copper plane to the same temperature.

bit of solder will not short out two tracks which just happen to be adjacent. For surface mounted components there is a solder paste phototool required as well.

2 The problem

A p.c.b. is usually tracked with assistance from a computer and a graphics terminal, known as a CAD station, and the process is known as Computer Aided Design (C.A.D.). The C.A.D. programs ensure that what is tracked faithfully reflects the net list required by the design. These programs include ones known as *autorouters* which automatically track the board from the net list as far as they are able, i.e. they put in the easy ones. Other programs allow human interaction with the untracked net lists to try to achieve as much tracking as possible. Any net or parts of net (links) which can not be tracked in copper have to be put on the finished board by hand as wire links, at extra cost. To keep the cost of manufacture of the board down as much as possible, wire links must be kept to a minimum, or eliminated, which takes extra design time.

When the design has been tracked it is converted into Numerical Control Data files which drive the photo plotter and thereby produce the *artworks* required. Artworks are what the photoplotter produces; phototools are used to make the board, they can be the same thing.

A photo plotter usually consists of a flat bed upon which an unexposed photographic film is placed and is exposed by a controllable light source which can be moved over the bed. The actual position is controlled, in X and Y coordinates, by suitable motors; the light source can be turned on and off, usually by a shutter. The light gives rise to a spot on the bed and the size of this spot can be changed. The details of how this is done do not concern us here.

The photographic film produced is an *artwork*. On a simplified view, photographic films consist of a light sensitive part and a support medium. Because the light sensitive part (crystals of silver salts embedded within a gelatine medium) is basically jelly it is supported on a transparent medium which keeps its shape better (can be glass but more usually mylar). The film is thus asymmetrical; it has an emulsion side and an 'other' side. When a film is used as a phototool, it is necessary to get the pattern onto the board as accurately as possible. The emulsion, where the pattern is, should be in contact with the board; if it is away from the board it will have the support medium between it and the target film, the source of illumination will cast shadows of the pattern onto the target film and the result will be a useless fuzzy image. So, phototools are always used 'emulsion to emulsion'.

When a phototool is used it is not just placed on the board anywhere, it has to be carefully positioned, for example on a two sided board the two sides must be positioned so that, when a hole is drilled through it, it goes through the correct pads on both sides. The method of achieving this degree of accuracy is with the use of *tooling holes*. These are holes in the workpiece (the board) through which little pegs are inserted and on which the phototool is placed. The phototool has tooling holes in it which correspond to the holes in the board; these stop the tool and workpiece from slipping over each other. There are a number of different tooling systems available but the simplest to explain is the '*dowel and slot*' system. This consists of a round hole through which an accurate peg (dowel) is placed; the phototool can then be placed accurately over this, the two are now perfectly aligned, but only at the actual datum point. The phototool can swing round the work piece. To prevent this there is a slot, with an accurate width, cut some distance from the hole, a peg placed through both slots positions the two pieces accurately in space. The length of the slot has to point straight at the hole. The second hole is a slot because as most substances expand and contract with changes in temperature and photographic emulsions expand and contract with changes in humidity; if it were a round hole some times the phototool might have to be stretcted slightly to fit between them and at other times might be too long and lift slightly and produce a fuzzy image: the slot allows for such slight movements. Obviously the inaccuracy at a point increases with the distance of that point from the round dowel hole. The p.c.b. making system is designed to cope with small tolerances but not fuzzy images or damaged tooling holes.

If we stick with the slot-and-dowel tooling system the round dowel can be either on the left or on the right, and to add to the confusion a phototool can be turned over. For example, a phototool, emulsion *up* with the round dowel on the *right* can be made into a phototool emulsion *down*, round dowel *left* simply by turning it over; but it can not be made into an emulsion *down*, round dowel *right*.

Similarly, if there is to be any writing on the board then it is a good idea for it to be readable. Thus a phototool for the top layer of a board with the round dowel on the right will also have the round dowel on the right but emulsion down (emulsion to emulsion contact) and the writing should be readable (when seen through the phototool). Should this phototool be turned over then it will be: emulsion up, round dowel left, mirror writing. Mirror writing is normally termed 'reading wrong', and, by analogy, normal writing is termed 'reading right'.

As we saw in the introduction, sometimes phototools require black where material is needed and sometimes are required to be clear there. I generally refer to this property as the 'features', which can be black or clear.

We are now in a position to state what we need to know in order to produce a phototool: namely:

Emulsion	(up/down)
Tooling	(round dowel: right/left)
Reading	(right/wrong)
Features	(black/clear).

In use phototools wear out, they become stretched, scratched or dusty, the tooling holes become worn and oversize, and so there is a need to replace them periodically. Within I.C.L. phototools are sometimes known as 'production artworks' and they are produced from 'master artworks' by a photographic process: a contact print. One of the most obvious properties of a contact print is that it produces a negative: what was clear on the original becomes black on the print and vice-versa, also it must be an emulsion to emulsion contact. Thus, when making a contact print, the emulsion changes (up to down, down to up), the tooling remains the same, the reading stays the same (think about it) and the features change (black to clear, clear to black). The resulting contact print can of course be turned over; see above for what happens then.

By knowing the production artwork requirements and by working the contact printing process backwards we can derive the requirements for master artworks.

At the end of the design process, when the Numerical Control photoplotter tapes are being produced, all the above facts must be taken into account if the artworks to be produced are to be correct. To 'assist' with this each type of board (family) has a published specification which gives details of the above properties for each of the layers. They are known as Artwork Specifications.

When the photoplotter tapes are sent for plotting they go along with a sheet of operating instructions (known as a *traveller*) which gives details of how the various files are to be plotted. The photoplotters themselves impose constraints on how the film can be plotted. For accuracy they are all plotted emulsion up (the light comes from above, a simple variation on the 'emulsion to emulsion' theme). The plotters which move the light mechanically can only illuminate the features which therefore always come out black (laser plotters are more versatile but the basic problems remain the same). So, the photoplotters can only plot emulsion up, black features. They can, however, plot X-coordinates negatively (by switch) and thus give either normal or X-mirrored plots. Also, the unexposed film can be punched with the round hole on the right or on the left (as a shorthand notation on the traveller, this is called Film Figure A (for round hole left) and Film Figure B (for round hole right).) (Film Figures C etc. are used for tooling systems other than slot and dowel).

There is obviously some conversion necessary from the artwork specifications, as published, to the instructions for plotting. A program was written to do this which also printed out the traveller and offered guide lines for the designer. This program took as its starting point the production artwork specifications, as published, for about eleven different technologies (families of boards), and, using arguments similar to those above, converted the production artwork requirements into the master artwork requirements and then the plotting requirements; it also worked out the requirements for laser plotting (which can plot clear features as well as black features, as required, by use of an 'inverse video' facility).

This traveller, despite its value in the field in reducing significantly the number of errors that give rise to incorrectly plotted artworks, is only as good as the specifications that it knows about. These have to be kept up-to-date in line with changing needs and technologies; so the seeds were sown to formalise the rules for their production and to write a program to produce them.

The artwork production rules seemed simple enough. Upward facing laminate needs a downward facing emulsion phototool, downward facing laminate needs upward facing emulsion, etc: what could be simpler? Indeed, a simple program was written to do this. It assumed a multi-layer board and accepted definitions of various laminate structures, with pre-preg between. It even drew pictures of the various pieces for the bonding department to follow (see Fig. 3). But the specification it produced seemed somehow suspect, and as it was only an experiment it was not pursued further.

It was when a version of Prolog became available and I was looking for a suitable problem to use to learn Prolog that I thought this would be suitably simple and might have useful results as an added bonus. The objectives were therefore threefold: (1) to learn Prolog, (2) to try to identify what the rules were for writing artwork specifications, (3) to try to identify what extra

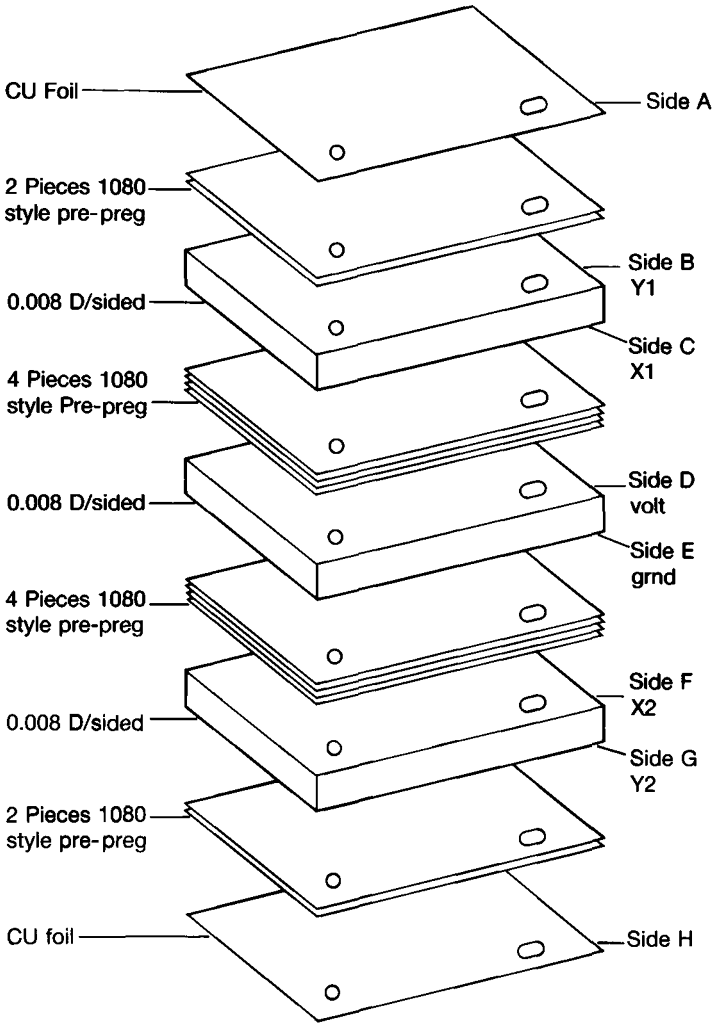

Fig. 3 Typical multilayer board construction

knowledge (data?) was needed to make use of those rules. If this could be done, we would be in a position to write a program (in Pascal for example) which would know which questions to ask and could then write artwork specifications by asking them. This was a recognised Artificial Intelligence technique.

3 A specification writer

With these thoughts in mind I sat down and wrote out as many rules as I could find, using one of the artwork specifications as a starting point. I started off restricting myself to the copper layers as they seemed obvious and straightforward and I used them to find all the traditional pitfalls of Prolog (which I duly fell down).

Despite their apparent simplicity, even the copper layers were not as straightforward as I expected. The designer can be designing either logic layers (tracks and pads) or power layers (pads and thermal barriers). If he is designing a logic layer the features he is designing are to end up as copper, whereas on power layers the features designed are to end up as absence of copper. Not too difficult so far. If, however, the target layers are to be made with a print and etch process then on the phototools those areas required as copper are to be clear but for a manufacturing process of print and tin lead plate the phototools need black where copper is required. The fact that power layers are never made with a print and tin lead plate process does not alter the logic.

With that the copper layers seemed to be under control. Gold finger plating patterns seemed straightforward: designers design gold fingers; phototools need black where gold is required.

Next, try the non-metal layers: the legend features designed are where the ink is to go, the screen printing process used to make legends needs black where the ink is to go – straightforward. Solder resist; sometimes the design requires resist over the tracks only, at other times it is required all over except where the pads are. For the purposes of this discussion we ignore the facts that tracked resists must be kept away from the pads and that, generally, solder side resist is tracked, component side is all over. For a screen printed resist, a tracked resist implies black features but an all over resist needs clear features. Just to complicate the issue there is also a dry film resist manufacturing process. Some research eventually revealed that this process needed a clear artwork where resist was required, so we end up with a situation like that for copper.

One assumption for all the rules is that the round dowel is on the right and that no artwork can be turned over until after it is specified.

So far we have considered the computation of the features and the tooling system used. Next consider the reading: for an upward facing surface the reading is right and for a downward facing surface the reading is wrong. This extension of the rule for the copper laminates to the non metal phototools served well throughout the testing process, which is more than can be said for the emulsion orientation rules. For the copper layers it could not be anything else other than the rule we started with (upper surface, emulsion down; lower surface, emulsion up), could it?

With the rules as stated above, the Prolog program was given information about four of the most common artwork specifications and the results were compared with the actual specification. All seemed well except that the specification for solder resist on two of the artworks seemed to be the wrong way round (the solder side had the specification expected of the component side etc.) and so, without thinking too much about it, I swopped over the definitions of the two sides. This time the other two artwork specifications came out wrong. Consternation! Further questions revealed that for a silk screen process the phototool is not used in contact with the board directly, but is used to make the silk screen which is used in contact with the board! Thus for an upward facing laminate the silk screen is downward facing, and, in order to make that, the phototool has to be upward facing. So, a doubling of the emulsion rules in the Prolog program and all the rules passed. The resulting Prolog program showed a greater degree of symmetry as well.

4 What we found

One of the usual pitfalls of Prolog for a novice is failure to have what is known as a 'state variable'. Once this deficit was recognised, in our case a number representing which surface we are dealing with, other things started to become obvious. One of these was that, for each surface we had to state what was being designed for that layer and also how each layer was going to be made. In retrospect it is obvious, but at the time it was not so, that the details of an artwork specification depend firstly upon what was (or is to be) designed and, secondly, how it is to be made (what process is to be employed in its manufacture). These two together create the specification.

During the course of the development of the program the rules and the layer details become distinct; indeed, at one point they were separated into different files. One file held the rules while the other held the layer details and manufacturing methods (see Appendices One and Two). This had the advantage that each layer could be given a name, and different details files could be set up for each technology (putative artwork specification).

The way the program seems to work is that for each layer in turn, it takes the object designed, works out what internal items are required or created by it, and then looks to see how these items are to be manufactured.

The results of this program are that we think we know what the rules are for establishing the characteristics of artwork specifications. We know what information is needed to do that and are in a position to write a program (Pascal, FORTRAN etc.) to do it. But more importantly, it was discovered that the main driving force behind all this is that the various machines and methods used to make the board dictate the required properties of the artwork specification.

For example, none of the current artwork specifications cater for the dry film solder resist process. It should now be possible to work out an artwork specification for this process. We know what properties it has, it is a direct process (i.e. not a silk screen process), and thus emulsion up for the downward facing solder side, and it has to be clear in those places where resist is required (black where no resist required). So we can compute an artwork specification for it. If this is done and the results are taken through to the traveller generator, the instructions generated for plotting it differ from those for wet resist only in the film figure. The consequence of this is that if data from an official artwork specification are used to plot data intended for a dry film process then the photoplotter starts at the left hand side and then moves left and hits the end stop instead of going to the right and plotting normally.

5 Review

What started off as a very ill defined problem (but a well defined situation) was able, by using a modern programming language, to be refined and in fact crystallised out into a number of areas which may be considered distinct. In addition, the general shape of the solution, only visible because of the type of language used, permitted an inductive leap to identify the class of solution which should have been obvious but which this made almost explicit. It allows us to know what questions we should ask when the situation changes in the future.

By a further analogous step it also seems to be saying to us that most, possibly all, of the rules which designers have to work with are implied by the machine and technologies which we use to make our boards. If we could capture these rules (they could also be physical rules of nature) and relate them to the manufacturing machines then we could have better control of the design criteria and use them for a better design for manufacture.

The contents of eleven artwork specifications can now be expressed as a set of rules describing the relationship between the design process and the manufacturing process and a set of layer definitions to which the rules are applied.

Acknowledgements

I would like to thank:

Pat Kirby of the Institute of Circuit Technology, for teaching me about p.c.b. manufacture.

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Ian Beeson and Steve Oakey of Manchester Polytechnic for teaching me Prolog.

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Postscript

While this paper was going to press further developments have taken place. Firstly, the rules, disclosed by the above process, have been coded in Pascal as part of a demonstration. This program produces artwork specifications for given layers by asking the necessary questions. The output from this is in a format which could be read into the traveller generator when this is updated. It is also displayed on the screen in a readable form. About the same time that this was going on four descriptions were produced which should cover the range of board types as currently designed and made. As an exercise these descriptions were given to the artwork specification writer and specifications produced. Later, along with other important developments, these specifications were embedded within a special version of the traveller generator and the outputs from this are soon to be reviewed by a select panel to see how close to reality they are. If they prove to be realistic these four descriptions will be incorporated into a new version of the traveller generator and so avoid all the problems created by the old specifications.

To continue the 'design to manufacture' theme, the main manufacturability criteria for printed circuit board designs go back to the *bonding* specifications (see Fig. 3). I have developed a notation for describing these and it is this description, rather than an interactive question and answer session, which should drive the artwork specification writer.

Appendix One

The rules in Prolog as they appeared in the final Prolog program.

It shows how the three values, emulsion orientation, reading and features, are calculated from the laminate surface and the design type and manufacturing process.

```
use(screenp,Surface) :-
    process(wetresist,Surface).
use(screenp,Surface) :-
    design(legend,Surface);
    design(paste,Surface).
laminate(upper,Bill) :-
    layer(Fred),
```

```
    Bill is Fred + Fred.
laminate(lower,Bill) :-
    layer(Fred),
    Bill is Fred + Fred - 1.
side(soldersid, Surface) :- laminate(lower,Surface).
side(component, Surface) :- laminate(upper,Surface).
reading(right, Surface) :-
    laminate(upper, Surface).
reading(wrong, Surface) :-
    laminate(lower, Surface).
emulsion(down, Surface) :-
    laminate(upper, Surface),
    not(use(screenp, Surface)).
emulsion(up , Surface) :-
    laminate(lower, Surface),
    not(use(screenp, Surface)).
emulsion(up , Surface) :-
    laminate(upper, Surface),
    use(screenp, Surface).
emulsion(down, Surface) :-
    laminate(lower, Surface),
    use(screenp, Surface).
item(    ag, Surface) :- design(   gold, Surface).
item(    cu, Surface) :- design(  logic, Surface).
item( notcu, Surface) :- design( power, Surface).
item(   ink, Surface) :- design(legend, Surface).
item(   ink, Surface) :- design(  paste, Surface).
item(   ink, Surface) :- design(trackedresist, Surface).
item(notink, Surface) :- design( alloverresist, Surface).
features(black, Surface) :-
    process(gold, Surface),
    item(ag, Surface).
features(black, Surface) :-
    process(dryresist, Surface),
    item(notink, Surface).
features(clear, Surface) :-
    process(dryresist, Surface),
    item(ink, Surface).
features(clear, Surface) :-
    use(screenp, Surface),
    item(notink, Surface).
features(black, Surface) :-
    use(screenp, Surface),
    item(ink, Surface).
features(clear, Surface) :-
    process(ptlp, Surface),
    item(notcu, Surface).
features(black, Surface) :-
    process(ptlp, Surface),
    item(cu, Surface).
features(black, Surface) :-
    process(petch, Surface),
    item(notcu, Surface).
features(clear, Surface) :-
    process(petch, Surface),
    item(cu, Surface).
answer(A,B,C,D) :-
    reading(A,B), features(C,B), emulsion(D,B).
```

```
doit(Y)
    write('For layer '), write(Y),
    write(' side '),side(S,Y),write(S),
    write('   '),named(Nam,Y),write(Nam),
    write(' Design '),design(A,Y),write(A),
    write(' Manuf '),process(B,Y),write(B),nl,
    write(' Production artwork requirement is :-'),nl,
    answer(X,Y,Z,T),
    write(' Features are'),write(Z),
    write(' Emulsion '),write(T),
    write(' Reading '),write(X),
    write('.'),nl

run(N) :-
    doit(N),
    nl, M is N+1,
    run(M).
```

Appendix Two

The description file in Prolog for one of the board types used.

This is the description of a board type for which an artwork specification is required.

This file contains the necessary descriptions of a real board with the layers, their names, what design goes on each layer and the process used to make each layer.

```
layer(1).
layer(2).
layer(3).
layer(4).
layer(5).
layer(6).
layer(7).
layer(8).
/* Details for Mark 2 boards */
named(ss,1).
named(cs,2).
named(yl,3).
named(xl,4).
named(pow,5).
named(gnd,6).
named(x2,7).
named(y2,8).
named(gold,9).
named(gold,10).
named(srss,11).
named(srcs,12).
named(legss,13).
named(legcs,14).
design(logic, 1).
design(logic, 2).
design(logic, 3).
design(logic, 4).
design(power, 5).
design(power, 6).
design(logic, 7).
design(logic, 8).
design(gold , 9)
design(gold , 10).
design(trackedresist, 11).
design(trackedresist, 12).
design(legend, 13).
design(legend, 14).
process(ptlp,1).
process(ptlp,2).
process(petch,3).
process(petch,4).
process(petch,5).
process(petch,6).
process(petch,7).
process(petch,8).
process(gold,9).
process(gold,10).
process(wetresist,11).
process(wetresist,12).
process(legend,13).
process(legend,14).
```

Elastomer technology for probing high density printed circuit boards

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Abstract

With the increasing density of printed circuit boards and the consequential reduction in the spacing of test points, testing by the traditional method of probing with fine wires has become increasingly difficult. The paper describes a method developed by ICL, known as Zebra testing, which uses strips of an elastomer material traversed by very fine conducting channels. Whilst a spacing of about 1·27 mm is the practical lower limit for probes, the zebra technique can probe down to spacings of approximately 0·4064 mm.

1 Testing printed circuit boards: the practical problem

The many functions of a modern computer are performed by the integrated circuits carried on the printed circuit boards (PCBs), and it is obviously of vital importance that these boards can be tested thoroughly. This is taken into account in the design, and all boards are manufactured with test points provided, to which test probes can be applied. But as technology has advanced the boards have become more densely populated and the spacings between the test points have become smaller, and consequently the probing more difficult.

Test point spacings as low as 0·635 mm are now achieved, needing wire probes of diameter less than this. Test probes of 0·508 mm diameter can be obtained but are extremely fragile and difficult to handle; thus there is the problem of devising a practical method of testing boards of such high density.

2 Elastomer technology

The solution developed by ICL, called Zebra testing, uses strips of an elastomer material (a plastic with non-linear elastic properties) traversed by very fine conducting channels at a constant spacing. Such material is in regular industrial production; it is used, for example, to make the connections to the liquid crystal displays in digital watches.

ICL purchases supplies from TECKNIT in Milton Keynes, who are one of the world's largest producers of elastomer. The elastomer has very high insulation resistance, of the order of 10^{12} ohms. The conductors can be of carbon, with a resistance of the order of 10^3 ohms, or metallic (silver, gold or an alloy) with resistance of less than 1 ohm. For PCB testing we need conductors of very small thickness and as low resistance as possible; the material we choose has silver conductors with thickness and spacing both 0·127 mm giving resistance of approximately 0·3 ohm.

The principle, illustrated in Fig. 1 (which, incidentally, makes clear the reason for the name Zebra) is very simple. If the Zebra is placed over the board, electrical connection to a test point can be made through any channels that are in contact with that point; and as the channels are so fine and so closely spaced it is possible to discriminate between very closely spaced test points.

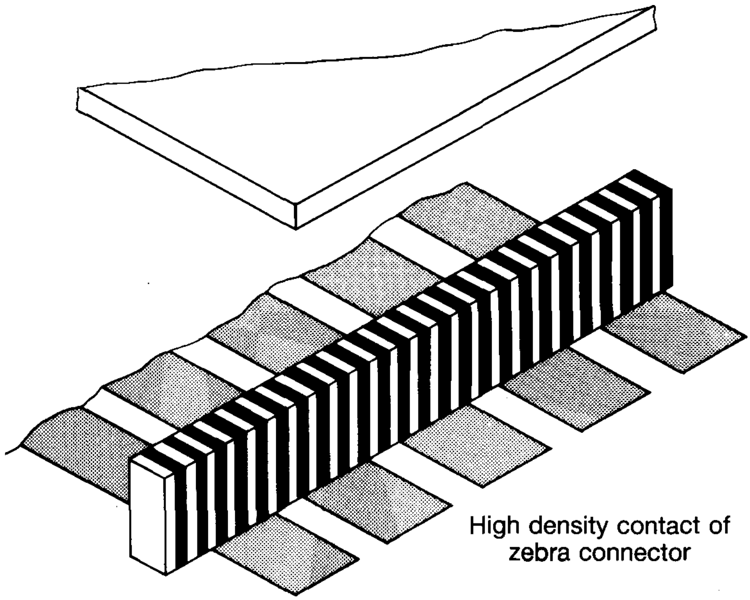


Fig. 1 High density contact of Zebra connector

3 Evaluation of the zebra: the test rig

Figure 2 is the diagram of the rig that was designed to evaluate the potential of this material as a test probe. The essence is that four strips, arranged in a square, are sandwiched between two identical boards that carry the test pattern of tracks, each being the mirror image of the other. Good contact is ensured by applying a load to the upper board.

In PCB manufacture a bare board is made first and must be tested before any integrated circuit or other components are attached; this evaluation was

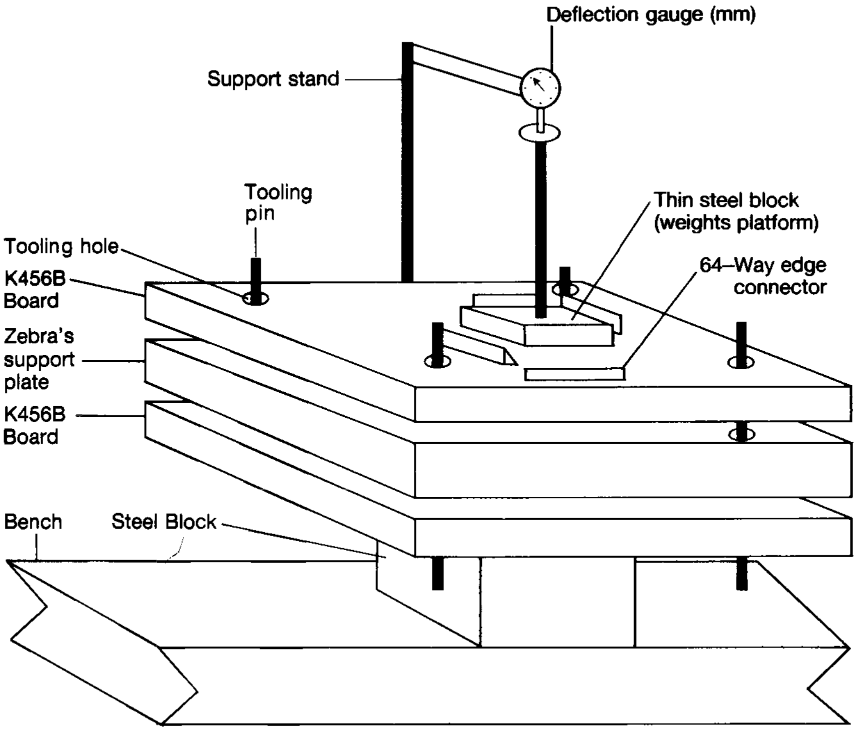


Fig. 2 Test rig loading arrangement and setup

therefore carried out with bare boards, but will be extended to loaded boards shortly. The test pattern chosen was that of the board carrying one of the latest integrated circuits used in ICL's products, a 256-pin flat-pack surface-mounted device. This represents one of the most advanced circuit technologies available in the world at this time and requires a board with the highest density possible for contact pins.

4 Evaluation tests: electrical and mechanical

Several tests were performed to evaluate the Zebra:

- contact resistance variation with load to determine which zebra height deformation yields the lowest contact resistance
- AC and DC current carrying capacity to determine its suitability for loaded board trials
- contact resistance with repeated actuations to determine the Zebra's potential for use in a high volume manufacturing plant.

5 Evaluation results

The graph of Fig. 3 shows the force applied against the measured contact resistance. The lowest contact resistance is 0·3 ohms, which results from a

12% height reduction in the Zebra. This is ideal for probing bare boards. The minimum and maximum values for this resistance arise because of tolerances in the Zebra connector.

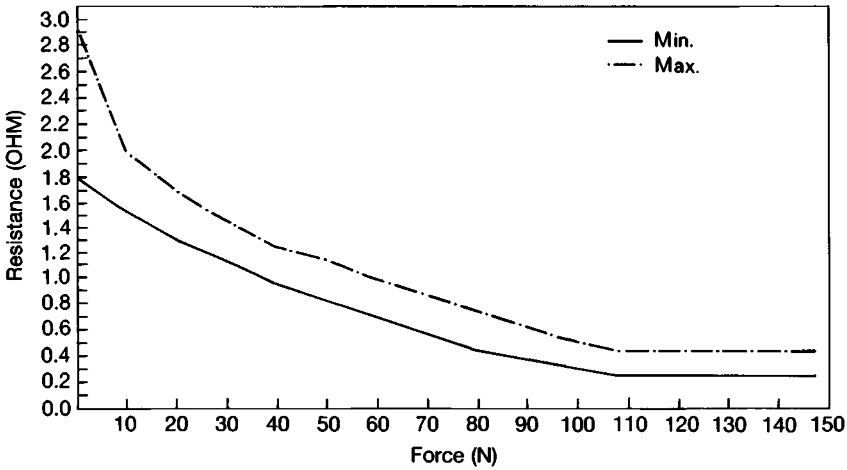


Fig. 3 Zebra contact resistance characteristics (using 5.08 mm support plate)

The graph in Fig. 4 shows the peak current carried by the Zebra against pulse width, for a duty cycle of 100:1. The maximum current capacity is 20 amps for a pulse width less than 0·5 millisecond.

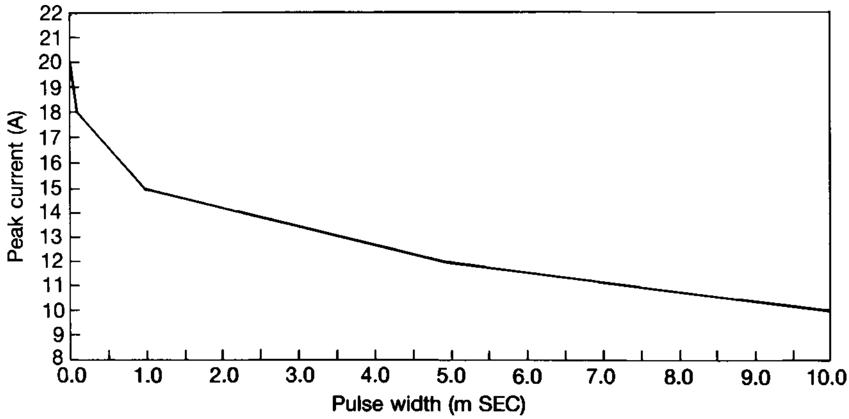


Fig. 4 Relation between peak current and pulse width (100:1 duty cycle)

The AC current carrying capacity was 0·65 amps, and independent of the frequency.

The graph in Fig. 5 displays the number of actuations against contact resistance. The test was repeated for several reliefs in the support plate cutout:

Test 1, parallel cutout in support plate
Test 2, parallel cutout with 0·25 mm relief
Test 3, parallel cutout with 0·75 mm relief

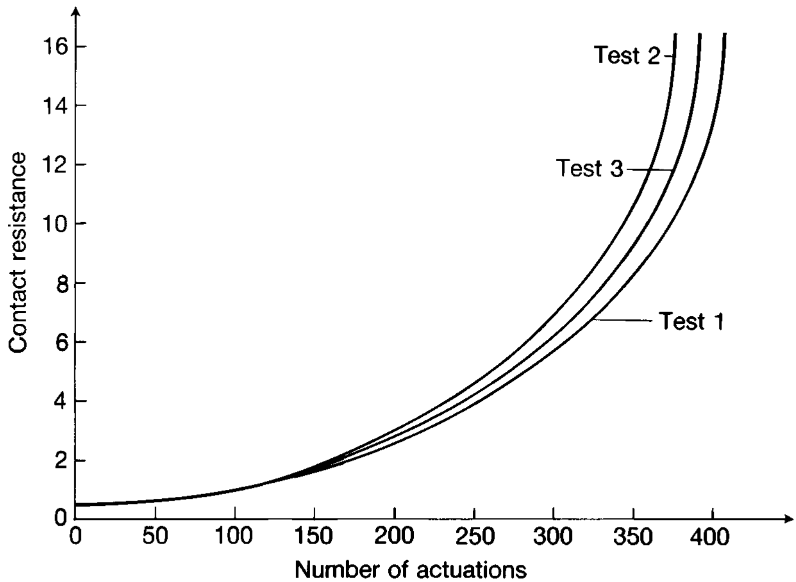


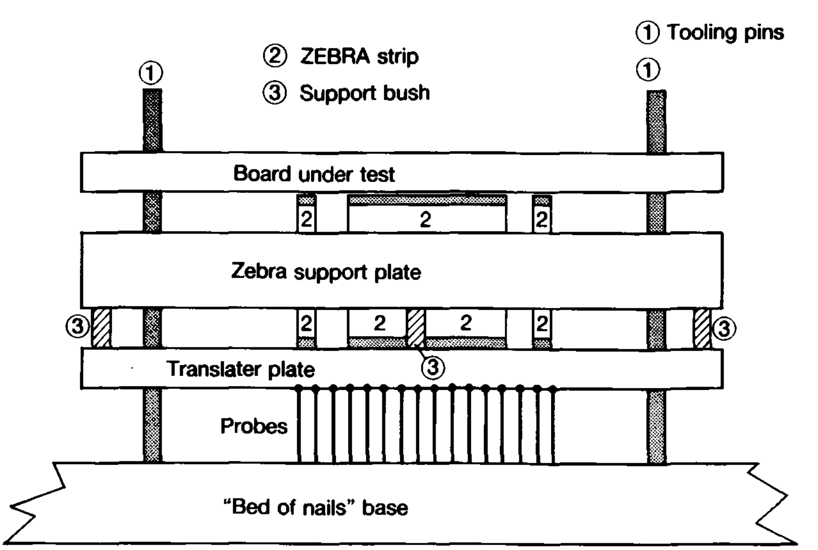
Fig. 5 Relation between contact resistance and number of actuations

Appreciable contact resistance degradation occurs after approximately 200 actuations, and is independent of relief.

6 Future work

The proposed use of the Zebra is shown in Fig. 6. An inexpensive 2·54 mm "bed of nails" bare board tester can be configured to test a high density test pattern on the board under test, via the Zebra strips and the translator plate. This reduces the necessity for additional expensive test equipment for exclusive testing of high density pattern PCBs.

Future work will also involve the testing of high density loaded boards, expected to occur within the next few months.



BASIC JIG ADAPTER DESIGN USING ZEBRA STRIPS FOR PROBING

Fig. 6

7 Conclusions

The evaluation tests performed for probing and connecting high density printed circuit boards conclude that conductive elastomer technology holds the key to the future.

The type of connector used exhibits excellent contact resistance and current carrying capability properties. The long term contact resistance reliability needs to be investigated further. This will be taken up with TECKNIT.

The ability to probe high density test patterns via zebra connectors will provide simple and inexpensive test fixtures and test machines, with consequential reductions in the cost of testing.

The Effects of Backdriving Surface Mounted Digital Integrated Circuits

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Abstract

The use of in-circuit testers makes it easy to check the operation of every component on a printed circuit board individually using a test fixture of spring loaded test probes commonly known as a 'bed of nails'.

During this in-circuit testing, however, not only is the input of the device under test (DUT) driven to different logic levels, but the outputs of preceding devices in the circuit are backdriven or overdriven. The backdriven components could, depending on the actual logic state, be stressed to harmful levels. The stress is a result of large currents flowing in the output stages leading to high power dissipation resulting in greater than normal chip temperatures and possible failure.

The purpose of this study is to investigate the effects of backdriving surface mounted high speed TTL devices. The main areas covered by the study are:

(i) Junction temperature rise during backdriving
(ii) Rate of fall of peak junction temperature after backdriving ceases
(iii) Device reliability after backdriving

No significant degradation of the backdriven components was discovered during the 2,000 hour life test, with the non-backdriven devices actually recording more failures, although very marginal.

1 Introduction

A number of studies have been conducted into the effects of backdriven stress on digital I.C.s [Ref. 2, 3] with some concentrating on the thermal aspect in particular.

ICL sponsored ElectronikCentralen to perform a study which concentrated on measuring the chip temperature rise of various devices from LS, AS, ALS and FAST technologies during backdriving and analysed long term reliability of components following backdriving [Ref. 1].

The present investigation followed similar lines but used surface mounted components to find if package style had any impact.

The three technologies were:

1. FAST (F) types from Fairchild & Mullard.
2. LOW POWER SCHOTTKY (LS) types from Texas Instruments.
3. ADVANCED SCHOTTKY (AS) types from Texas Instruments.

The device types used were all 74XX245.

The aim of the study was to determine whether backdriving stresses cause damage to I.C.s whilst undergoing test in in-circuit testing systems. During backdriving high currents in the output stage of the I.C. will cause localised heating in the resistors, transistors and conductors, including both chip metallisation and bond wires. In the short term, this heating effect can be intense, but with no resultant detectable increase in overall package temperature. Damage caused by this localised heating may not be apparent initially unless it is catastrophic, e.g. bond wire failure.

Since this study is based on high speed devices with small chip geometries, the backdrive current densities will be quite considerable and the localised heating of the output devices must be determined. To measure the chip temperatures use is made of diodes built into the circuit which, although not primarily intended for this, make almost ideal temperature sensors, with their forward voltage drop being linearly proportional to the junction temperature.

Together with chip temperature and backdrive current measurement, this study also analyses the effect of a 2000 hour accelerated life test, equivalent to 7 years normal life, on backdriven component parameters, these being data logged at 0 hr, 168 hrs, 500 hrs, 1000 hrs and 2000 hrs to give information regarding device degradation.

All the experimental work and results in this study was provided by the Department of Electronic & Electrical Engineering, University of Technology, Loughborough, as part of a contract with ICL [Ref. 10].

The component characterisation, failure analysis and data logging plus drift analysis was provided by ICL Kidsgrove.

2 Devices used

All devices used were 74XX245 types. These are OCTAL BI-DIRECTIONAL TRANSCEIVERS WITH 3-STATE OUTPUTS. They are medium scale integration surface mounted, small outline (SO20) plastic package TTL logic devices which fall into 3 categories:

1. 74LS245 low power Schottky TTL
2. 74F245 FAST TTL
3. 74AS245 advanced Schottky TTL.

With exception of the 74F245 I.C.s from Fairchild, all devices from a particular manufacturer were of the same date code/batch number.

Since the devices are bidirectional it was considered of greater interest to backdrive the B port.

DEVICE NO.	MANUFACT-URER	DEVICE TYPE	TECH-NOLOGY	DATE CODE	DEVICE QUANTITIES		
					LIFE BACK DRIVEN	TEST NOT B/D	CHIP TEMP TEST
1–56	Texas Instruments	74LS245	LS	TI605BR	20	20	5
101–174	Mullard	74F245	FAST	KK8613A	25	25	5
210–260	Texas Instruments	74AS245	AS	TI535XF	25	25	5
301–310	Fairchild	74F245	FAST	F8542	4	4	2
311–360	Fairchild	74F245	FAST	SC8612	21	21	5

3 Backdriving

3.1 Backdriving technique

In order to test individual digital integrated circuits in an assembled printed circuit board, the logic level of the device preceding the one under test must be overdriven, i.e. if its output is at logic high it must be driven to logic low to ensure that the device under test operates correctly at both logic levels. This overdrive, or backdrive, signal will normally be as short as possible, but due to the low impedance of the output stage of the device, the currents involved will be far in excess of those recommended by the manufacturers [Ref. 4, 5, 6].

Figure 1 shows how devices are subjected to backdrive currents when other devices are being tested. The duration of these backdrive currents can have a great effect on heat generation, and it is advantageous to restrict the time to a minimum [Ref. 7].

3.2 Backdrive currents

Two levels of backdriving are possible and each subjects different parts of the output stage to abnormal currents. These can be considered separately.

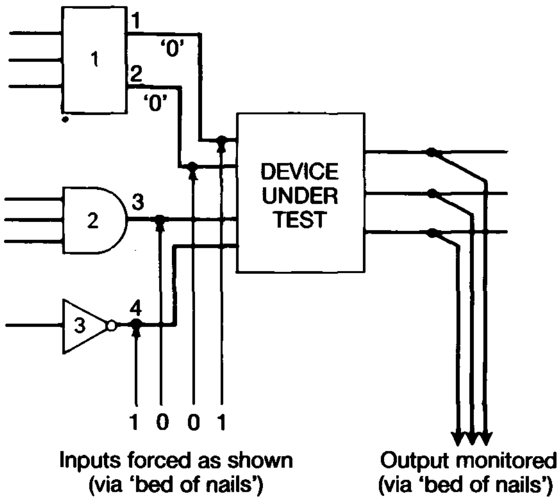

Fig. 1 Diagram showing how devices become backdriven during incircuit testing

When the output of the device is in the low state and is then forced high, this is referred to as backdrive high. Similarly, when the output is high and forced low, this is backdrive low. Figures 2 and 3 illustrate these conditions together with the points at which heat is generated.

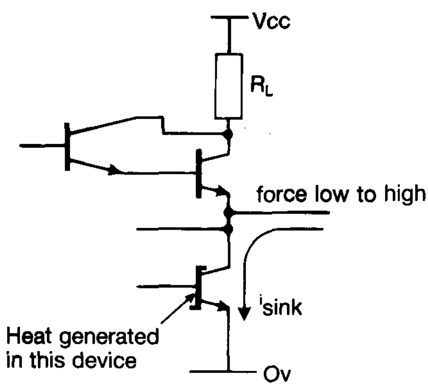

Fig. 2 'Backdrive high' forcing normally low outputs high

Since the output stage is non-symmetrical, mainly because of the output resistor RL, the backdrive high current is much larger than the backdrive low current. This leads us to suspect that the device is more likely to be damaged by backdrive high conditions than backdrive low. Owing to variations between outputs of the same device, it is important to know worst case conditions when attempting a study of heat related problems. Backdrive currents, high and low, for each output of the devices used for these tests were

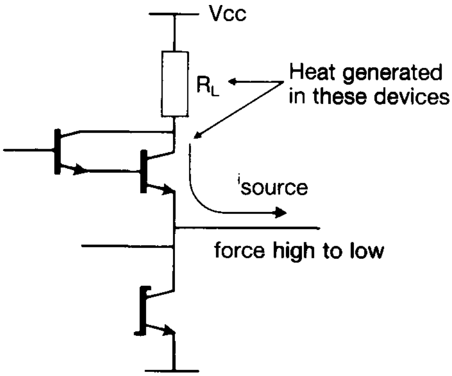

Fig. 3 'Backdrive low' forcing normally high outputs low

recorded. Backdrive current measurement was controlled by means of a microcomputer.

3.3 *Heat generation*

As described above, the large currents that can be encountered during backdriving lead to heat generation in one of the output transistors. The amount of heat will depend on a number of factors:

(i) Voltage level of backdrive pulse
(ii) Backdrive current
(iii) Length of applied backdrive pulse
(iv) Duty cycle of applied pulse.

Considering the factors above, the voltage level must be generally set at normal maximum, or minimum, logic levels, but in turn this governs the backdrive current. The time of applied signal is generally kept to a minimum which is again governed by the required test. Part of this study investigates chip temperature as a function of pulse length. Finally, duty cycle is very important since damage can be caused by heat build-up due to repetitive pulses. This study also investigated the fall in chip temperature after backdrive signals of various lengths have been applied. This can indicate safe repetition rates, or duty cycles.

3.4 *Other possible failure mechanisms*

3.4.1 Bond wire fusing. This is a catastrophic failure of bond wires between chip and lead frame due to high current flow. The 0v bond wire is particularly at risk because of the cumulative current when multiple output devices are simultaneously backdriven to a high level.

3.4.2 Chip metallisation damage. There is a similarity between bond wire fusing and chip metallisation damage where heat builds up at the chip-to-bond wire interface. This failure can occur in three areas. The chip metallisation can fail, the bond can fatigue or the bond wire can fuse.

3.4.3 Heating effects. Large currents can cause localised 'hot spots' to form in the semiconductor material. Since digital I.C.s are not designed to normally carry large currents (c.f. power devices) then due to the manufacturing process it is possible for 'hot spots' to occur during backdriving.

3.4.4 Miscellaneous effects. These fall mainly into the areas of:

(i) Avalanching, or secondary breakdown, of the p–n junction
(ii) Thermal stresses caused by different coefficients of thermal expansion of the chip and packaging material.
(iii) Electromigration of the surface metallisation on the chip.

4 Chip temperature tests

4.1 Temperature sensing element

One possible cause of failure of the device during backdriving is excessive temperature rise of the chips. Thus measuring chip temperature during backdriving is important. Since it is necessary to measure actual chip temperature within the packaged device, no value is gained from measuring external package temperature, either by contacting or non-contacting methods. One method is to use an 'on chip' sensor as close as possible to the output transistors. For the majority of digital I.C.s such devices are present, although not intended for this purpose. Most of the device components have non-linear characteristics but a forward p–n junction has a practically linear voltage relationship to temperature over a range of temperatures sufficient for this study [Ref. 8 & 9).

4.2 Choice of sensing element

There are a number of p–n junctions throughout the I.C. which could be used to sense the temperature of the chip, but since the temperature of the output transistors is of prime importance a p–n junction close to the output stage is the best choice. Diodes are fitted at the inputs to protect against negative overshoot transients, but since the input stage is physically isolated from the output, where heat is generated, these diodes would never reach the same peak temperature. However, the substrate diode used to clamp the output signal and prevent negative excursions, caused by coupling effects, is a much better choice since it is situated very close to the output pull-down transistor and consequently should reach practically the same peak temperature. This diode is physically very close to the output transistor, typically 10 μm, and consequently a close relationship is obtained between diode and transistor temperatures.

Other studies have suggested that even using a 'local' diode, there still is a sufficient time delay before the diode responds to the rapid rise in true junction temperature.

For this study the substrate diode was used to measure chip temperatures since it is accessed easily. For actual measurement of temperatures, a calibration curve of forward voltage drop as a function of temperature is generated from which a voltage during the dynamic test relates to a particular chip temperature.

4.3 Temperature measurement

As stated above the output clamping diode was used as temperature sensor. Before the diode can be used to effectively measure temperature it is necessary to generate some form of calibration curve of forward voltage vs temperature. To obtain such curves a constant current, 100 μA, was chosen so that self heating is not encountered. This is passed through the output diode whilst the I.C. is maintained at constant temperature in a controlled oven. Forward voltage is then measured, and this is repeated for three temperatures to obtain the dV/dT relationship. Only two temperatures are required as the relationship is linear, the third acts as a check point. Since backdrive currents can vary, not only between devices but also between outputs of the same device, they were monitored on the test samples to obtain worst-case devices on which to examine chip temperature. This worst-case output port was then used on each I.C. in the batch for all tests associated with chip temperature tests. All tests were carried out with inputs connected to 0v and the Vcc pin unconnected.

4.4 Test set-up for chip temperature tests

The equipment used consisted essentially of purpose built circuitry to perform the switching functions, connected to a sample-and-hold circuit and then to a voltmeter, all controlled by a microcomputer via an IEEE bus or parallel ports as applicable. Application of backdrive signals and control of the Vcc connection to the device under test was achieved by the use of power MOSFET devices (Fig. 4), having switching times of the order of 20 nS. Control signals for these, together with the sample/hold pulse, were derived from the microcomputer parallel port.

The DUT ports are set to logic '0' and 4·5V backdrive pulse is applied to all outputs. At the end of the pulse, Vcc to the DUT is reduced to zero, whilst simultaneously reducing the backdrive signal to zero. Power MOSFETS TR3 and TR4 control Vcc, and TR1 and TR2 control the backdrive signal. Power down is achieved within 1 μS, and after this time unused outputs are unconnected and the test output is connected to a 100 μA constant current supply. The forward voltage drop at this output is sampled. The microcomputer reads the digital voltmeter and displays a temperature rise in °C. Drive pulse lengths of 10 μS, 1 mS, 10 mS and 20 mS were used and the corresponding temperature rises recorded.

The rate of fall of the chip temperature after backdriving was studied by delaying the sample/hold signal. A maximum time of 15 mS was used, by which time temperature rises had decayed almost to zero.

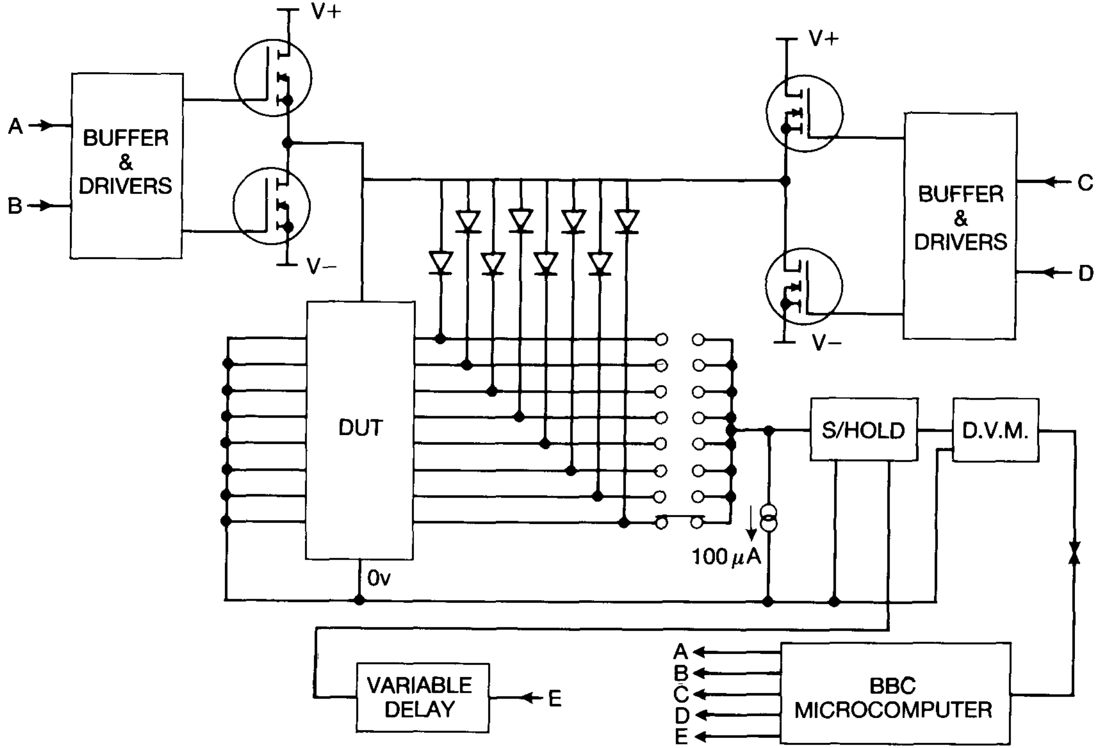

Fig. 4 Test set up for Chip Temperature Measurements

5 Backdriving tests

5.1 Backdriving conditions

Since the devices are bi-directional, each of the 8 transceivers has 2 ports. From the manufacturers' data it can be seen that the B port can supply, or sink, higher currents and must therefore be of lower impedance. It was therefore considered of more use to use ports A as inputs and B as outputs. All 8 outputs were backdriven simultaneously to give worst case conditions. The length of the backdrive pulse was set to 20 mS with a rest between pulses of 2 seconds i.e. 100:1 duty cycle. Voltage levels of 0·1V for backdrive low and 4·5V for backdrive high were selected. Twenty-five pulses were applied to the DUT and Vcc was maintained at 5·0V throughout the test. Figure 5 shows the typical backdrive pulse train used for the tests. Throughout the entire test, programmable voltage comparators monitored all outputs to ensure that both backdrive levels and normal logic levels were obtained from the DUT. This monitoring of voltage levels instantly showed up failures (as was the case with the 2 failures observed). Backdrive signals were applied to the ports by the power MOSFETS; 2 per output port, 1 for backdriving high and 1 for low. These were controlled by a microcomputer using the parallel port. Each output of the DUT was connected to a programmable voltage comparator to check the backdrive or logic levels. These comparators were logically AND ed and the output fed back to the microcomputer for automatic monitoring.

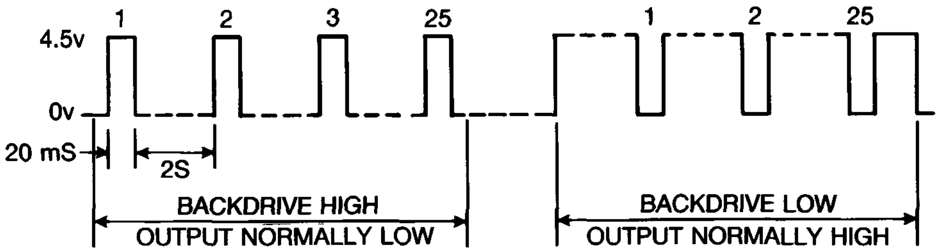

Fig. 5 Backdrive pulse train applied to device under test

5.2 Accelerated life tests

The structure of the life testing is shown in Fig. 6, essentially subjecting 190 devices to a dynamic test at 125°C for 2000 hours. Half of the components were subjected to a series of backdrive pulses prior to the test.

All devices were characterised using a Sentry test system at ICL Kidsgrove at all stages, firstly after mounting on printed circuit board carriers, secondly after backdriving, and then at 168 hours, 500 hours and 1000 hours during the test, and finally at the end of the 2000 hours accelerated life test.

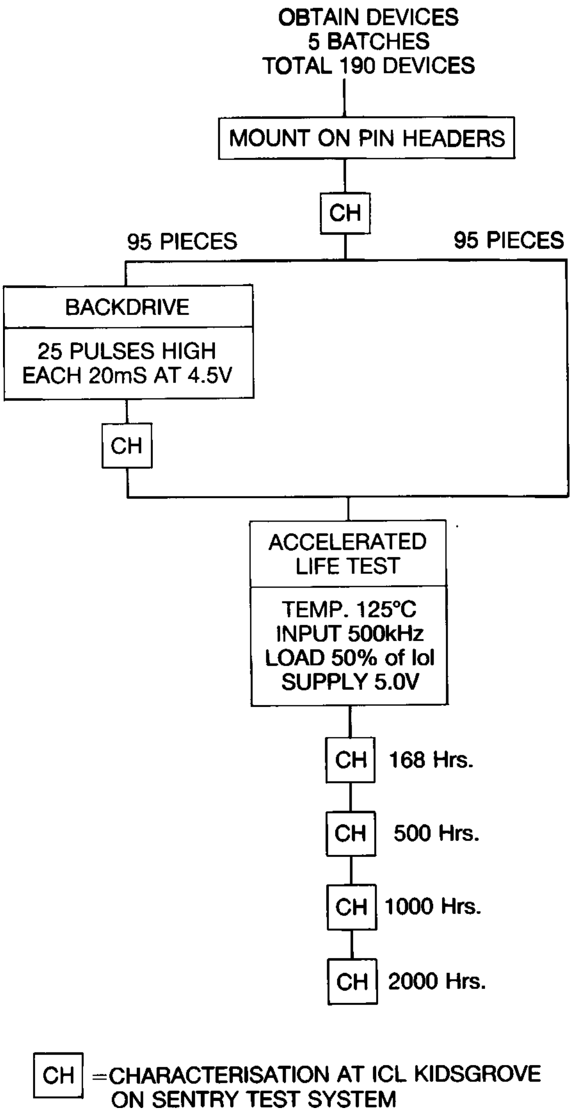

Fig. 6 Structure for the 2000 hours accelerated life test

During the life test the devices were subjected to input signals at a frequency of 500KHz, whilst all the B ports were loaded to sink a current of 50% of the maximum recommended low level output current I_{OL}.

Large programmable burn-in boards were used, each capable of holding 50 devices. Also on the boards was all the necessary drive circuitry together with the monitoring facilities to check that each row of components were being driven properly. All this extra circuitry was constructed using 54XX military specification devices since they were operating at a temperature of 125°C. All burn-in sockets were of the low insertion force type.

6 Results

6.1 Chip temperature tests

As described in section 4.4, the first requirement was to generate a calibration curve of voltage against temperature. Figure 7 shows how the relationship between digital voltmeter reading and temperature is obtained.

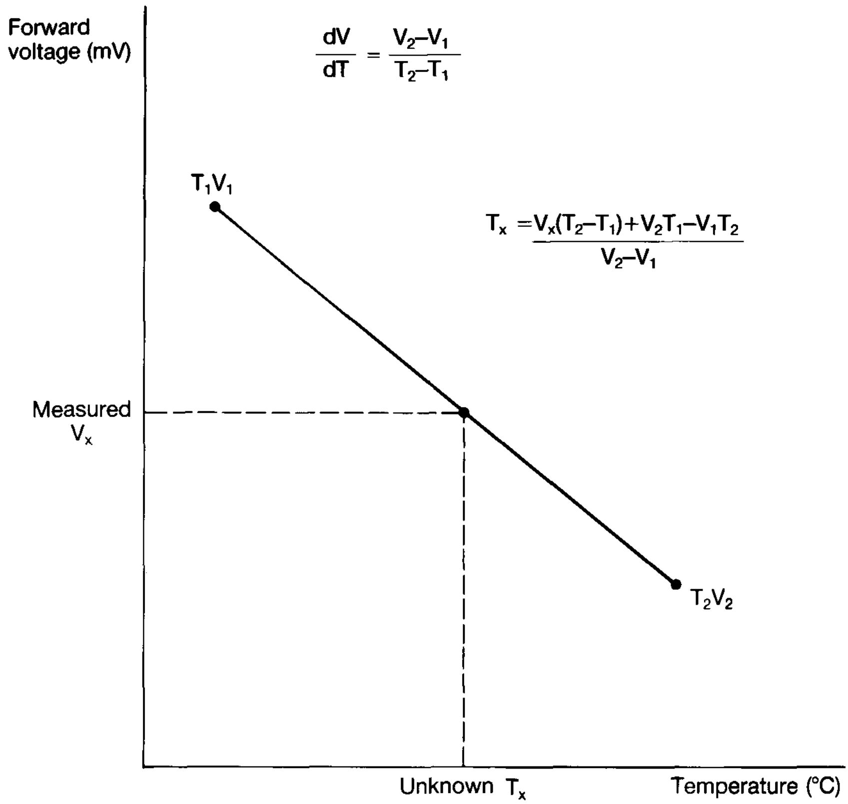

Fig. 7 Voltage relationship to temperature for substrate diode

Each batch used for these tests consisted of 5 devices, with the exception of serial numbers 301–310 where only 2 devices were used. In order to simplify results average values were recorded throughout each batch. All Fairchild 74F245 devices were taken as one batch since no significant differences were recorded. The values of chip temperature against pulse width are shown in

Fig. 8. It should be noted that only the Fairchild devices showed any marked temperature rise at a pulse width of 100 μS, and these devices overall had the highest temperature rise.

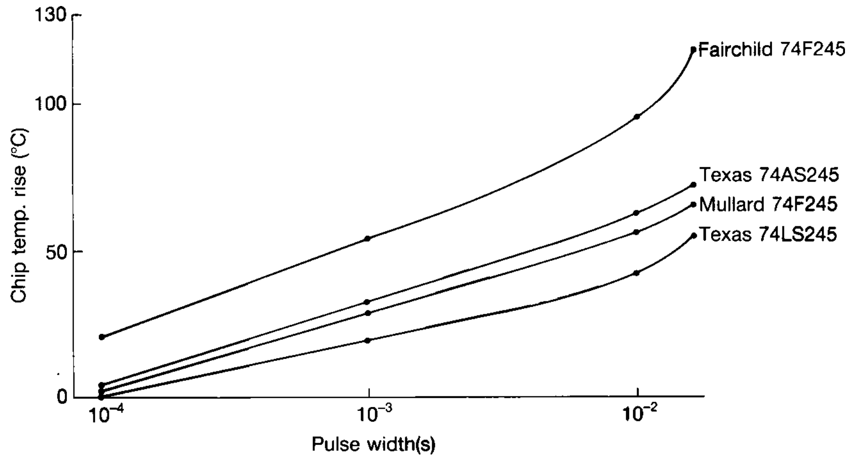

Fig. 8 Variation of chip temperature rise with pulse width

The study to investigate rate of decay of temperature at the end of the backdrive pulse, again for different pulse widths, gave the results shown in Figs. 9 to 12. Chip temperatures at increasing times from the end of the

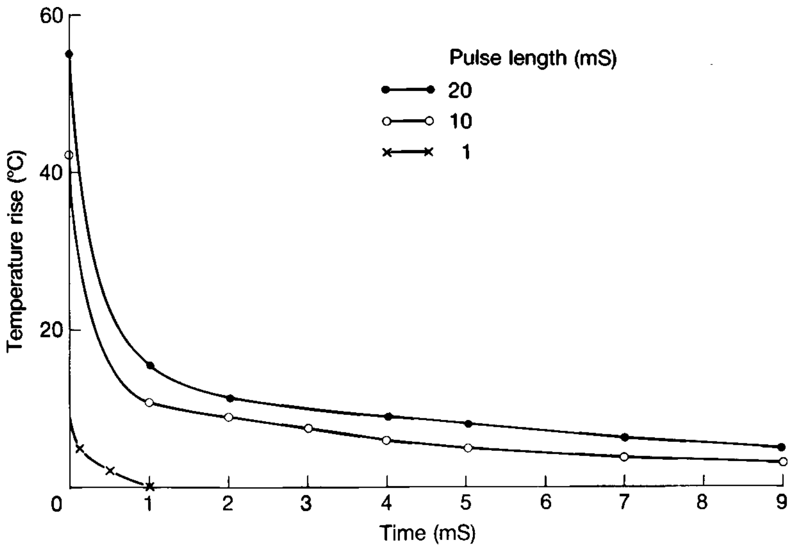

Fig. 9 Chip temperature after backdriving for Texas Instruments 74LS245

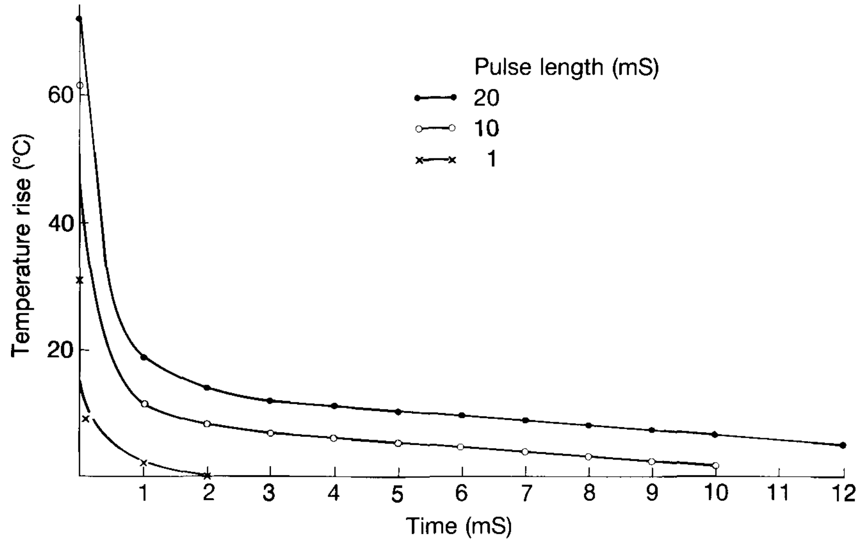

Fig. 10 Chip temperature after backdriving for Texas Instruments 74AS245

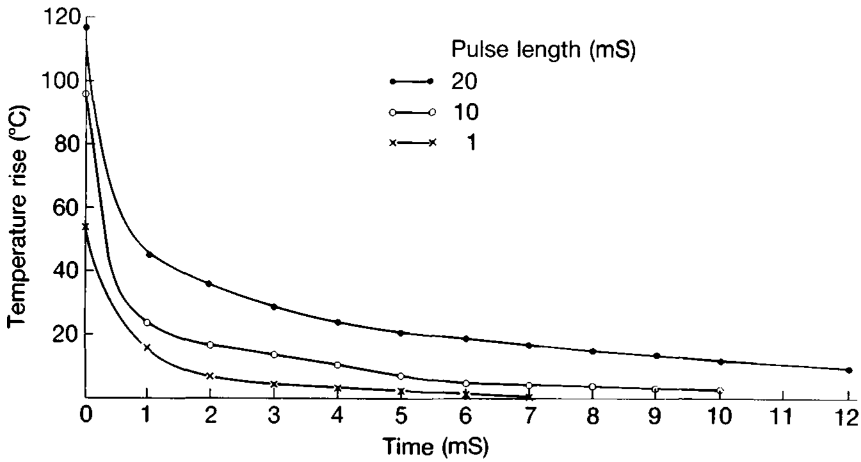

Fig. 11 Chip temperature after backdriving for Fairchild 74F245

backdrive pulse are obtained by delaying the sample signal by up to 15 mS, a time at which generally the chip temperature rise is practically zero. These tests were performed with repetitive backdrive signals, the delay increasing for each pulse, but care was taken to ensure that no cumulative temperature rise was obtained by having sufficient rest time between pulses; this was of the order of 2 seconds.

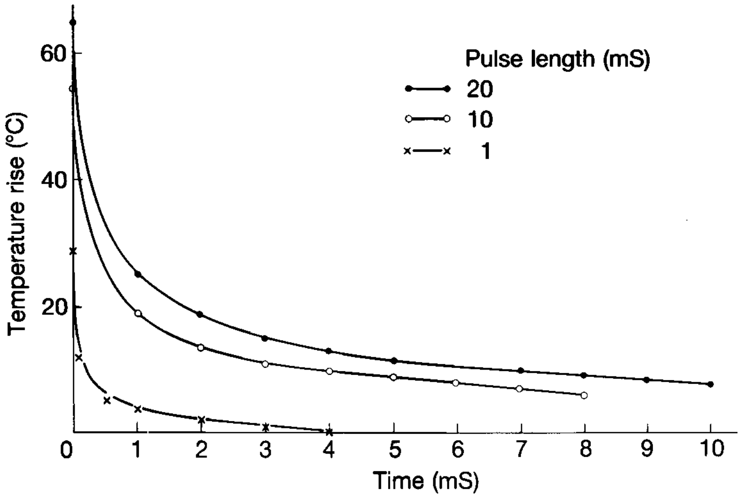

Fig. 12 Chip temperature after backdriving for Mullard 74F245

From the graphs obtained showing decay in chip temperature rise it was obvious that cumulative effects would not occur for rest times >1 second. This also gave extra confidence that during backdriving prior to the accelerated life test no cumulative temperature effects would be encountered using a backdrive pulse of 20 mS with a rest time of 2 seconds.

6.2 Data-logged device characteristics

As shown in Fig. 5 devices were characterised at ICL Kidsgrove using the Sentry test system throughout the tests. A list of device characteristics logged is shown in Fig. 13.

Symbol	Parameter
V_{ON}	High level output voltage
V_{OL}	Low level output voltage
V_{IK}	Input clamp voltage
I_{IH}	High level input current
I_{IL}	Low level input current
I_{OZ}	Tri-state (high impedance) output current
I_{OL}	Low level output current
I_{OS}	Short circuit output current
I_{CC}	Supply current

Fig. 13 Device parameters data-logged

6.3 Initial failures

The devices, being surface mounted, were mounted on small printed circuit boards which contained stake pins for easy access via a socket. They were then all data-logged on a Sentry test system. At this point device No. 51, Texas 74LS245, failed but visual inspection revealed a solder short circuit. This was rectified and the device then passed. Mullard 74F245 device No. 128 failed because of an internal short circuit and Texas 74AS245 devices Nos. 204, 231, 238 and 244 failed logically. None of these failures were included in any test results.

6.4 Failures detected during backdriving

Of the 95 devices backdriven, 2 did not complete the test because of failure after a backdrive high pulse. Device No. 105 failed after the 11th backdrive high pulse and No. 122 failed after the 3rd backdrive high pulse.

Analysis of the devices showed that Nos. 105 and 122, both 74F245 types, from Mullard, had failures consistent with that of open circuit 0v bond wires. This was demonstrated by testing a device from the same batch with its 0v pin disconnected. Unfortunately the de-capping process destroyed the bond wires.

A third device, No. 202 a 74AS245 from Texas Instruments, which passed the backdriving test did in fact fail at the Sentry re-characterisation stage prior to the commencement of the life test. It failed short circuit tests but analysis could not identify any specific cause.

Examination revealed that the Mullard batch of 74F245s had only one 0v bond wire whilst the Texas Instrument's 74AS245 and the Fairchild 74F245s had 2 bond wires for both the 0v and +5V connections.

6.5 Failures detected during life test

Following backdriving and re-characterisation, 92 devices together with 95 control devices were submitted to the life test of 2000 hours duration. A total of 13 devices failed of which 2 (Nos. 7 and 229) failed due to poor solder joints on the pcb carrier. These were repaired and continued without further failure to the end of the life test.

Three other devices (Nos. 215, 216 and 217), all Texas 74AS245, failed at 2000 hours. These however showed signs of damage to the packages in the form of cracks and it seems likely that incorrect insertion into the burn-in boards was to blame. This possibility showed up initially as incorrect orientation of the devices on the conductive foam used to transport them between Loughborough University and ICL. Only these 3 devices were differently orientated and it would appear to be safe to assume that they were accidently destroyed rather than failed as a result of backdriving. Subsequent failure analysis confirmed they were damaged due to excessive heating.

The remaining 8 devices are considered to be the only true failures during the life test. These have been split into backdriven and control groups with the times to fail.

Non-backdriven group

Device	168 hr	500 hr	1000 hr	2000 hr	Failure Analysis
No. 27 LS T1				Fail	Fails as though Ov bond wire O/C no visible damage
No. 137 F. Mull			marg #1		device passes test
No. 148 F. Mull				Fail #3	DC parametric failure no visible damage
No. 149 F. Mull		marg #4	fail		all O/P fail functionally, no visible die damage

Backdriven group

Device	168 hr	500 hr	1000 hr	2000 hr	Failure Analysis
No. 106 F. Mull	fail				Fails as though 0v bond wire O/C
No. 110 F. Mull			marg #2		device passes test
No. 118 F. Mull		marg #5			device passes test
No. 331 F. Fair				fail #6	DC parametric failure

Note
Fail indicates a functional failure and the component not returned to the life test.
Marg indicates a marginal failure but with the device still functioning. These components were returned to continue the life test.
Details on the fails marked (#1, etc.) are given below:
#1 and #2 failed TPZH port B to A

Fail/ Marg	**Vol at VCCL**	**550 mV limit**	**I out S/C**	**100 mA limit**
	Number O/Ps failed	Value	Number of O/Ps failed	Value
#3	1	720 mV	1	98·1 mA
#4	5	658 to 796 mV	3	80·7 to 96·3 mA
#5	1	552 mV	—	—
#6	5	552 to 660 mV	—	—

6.6 Results of devices surviving the life test

The purpose of this section is not to analyse component failures, since in this group there clearly are none, but to look for any possible changes or drifts in the parameters of the backdriven devices and use the non backdriven ones as a reference part.

A total of 174 devices, comprising both backdriven and non-backdriven parts surviving the life test provided approximately 185 000 measurements to analyse. This was clearly far too much for normal analysis. Some way of condensing the information was needed, but none of it was redundant.

The tests were performed by a Sentry tester using a different program for each of the three device types (LS, AS & F). Consequently it is not possible to compare the three directly as some of the parameters are different.

Because both backdriven and control devices came from the same samples their initial parameters (before backdriving) should be very similar. Thus one way to analyse the data is to look at how the two sets drifted as the life test progressed. If the backdriven group drifted significantly more or less than the control group then we could conclude that backdriving had affected the devices.

For each device, the measurements at the different intervals were compared to find the drifts. Two sorts were looked at; the drift since the initial log and the drift since the previous measurement. By taking the maximum value in each case the amount of data was reduced by nearly two thirds.

There was still no pattern apparent at this stage to it was decided to group together all the devices of the same type and manufacturer, giving four groups. The backdriven and control devices were compared within each group. It was important to reduce drastically the amount of information presented while keeping track of significant variations. To this end three sets of figures were found; the mean drift, the maximum drift occurring and the corresponding device number, and a representation of the spread in the drifts about the mean value (the standard deviation). This gave a more manageable set of figures.

The results for the two sorts of maximum were found to be similar, so only those for the first set, the drifts occurring since the initial log-in, are given. Those for the drifts occurring from one log to the next were a little smaller in magnitude but showed the same trends. These figures are presented together with the failure limits used by the tester and a 'typical initial value' for the measurement with which the drifts may be compared. This value has been rounded to the accuracy of the tester where applicable. The four groups are shown in Tables 1, 2, 3 and 4.

It can be seen that in general, the results for the backdriven batch closely match those for the control batch.

7 Conclusions

The results obtained from the junction temperature tests show that after applying a backdrive high pulse of 20 mS, Fairchild 74F245 devices heated up the most of all the device families tested, with a rise of 125°C. Even

Table 1 Device type: LS (Texas)

Parameter	Typical Initial Value	Fail Limits <	Fail Limits >	Maximum Drift: Backdriven Dev	Maximum Drift: Backdriven Value	Maximum Drift: Control Dev	Maximum Drift: Control Value	Worst Standard Deviation: Backdriving	Worst Standard Deviation: Control
I Input s/c	−10 µA		3·0 mA	1	10 µA	21	10 µA	6·4 µA	7·3 µA
Cat sup I	76 mA	0·5	180 mA	10	12 mA	21	730 mA	730 µA	930 µA
I leak hi-z	−30 µA	−200	200 µA	20	10 µA	25	10 µA	3·1 µA	4·9 µA
Cat fn test	15 ns		19 ns	10	5·8 ns	21	5·8 ns	140 ps	130 ps
V oh	3·2 V		2·4 V	2	80 mV	21	50 mV	8·9 mV	6·7 mV
V ol	270 mV		500 mV	1	96 mV	25	140 mV	71 mV	50 mV
I out S/C	−69 mA		−30 mA	10	5·0 mA	29	4·6 mA	1·9 mA	1·0 mA
I ol 1	−30 nA		20 µA	1	100 nA	21	100 nA	96 nA	94 nA
I ol 2	−54 µA	−200	µA	13	22 µA	21	21 µA	3·6 µA	5·9 µA
I cc 3	51 mA		95 mA	3	13 mA	24	13 mA	710 µA	350 µA
I ih 2	−20 nA		100 µA	1	100 nA	21	100 nA	99 nA	94 nA
I il 3	−10 µA		20 µA	1	10 µA	21	10 µA	6·4 µA	6·4 µA
I il 1	−40 µA	−200	µA	4	10 µA	22	10 µA	5·7 µA	6·1 µA
V Clamp	2 typs	−1·5	V	18	140 mV	21	130 mV	68 mV	49 mV

Table 2 Device type: AS (Texas)

Parameter	Typical Initial Value	Fail Limits <	Fail Limits >	Maximum Drift: Backdriven Dev	Maximum Drift: Backdriven Value	Maximum Drift: Control Dev	Maximum Drift: Control Value	Worst Standard Deviation: Backdriving	Worst Standard Deviation: Control
I input S/C	−10 μA		3·0 mA	201	10 μA	227	10 μA	5·3 μA	4·9 μA
Cat sup I	71 mA	0·5	246 mA	208	8·0 mA	227	8·0 mA	1·1 mA	1·4 mA
I leak hi-z	−200 μA	−1·1	1·0 μA	222	200 μA	229	200 μA	12 μA	9·3 μA
Cat nf test	5·7 ns		10 ns	203	3·5 ns	229	1·4 ns	87 ps	97 ps
V oh at −3 mA	3·0 V	2·4	V	220	70 mV	232	50 mV	37 mV	29 mV
V oh at −15 mA	2·9 V	2·4	V	211	90 mV	249	60 mV	42 mV	35 mV
V ol at 448 mA	360 mV	550	mV	206	160 mV	229	220 mV	12 mV	22 mV
−I out S/C	−94 mA	−112	−30 mA	211	11 mA	229	12 mA	2·4 mA	2·4 mA
Iccl at Vcch	100 mA		143 mA	206	10 mA	248	12 mA	1·3 mA	2·0 mA
Iccl at Vcch	65 mA		97 mA	201	6·0 mA	247	6·0 mA	940 μA	980 μA
Iccz at Vcch	80 mA		123 mA	203	8·0 mA	228	8·0 mA	1·3 mA	1·1 mA
I ib at Vcch	730 μA		100 μA	220	2·7 μA	233	2·9 μA	870 nA	810 nA
I ih at Vcch	−10 μA		20 μA	201	10 μA	227	10 μA	5·5 μA	4·9 μA
I il at Vcch	−390 μA	−750	μA	218	70 μA	228	30 μA	23 μA	10 μA
V clamp	−640 mV	−1·2	V	201	110 mV	227	90 mV	7·7 mV	8·9 mV

Table 3 Device type: F (Mullard)

Parameter	Typical Initial Value	Fail Limits <	Fail Limits >	Maximum Drift: Backdriven Dev	Maximum Drift: Backdriven Value	Maximum Drift: Control Dev	Maximum Drift: Control Value	Worst Standard Deviation: Back driving	Worst Standard Deviation: Control
I input S/C	−10 µA		3·0 mA	101	10 µA	132	10 µA	2·7 µA	2·4 µA
Cat sup I	92 mA	0·5	286 mA	102	4·0 mA	136	14 mA	1·6 mA	4·9 mA
I leak hi-z	−320 µA	−1·0	1·0 µA	130	20 µA	135	40 µA	9·2 µA	18 µA
Cat fn tst	6·9 nS	1·7	13 ns	118	1·8 ns	136	1·7 ns	130 ps	73 ps
V oh at Vccl	3·2 V	2·0	V	120	80 mV	140	90 mV	27 mV	28 mV
V oh at −3 mA	3·2 V	2·4	V	125	80 mV	151	60 mV	20 mV	7·8 mV
V oh at Vccl	480 mV		550 mV	124	54 mV	140	49 mV	27 mV	28 mV
−Iout S/C 1	−150 mA	−225	−100 mA	119	6·9 mA	135	6·9 mA	2·2 mA	2·5 mA
−Iout S/C 2	−85 mA	−150	−60 mA	119	2·7 mA	136	3·6 mA	1·1 mA	1·3 mA
Iccl at Vcch	89 mA		143 mA	101	4·0 mA	136	14 mA	1·9 mA	4·3 mA
Icch at Vcch	78 mA		143 mA	102	4·0 mA	136	10 mA	2·4 mA	4·2 mA
Iccz at Vcch	97 mA		143 mA	108	6·0 mA	136	16 mA	2·1 mA	5·2 mA
I ib at Vcch	19 mA		1·0 mA	102	3·0 µA	135	5·9 µA	1·5 µA	2·3 µA
I ih at Vcch	−10 µA		20 µA	101	10 µA	132	10 µA	1·9 µA	1·8 µA
I ih at Vcch	−340 µA	−1·0	mA	108	20 µA	136	50 µA	8·8 µA	19 µA
V clamp	−660 mV	−1·2	V	102	280 mV	113	190 mV	34 mV	29 mV

Table 4 Device type: F (Fairchild)

Parameter	Typical Initial Value	Fail Limits <	>	Maximum Drift: Backdriven Dev	Value	Control Dev	Value	Worst Standard Deviation: Backdriving	Control
I input S/C	0·0 µA		3·0 mA	317	20 µA	305	20 µA	2·0 µA	2·0 µA
Cat sup I	76 mA	0·5	286 mA	323	16 mA	341	6·0 mA	3·1 mA	2·0 mA
I leak hi-z	−370 µA	−1·0	1·0 mA	323	60 µA	305	20 µA	12 µA	5·1 µA
Cat fn test	6·6 ns	0·2	10 ns	320	1·8 ns	341	1·8 ns	96 ns	98 ns
V oh at Vccl	2·8 V	2·0	V	323	150 mV	345	70 mV	31 mV	31 mV
V oh at −3 mA	3·1 V	2·4	V	303	160 mV	305	70 mV	48 mV	36 mV
V ol at Vccl	360 mV		550 mV	322	66 mV	338	70 mV	3·2 mV	3·1 mV
−Iout S/C 1	−150 mA	−225	−100 mA	320	12 mA	306	7·1 mA	3·0 mA	3·5 mA
−Iout S/C 2	−95 mA	−150	−60 mA	323	8·0 mA	306	5·8 mA	1·8 mA	2·2 mA
Iccl at Vcch	88 mA		143 mA	323	16 mA	333	6·0 mA	2·6 mA	730 µA
Icch at Vcch	67 mA		143 mA	323	14 mA	308	4·0 mA	2·8 mA	2·0 mA
Iccz at Vcch	80 mA		143 mA	323	18 mA	341	6·0 mA	3·6 mA	1·5 mA
I ib at Vcch	1·6 µA		1·0 mA	301	19 µA	352	3·0 µA	20 µA	550 nA
I ih at Vcch	0·0 µA		20 µA	327	20 µA	305	20 µA	2·0 µA	2·0 µA
I ih at Vcch	−410 µA	−1·0	mA	323	80 µA	339	50 µA	34 µA	11 µA
V clamp	−390 mV	−1·2	V	301	170 mV	305	170 mV	34 µA	39 µA

allowing for an ambient temperature of 25°C, this still gives a good margin before reaching the secondary breakdown temperature of approximately 180°C.

The results of the cooldown times following backdriving give valuable help in defining the duty cycle of multiple backdrive pulses. If adequate cooldown time is not allowed between pulses then clearly a ramping effect will take the temperature higher than expected.

Clearly since Fairchild 74F245 devices heated up the most it was no surprise to find they took longer to cool down i.e. after the 20 mS pulse it took 12 mS to fall to 6°C rise. By extrapolating the curve, the time required to reach approximately zero temperature rise would be in the order of 40 mS. This means a duty cycle of at least 2:1 is required to avoid a ramping effect if only junction cooling is considered and not bond wires.

The results of the life tests suggest that providing the bond wires survive backdriving there is no noticeable long term reliability effect on the device. This is demonstrated by only 2 backdriven devices failing against 3 in the non-backdriven group and the parametric drifts recorded were similar for both groups.

Of the devices that survived to the end of the life test, backdriving had no noticeable effect on the LS sample. The AS sample showed slight differences between the backdriven and the control groups but nothing of significance one way or the other. The F (Mullard) sample had smaller drifts for the backdriven group, while the F (Fairchild) group had larger ones.

The 2000-hour life test corresponds to a period of around seven years under normal operating conditions. None of the drifts encountered here were sufficient to bring the devices anywhere near to failing during this time.

The evidence of this study clearly indicates that the limiting factor in backdriving the devices tested is the bond wires, NOT the silicon. The length of backdrive time will be a function of the number of simultaneously backdriven outputs since the cumulative current passes through the 0v bond wire.

The double bond wire construction, although intended for improving the device's parametric performance, does provide an increased capability for handling longer backdriving pulses. Because of uncertainty in guaranteeing double bond wires the prudent decision would be to assume only one and compensate the backdriving times accordingly.

Since the results were similar to those obtained by the ElectronikCentralen work [Ref. 1] it can be assumed that surface mounted packaged components behave similarly to their through-hole counterparts when backdriven.

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Reliability of surface mounted component soldered joints produced by vapour phase, infrared and wave soldering techniques

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Abstract

A description is given of a test programme to assess the reliability of both wave and reflow soldered joints between leaded plastic encapsulated chip carriers (PLCCs) and epoxy glass printed circuit boards (FR4). Thermally cycled boards were compared with power cycled boards. The joints were assessed at intervals throughout the cycling programmes by a variety of destructive and non-destructive techniques, but metallography and pull testing were the principal methods employed.

1 Introduction

Over the past few years the electronics/computing manufacturing industry has seen a rapid transition from through-hole components soldered into holes in printed circuit boards (PCBs) to surface mounted components (SMCs) soldered directly onto the surface of the board. Some of these SMCs have leads, e.g. leaded plastic encapsulated chip carriers (PLCCs), but as the name implies these leads are soldered to the board surface and have no mechanical attachment to the board.

The advantages of surface mount technology include improvements in performance, cost reductions and further miniaturisation in an industry where size and space are increasingly at a premium. Compared with the well established through-hole technology, reliability has largely been unproven and a major programme has been underway at STL for the past five years to assess the long term reliability of SMC soldered joints.

As part of this programme large J-leaded PLCCs have been soldered onto epoxy glass (FR4) boards by both reflow (vapour phase and infrared) and double wave techniques. The boards have then been the subject of a comprehensive test programme to assess solder joint quality and reliability. A typical board is shown in Fig. 1.

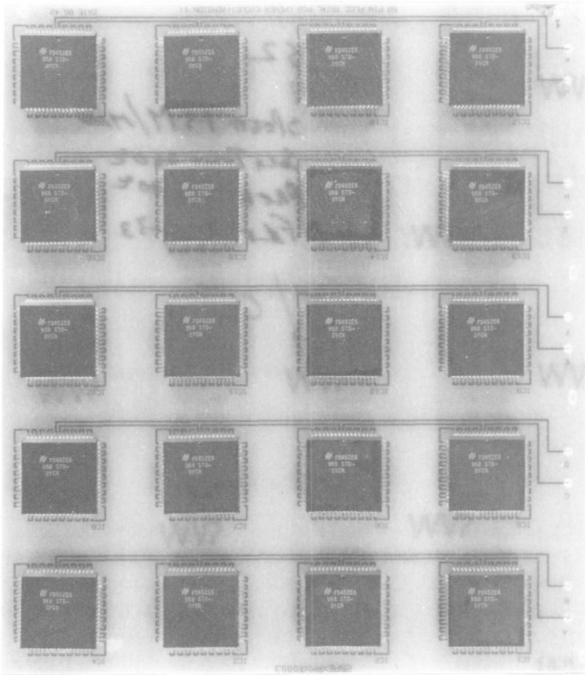

Fig. 1 View of 68 pin PLCCs soldered onto printed circuit boards

The PLCCs used (mainly 68-pin but also some 84-pin) have been from a number of suppliers including National Semiconductor, Texas Instruments and LSI Logic. The major reliability worry with the solder joints of these large packages is the increased stressing of the corner joints during thermal cycling due to thermal coefficient of expansion (TCE) mismatch between the package and the board. The design of the leads offers only limited compliance in the required direction and consequently the larger the package, and/or the larger the temperature range, the greater is the strain on the joints. Some production boards have literally thousands of soldered joints and any one weak or defective joint can cause a particular board to fail in service – hence the paramount importance of good quality, high reliability soldered joints.

With regard to the actual soldering process, the different thermal gradients produced by the different soldering methods, as well as differences in joint geometry, might be expected to affect the relevant properties of the joint, i.e. thermal fatigue and creep, hence a comparison was made between the three industry standard processes. In this respect although wave soldering of these four-sided packages is not in fact industry standard, the promising trials obtained at STL on a double-wave machine led to its inclusion in the programme.

2 Soldering

The soldering machines employed were as follows:

(a) Infrared (IR) reflow:
(Mannix HP600, Hedinair FX 14)
(b) Vapour phase (VP) reflow at 215°C:
(Hedinair, batch; ICI batch)
(c) Double Wave Soldering:
(Electrovert Europak)

For both the IR and VP reflow processes the standard production 62/36/2 Sn/Pb/Ag solder paste was screen printed onto the boards. The packages were then placed onto the boards by a semi-automatic process and the solder paste reflowed to produce the soldered joints. The IR process is an in-line oven, whereas the VP process entails immersing the assembly into an inert vapour.

The wave soldering process is very different in that the packages are glued in place on the board and are then immersed in a bath of molten solder to produce the joints. The double wave configuration of the molten solder minimises the risk of bridging between the leads.

Prior to soldering, the packages were examined for co-planarity, solderability, and the only cause for rejection was the occasional bent lead.

3 Test programme

The test programme was designed to accelerate the standard soldered joint failure mechanisms of thermal fatigue and creep. These mechanisms are realistically accelerated by increasing maximum temperatures and temperature ranges to a level where the inherent material properties are not significantly changed.

3.1 Thermal Cycling

Two thermal cycling tests were employed, 125°C to −55°C and 100°C to −40°C. The former tests were considered to be severe bearing in mind the 120°C glass transition temperature of the board (where the board will tend to become plastic and may permanently deform) and also that the temperature range greatly exceeded that likely to be seen in most PLCC service conditions. However, since a tremendous amount of work has been published (1)(2) using very similar tests (usually for ceramic packages in high reliability applications) it was decided to include it.

3.2 Power Cycling

Power cycling entails simply switching the board on and off to produce localised heating effects in the soldered joints.

Two power cycling tests at 50°C and 70°C ambients were selected, the solder joints in both cases exceeding the ambient by approximately 30°C in the power-on cycle. This was considered a more realistic test than the straight thermal cycling due to the thermal gradients produced across the board/package interface. These were observed using both infrared thermal imaging techniques and fine wire thermocouples.

For both thermal and power cycling tests a 15 minute dwell time was incorporated at both temperature extremes to allow time for the damaging solder creep to occur. Maintaining the assembly at the higher temperature is particularly damaging to the joints.

No mechanical cycling/flexing tests were included in the programme, since the absence of any thermally activated degradation mechanism(s) was considered unrealistic. Although useful for comparing the compliance of different leaded packages, the inability of mechanical tests to yield meaningful reliability data greatly limits their usefulness.

3.3 Solder Joint Evaluation

During the course of the tests the boards were monitored for electrical continuity. At intervals throughout the tests, boards were removed for destructive examinations (metallography, optical/scanning electron microscope (SEM) examinations and pull testing).

Pull testing of the *individual* leads proved the most informative, giving a quantitative assessment of joint degradation and positive identification of the catastrophic (zero strength) failure. This testing of individual joints was made possible by using a Nd/YAG laser to cut through the individual leads and remove the whole package body without any mechanical disturbance of the solder joints.

4 Results

The amount of data generated on this test programme was considerable, including tens of thousands of destructive tests on aged soldered joints. Hence only the detailed results on the most severe test (125°C to −55°C thermal cycle) are reported here. However, it is extremely encouraging to note that no failures have been observed to date during power cycling of the 68-pin packages up to a minimum of 15 000 cycles. The work on the larger 84-pin packages has only recently commenced but again no failures have been observed after approximately 1000 power cycles.

For a joint to be described as a failure, catastrophic failure of the joint must be evident, i.e. a zero strength joint as assessed by pull testing. In some cases, severe solder joint cracking is clearly evident (particularly in corner joints) but the joints are still intact and have reasonable strengths.

The pull test results on the 125°C to −55°C test are shown in Fig. 2. As can be seen, joint strengths fall off appreciably and the test appears to discriminate between the reflow and wave soldering processes.

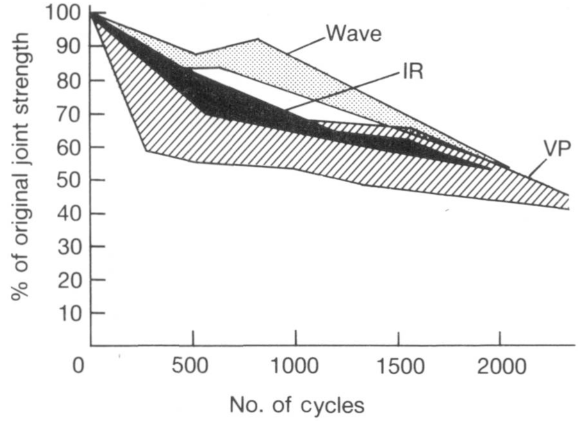

Fig. 2 Pull test results after thermal cycling (125°C to −55°C)

However, after a large number of cycles (greater than 1500) the joint strengths for all three soldering processes tend to converge. The surprising feature of these results is the superiority of the double-wave soldered joints particularly at less than 1500 cycles. This is further illustrated in Fig. 3 where the percentage of solder joint failures (zero strength joints) is shown. When describing 'failures' in this particular test, it should be borne in mind that this is an extremely severe test (approximately 20 times more severe than the 70°C power cycle test) and the results obtained are once again all considered satisfactory. Not surprisingly the failed soldered joints were either at or adjacent to package corners.

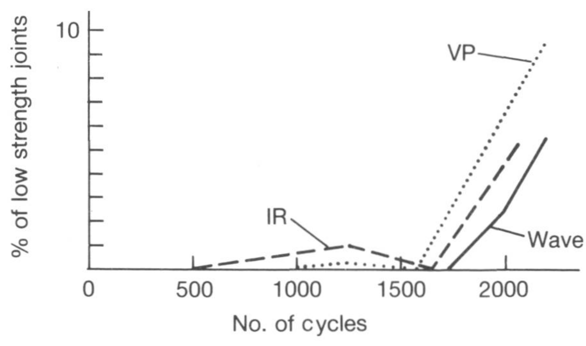

Fig. 3 Percentage of low strength joints (<1N) after thermal cycling (125°C to −55°C)

The reasons for the apparently superior performance of the wave soldered joints became evident after SEM/metallographic examinations. Figure 4 shows a typical cracked VP soldered corner joint after 2200 thermal cycles (125°C to −55°C); a similar double wave soldered joint after 1700 cycles is shown in Fig. 5. Microsections through these joints are shown in Figs 6 and 7 respectively. As can be seen, the inherently weaker 63/37 Sn/Pb solder (3) used in wave soldering had a multiplicity of fatigue cracks throughout the fillet in the Pb-rich phase (Figs 5 and 7). This appeared to have the effect of relieving the stress in the joint and producing additional compliance – hence an apparently superior fatigue performance.

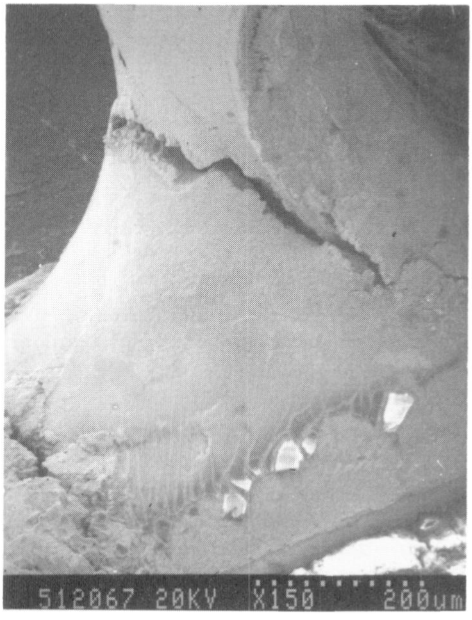

Fig. 4 Typical VP soldered corner joint after 2200 thermal cycles (125°C to −55°C)

In the case of reflowed joints, the stronger 62/36/2 Sn/Pb/Ag solder did not show this micro-cracking effect, the stress being concentrated at the solder/lead interface, resulting in eventual catastrophic failure within the darker Pb-rich phase at this interface (Figs 4 and 6). This effect was evident with both VP and IR soldered joints.

Microsectioning did not reveal any other significant differences, e.g. structural, joint geometry or degree of porosity, to explain this difference in performance.

Fig. 5 Typical double wave soldered corner joint after 1700 thermal cycles (125°C to −55°C)

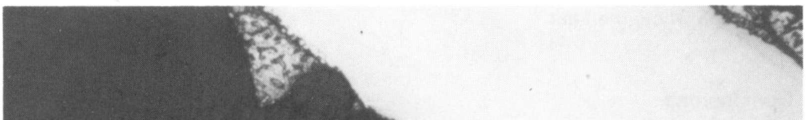

Fig. 6 Microsection through VP soldered corner joint after 2200 cycles (125°C to −55°C) Note cracking at lead/solder interface

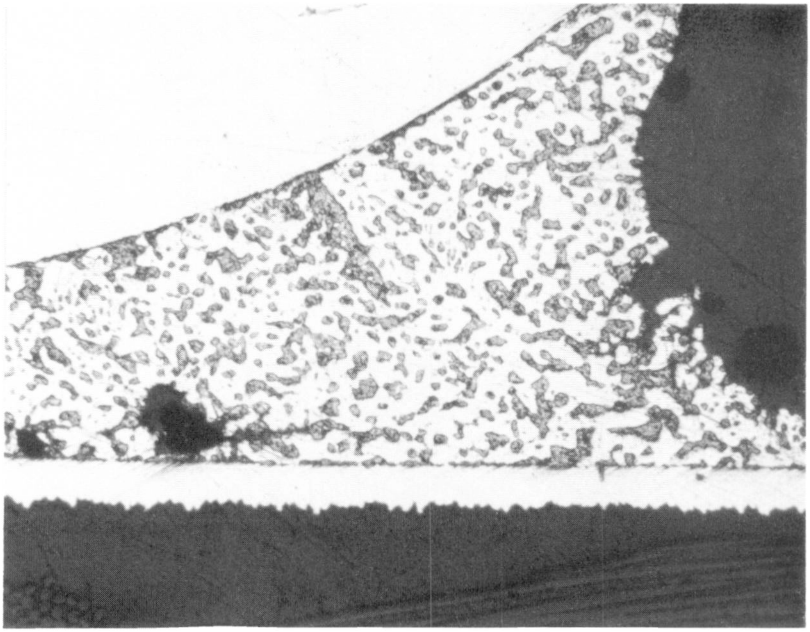

Fig. 7 Microsection through double wave soldered corner joint after 1700 thermal cycles (125°C to −55°C)
Note cracking within the fillet

5 Conclusions

1 The long term reliability of 68-pin J-leaded PLCC soldered joints on FR4 is excellent. Preliminary work to assess 84-pin PLCC joints suggests a similar situation.
2 The reliability of these SMC soldered joints is comparable with corresponding through hole technology and does not represent a reliability hazard in telecommunication or computing environments.
3 The slightly superior performance of the double-wave soldered joints compared with the reflowed joints (both IR and VP) is due to the different solders employed: the inherently weaker 63/37 Sn/Pb solder used in wave soldering giving the joint increased compliance and an apparent improved fatigue performance.
4 The performance of IR and VP soldered joints are comparable.

6 Acknowledgements

The authors are grateful to D.F.T. Roberts (programme design), L. Horsley (Scanning Electron Microscopy), B.M. Wright and M. Lazare (Metallography), and N. Finch of Frys Metals for assistance throughout the programme.

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MATERIALS SCIENCE SUPPORTING SERVICES

Materials evaluation

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Abstract

A major supplier of equipment has to ensure the quality of the products it makes whilst constantly introducing new and components to give improved performance. To aid in this activity STC/ICL maintains a specialist Materials Evaluation Centre, able to diagnose problems and measure properties of materials and to aid in selection, design and testing. This paper describes some of the analytical techniques used and shows how they have evolved over recent years. The improvements in laboratory productivity brought about by these developments are emphasised.

Materials examination and testing is a vital ancillary function necessary within any company of the complexity of STC-ICL which not only manufactures hardware but also incorporates many bought in items into its products. Production support is necessary to ensure that our products are of adequate quality and reliability, to aid our companies in the control of their manufacturing processes and to handle various field, production and other problems. The capability has to encompass a wide diversity of techniques backed by expertise in materials selection, processing and failure mechanisms. It is necessary to be able to mount validation programmes including accelerated testing, mechanical and physical property measurements at short notice.

The major manufacturing locations maintain local facilities and the Materials Evaluation Centre at STC Technology Ltd at Harlow fulfils a central role able to provide a comprehensive independent facility across the company. This Centre operates a range of modern analytical and microscopic equipments including scanning electron microscopes, Auger, X-Ray, gas analysis, as well as environmental and corrosion test cabinets and conventional chemical and metallurgical facilities.

To maintain a responsive, flexible and professional service the Materials Evaluation Centre is allied to a healthy project base which allows staffing levels to be varied according to demand and helps maintain key technical expertise. It is however not always possible to provide all the necessary expertise by this means and it is therefore necessary to supplement our capabilities by working with other companies and by judicious involvement with various universities, professional bodies including STACK* and Research Organisations and through collaborative projects. In this way we are able to handle problems covering a diverse range of topics including metals, semiconductors, plastics, glasses and ceramics, reliability and accelerated testing, interconnections, soldering & joining, laser processing, thermodynamics and electrochemistry, basic electronics, machine vision, leak testing, computer testing, wear and corrosion.

It is not normally our practice to install techniques which do not have regular use since it is not possible then to develop and maintain adequate expertise. We supplement our inhouse capability by the use of organisations where we can reliably get work done for use on an urgent basis. Occasionally we need a technique which we cannot access externally and decide to set up facilities with the intention of maintaining viability by taking on work from non-STC companies. An instance is moisture measurement in small packages where we operate the only UK facility. This provides an indispensible service to our colleagues in STC Submarine Systems and our components supply companies, where knowledge of how little moisture is left within an IC or laser package or cable is of paramount importance. Moisture can influence electrical properties, allow filamentary outgrowths of metals across electrical fields and lead to damage from corrosion.

The intention of this paper is to indicate the way in which Materials Evaluation Techniques are constantly evolving and improving in response to technical and commercial pressures and to give some indication of the type of work done. Although the article concentrates on the equipment and techniques we use, it must never be forgotten that the knowledge and experience of our staff is the most important resource we have.

If you visit Material Evaluation Laboratories you will doubtless be aware that they house increasing numbers of 'black boxes' with cathode ray tubes, keyboards and printers appearing, as elsewhere in industry. Computers now calculate results which were previously worked out manually and/or looked up in reference books. It is sometimes hard for today's new scientists to comprehend the strides which have been made in analysing phases† in materials at a microscopic level.

One particular area of analysis, the electron micro-probe microanalyser, serves as a useful illustration of the continuing evolution of analytical processes.

How does electron probe microanalysis work? A high voltage electron beam of 15 to 25 KeV is directed at the surface to be analysed. The beam penetrates

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*STACK – Standard Computer Komponenten – A worldwide collaborative body whose objective is to interchange information within the electronics industry.
†In this context a phase is a constituent part of a material which differs from other parts in its composition and/or structure.

to a depth of up to 2 microns (depending on the material and the beam energy) energising the electrons within the atoms to higher orbits. As these electrons return to their normal orbits they emit X-Rays which have energies/wavelengths characteristic of the atoms present enabling these atoms to be identified.

This single technique replaced what was essentially a form of microscopic pattern matching. The major chemical elements present were deduced by various chemical techniques including X-Ray fluorescence, a similar technique to electron probe analysis but using X-Ray themselves as the source of excitation, and the phases were identified by X-Ray diffraction which could only detect phases when present at at least 0·5% (and sometimes 5%) of the whole. Known structures of similar overall composition were compared with the sample being examined and phases were identified by shape, hardness, colour, reflectivity and response to localised chemical spot tests and etching.

When first introduced, electron probe analysis represented a massive improvement in capability both in detection limits and in the reliability of the results produced. Nevertheless analysis was slow, depending on sequential mechanical rotation of up to four diffraction crystals. The whole process sometimes took a full working day for one sample.

The next big step forward occurred in the late 1960s with the invention of energy-dispersive systems for the detection of X-Rays. This system uses a silicon detector which produces a characteristic current pulse on absorbing an X-Ray. The technique allows rapid sequential (effectively simultaneous) monitoring of all energies at one time but was practically limited to elements of atomic number greater than 23 (sodium) by the absorption of the beryllium window used to interface the measuring unit with the electron probe analyser. With this technique, element scans took only a few minutes although the lighter elements still had to be measured by crystal spectrometers in the old way.

The latest developments are the windowless detector and the ultra low absorption window which now allow the low energy X-Rays to reach the detector, eliminating totally the need for slow mechanical scanning for light elements.

In parallel with these developments, the application of computers to the interpretation, manipulation, storage and quantisation of the data has increasingly spared the operator from the routines involved in extraction of useful information from the raw data. Software routines compare current measurements with previously obtained standard data and allow for complex interactions which can sometimes take place as a result of the effect of X-Rays produced by one element interacting with the others present. Multiple images can be simultaneously displayed, and by superimposing coloured images of different elements, hitherto unsuspected boundary phases can be seen at the junction of materials.

e.g.

The data processor can be shared between machines. The net result is that today's machines combining modern scanning electron microscopes with resolutions of 2–3 nm, windowless detectors and sophisticated data processing cost no more in real terms than the machines of the 60s and 70s, have incomparably higher productivity and are superior technically. With all the computer aids it is important to have knowledgeable operators who never forget the underlying principles of the techniques they are using and are able to spot the unexpected edge effects, distortions and overlaps which escape even the best computer program.

The electron probe micro-analyser represents one of the more obvious areas of advance in Materials Evaluation and is probably now reaching maturity. Other techniques are in different stages of development.

Our ancestors in the eighteenth and nineteenth centuries, with no Scanning Electron Microscopes at their disposal, honed the optical microscope to perfection. Whilst modern lens coating techniques have helped to reduce light scattering it does not make financial sense to aim for the lens perfection achieved in earlier times. One area where optical microscopy is advancing is in data handling. The computerised image handling techniques, formerly applied only to particle and phase counting/measurement, are now being expanded to present similar displays to those available for SEMs including image enhancement, storage and superposition. Pattern recognition techniques are being developed to aid in the detection and classification of features of interest. Interest in X-Ray microscopy also lapsed with the development of electron probe analysers but is showing a resurgence with the call for high resolution microradiography for the semiconductor industry. These equipments can now detect 5 micron particles, compared with 40 microns only eight years ago. Current developments are aimed at taking this down to one or two microns.

Over and above the generalised trend to finer spatial resolution, lower detection limits and high productivity there is a continuing need for better techniques to identify and characterise small amounts of organic materials (e.g. plastics, oils, resins) and to non-destructively examine inside bulk materials. Historically organic materials were identified by careful measurement of the elements present. Modern methods of analysing organics evaluate their optical absorption or measure their molecular weight. The conventional optical absorption method was to mechanically scan a monochromator through the optical spectrum, using two or three equipments to cover various parts of their spectrum. This allowed detection of compounds in the infrared range and once identification was made, more accurate measurements could be made using the less distinctive, but more sensitive, peaks in the UV range. Today this laborious scanning process has been replaced by the fourier transform equipments which use an interference technique to detect all infra red wavelengths simultaneously.

More rapid measurements can be made and continued signal integration allows much greater (1000×) sensitivity. The technique, because of its rapidity, makes it possible to examine reactions as they occur.

The internal examination of samples is being addressed principally by two techniques; X-Ray radiography/microscopy, as already mentioned, and also scanning acoustic microscopy. The latter technique relies on the reflection of sound waves from discontinuities within samples such as tracks, holes and inclusions to produce pictures. The technique has been applied on a macroscale for many years to the examination of defects in sheets, tubes, etc. and particularly for the examination of welds. It is also used in medicine for scanning body tissue. Recently there has been much work to miniaturise the technique for the examination of fine detail. It has the great merit over X-Ray based techniques in that reflections are obtained from layers which, although in contact, are not actually bonded; whereas X-Ray radiography, relying on relative absorption, cannot detect these effects. The example below shows the technique applied to the examination of contacts made between a semiconductor chip and a ceramic chip carrier to see if true wetting of the bonded surfaces by the solder has occurred.

It is not the intention of this paper to catalogue all the techniques available to the modern Materials Evaluation Centre. Rather the aim is to show that examination techniques are constantly evolving, providing ever more powerful tools. Furthermore, we are not confined to the improvements made by the equipment suppliers themselves; STL has its own programmes of technique and data handling developments. Projects currently running are associated with moisture analysis in small packages, techniques for opening up and examining plastic encapsulated devices, improved quantification techniques in electron probe microanalysis, X-Ray Microscopy and the networking of images between instruments for on-line comparison purposes and directly to the customers' terminals where appropriate.

Having discussed some of the equipment improvements, some typical applications can be outlined. In order to maintain quality, incoming components are thoroughly checked and subjected to standard quality tests at our factories. Failing components are examined so that the cause of the defects are known in order to be sure that there are no implications with respect to other apparently satisfactory devices. We work with the suppliers to ensure that faults are remedied and quality maintained.

The photographs below show bridging between the leads of a device which had become contaminated during manufacture. This problem was encountered in a high reliability transistor where the composition of the gold plating used to screen the device had been altered by the codeposition of thallium. This had transferred onto the device surface during high temperature treatments in manufacture. Under the influence of a standing voltage difference between the leads, and in the presence of moisture, an electrolytic cell had formed, allowing material to be plated, joining the leads. Techniques to detect thallium and the presence of moisture had to be developed and validated for process control purposes.

Another example of such a problem, where special proving tests had to be devised, occurred recently with a cost sensitive product produced by the company in large volumes. The latest contained small coils, bought economically in the Far East, which were found to fail on shock testing. A major order depended on passing the qualification test and indeed the whole business was felt to be at risk. Since it was not possible to replace the component without a redesign of the product, a quality control test had to be developed to check incoming product against a very short timescale.

STL examined the coils and showed, by the use of careful decapsulation, that the fault was due to stress-related breakage of the coil wire at the termination point, not to overheating and consequent solder dissolution of the wire which was an alternative possibility. Attempts were made to simulate the failure with thermal cycling in the hope of sorting batches but this did not succeed. Sorting components, based on the degree of cure of the plastic encapsulant, also failed. A specially calibrated drop test was developed for the coils and shown to correlate with the incidence of failures in the test of the whole unit – this now forms the basis of a batch control process. However, of key importance was the demonstration that acoustic monitoring of devices during cooling from 100°C could be used to eliminate noisy devices, which showed a much higher failure rate than quiet ones. This enabled batches to be sorted prior to resubmission for the test, buying us the time in which to implement the new control test at the suppliers. As in many such cases the diversity of skills available to tackle the problem was extremely important and the company's credibility in this work was enhanced by our proven record of similar problem solving in the past. We were helped in the programme by the Welding Institute who radiographed numerous coils for us at very short notice.

It must be admitted that not all our work provides the stimulation of this type of investigation. Much of it is of a more routine nature supplementing the capabilities of the manufacturing house facilities with specific measurements and supplying specialist advice. However, as a consequence of its independence and professional status the Centre tends to become involved in major validation exercises even when evaluation facilities are available in the local unit.

Work for the factories provides approximately half of the work of the Materials Evaluation Centre. The rest of the time is spent on work for the advanced materials based research projects undertaken by STC's Central Research Activity at STL in fields such as Optoelectronics, VLSI, Cables, Interconnections, Displays and Superconductivity. All of these technologies, in the pursuit of higher performance and increased miniturisation, constantly press the limits of the analytical forefront of materials science, helping STL to develop and maintain a modern, comprehensive and responsive service for the whole of STC/ICL.

Fig. 1 Micrograph demonstrating the use of colour to highlight the presence of copper-tin brittle intermetallic phase within a soldered joint ($\times$ 10,800)

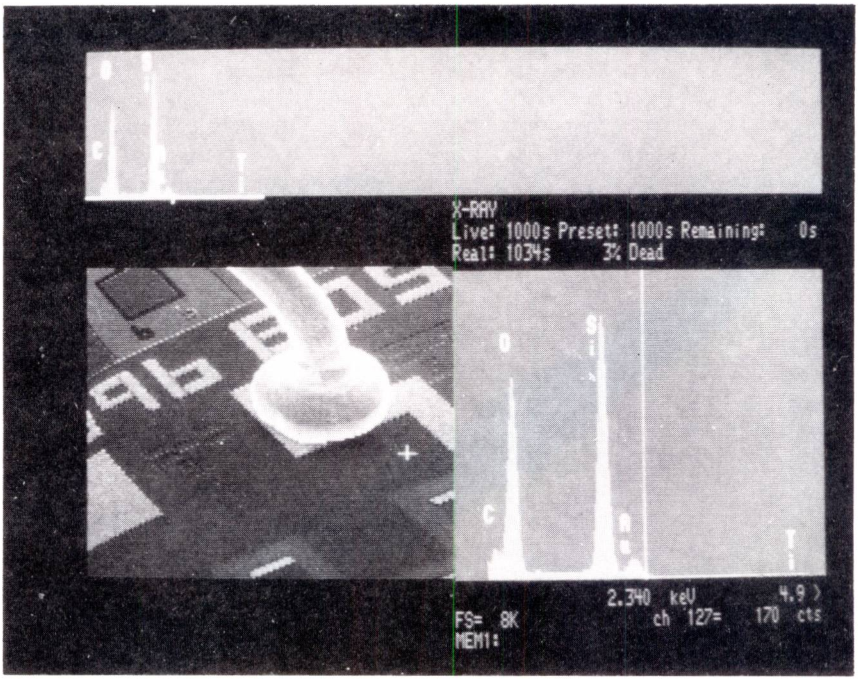

Fig. 2 Example of the display from a modern SEM/Probe Analyser + marks the analysis spot, elements are automatically labelled in the analysis. The right hand picture shows an expanded spectrum

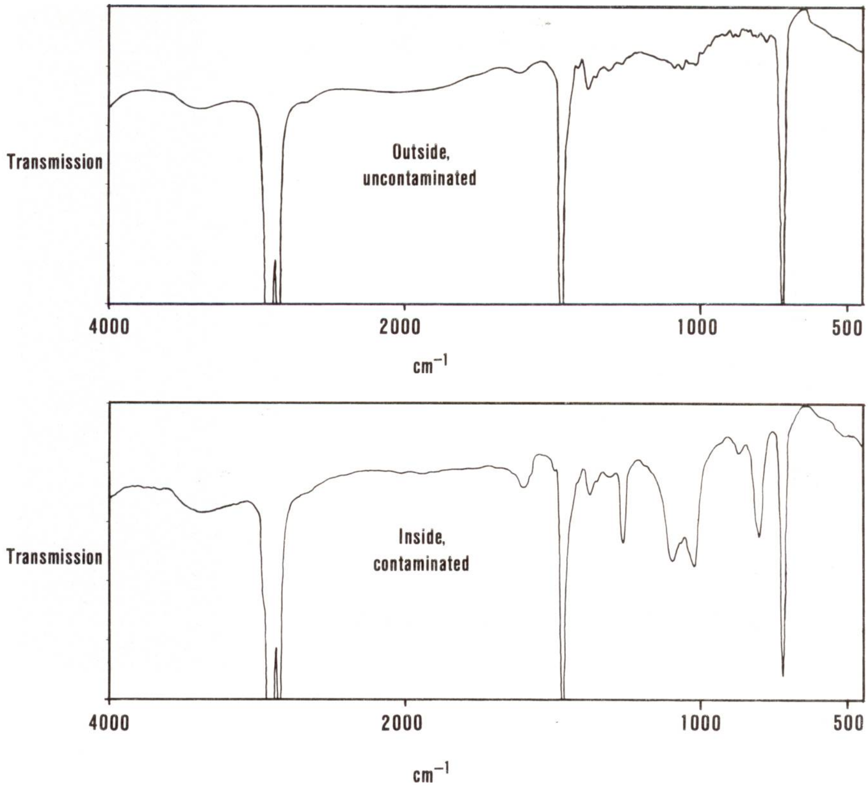

Fig. 3 Optical absorption spectra of two surfaces of a polythene cable. The traces of silicones, giving extra features on the inside spectrum, caused cracking of the cable

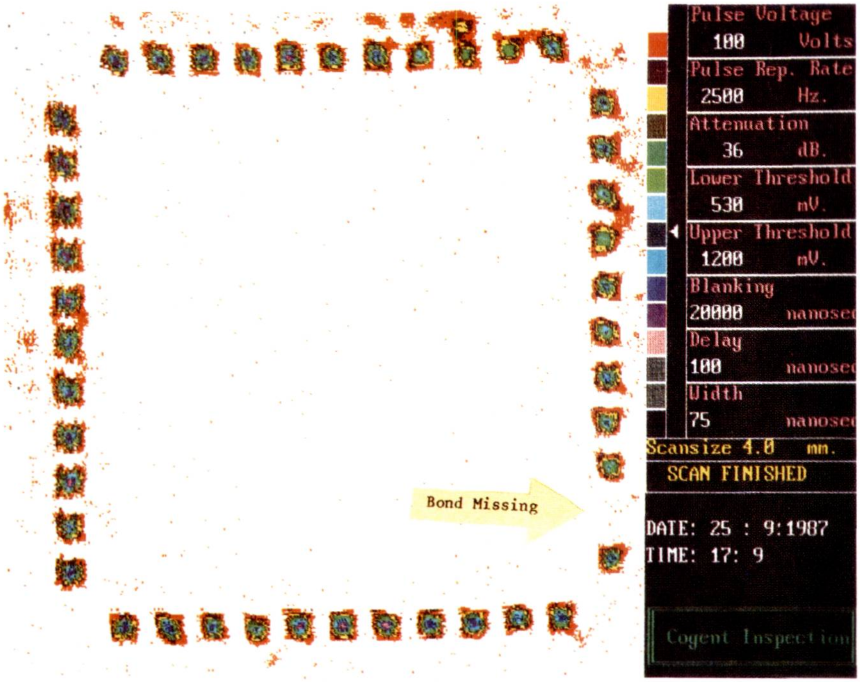

Fig. 4 Acoustic micrograph of a RISH (Research Initiative on Silicon Hybrids) flip chip device mounted on a silicon motherboard. The picture, taken by Fulmer Research shows that one joint has not formed on the bottom right hand side ($\times 2.4$)

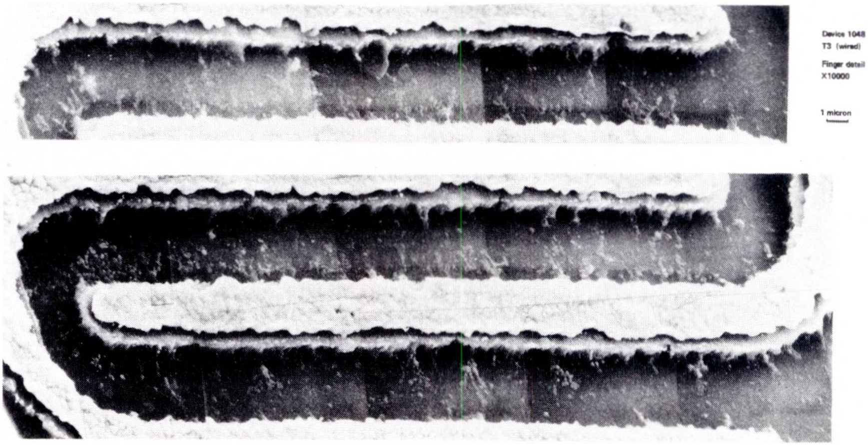

Fig. 5 Extensive dendrite formation between tracks on a silicon device as a result of the presence of moisture and contamination $\times 4{,}000$

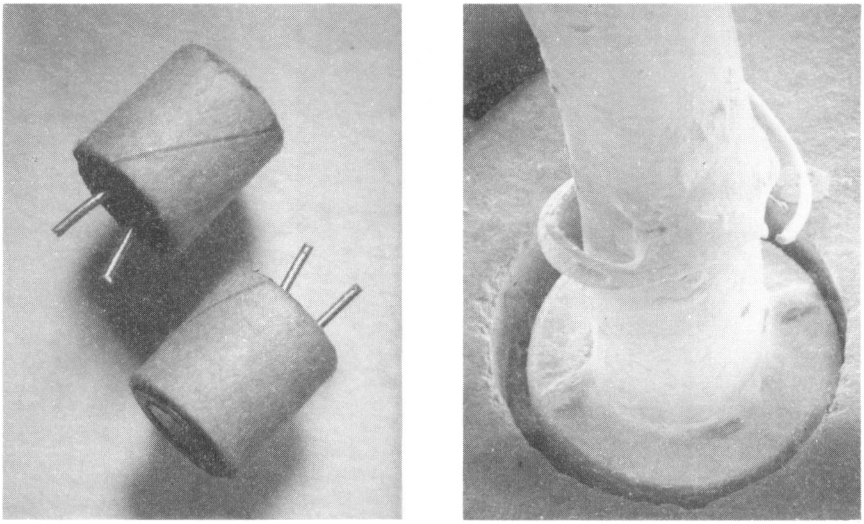

Fig. 6 Small coils which caused failures on the drop test. Right hand picture shows the break in the coil winding at the point where it is soldered to the external pins (left × 2.4, right × 48)

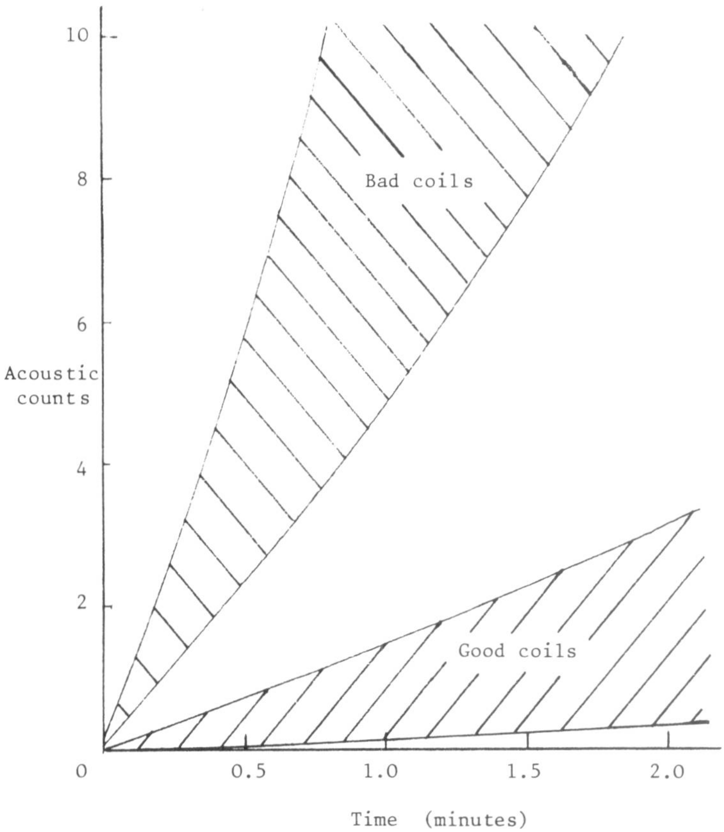

Fig. 7 The distinctly different results of acoustic emission testing of 'good' and 'bad' coils formed the basis of a sorting test

TECHNOLOGY AND HUMAN FACTORS IN INDUSTRY

On the human side of technology

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Abstract

The paper summarises the efforts of the leading automobile manufacturers in the USA, Japan and Europe to improve quality and productivity through the use of advanced technologies and reforms in human resource and industrial relations practices. It demonstrates that strategies that emphasise technology alone are inferior to those that seek to integrate the human resource reforms with the new technologies.

The Theoretical Perspective: Selected Vignettes

Consider the following vignettes drawn from our studies of two auto assembly plants located in North America.

From a visit to Plant W: Described by the plant manager as the "Highest Tech" auto assembly plant in North America.

On a tour of the plant our guide pointed out with considerable pride a walled off area he described as the "$5 million room". Once inside the room we saw two work stations each with a set of lasers beaming at door panels that had come in from external suppliers for inspection for "dimensionality" i.e., to see if they fit within all specifications. Attached to each laser workstation was a computer monitor and operator. I asked the operator to describe what he was doing.

"See all the data on my screen. Those numbers tell me whether or not the doors we get from our supplier fit our specifications in all dimensions. This is great stuff. Before we had this technology I used to always get in to fights with the guy I talked to at the supplier. I'd say a part wasn't right. He'd say it was ok when it left their shop and off we'd go. Now we have the same numbers and equipment so there's no debating."

I asked: "If they have the same technology and can produce the numbers and check the quality why do you need this technology here, aren't you duplicating what they are doing?"

"Yeah. But its simple: They lie!"

Plant C: A new North American assembly plant of a Japanese auto firm described by the plant manager as "about 70–80 percent automated". In the view of this plant manager:

"Full automation as pursued by some US companies is a bad idea. Harmony between man and machine is needed instead."

When on a plant tour I asked our guide to show me where they checked their incoming door panels for dimensionality, he said:

"We don't do that. We assume the supplier got it right. That's their responsibility. We worked with them at the start until we were confident in their ability."

I asked: "You mean you don't have a $5 million room with lasers?"

His answer: "We'll let our competitors have that technology."

These two vignettes illustrate the proposition that underlies a great deal of our empirical research on the relationship between human resource policies and new technology. That proposition can be stated quite simply: The greatest economic returns to new technology (IT as well as other forms) are achieved when technology strategies are fully integrated with human resource management policies. Stated differently, organisational performance is a function of the interaction of new technology *and* human resource system outcomes.

Theoretical Background

This general proposition can be traced back to the early socio-technical design theorists and advocates (Trist and Bamfort, 1951; Trist, 1982). The central proposition in those socio-technical models is that technical systems are interdependent with human systems. Therefore, organisational performance and human satisfaction will be jointly maximised when concerns for human motivation and group behaviour are adequately considered in the design of work systems. While this was a generic proposition, over time most of those studying socio-technical systems have tended to narrow their emphasis to a specific form of work organisation: autonomous work groups (Hackman, 1982; Trist, 1982). This is unfortunate for both theoretical and empirical reasons.

On theoretical grounds it has meant that inadequate consideration has been given to the full range of organisational and human resource considerations that affect the performance consequences of technology. On empirical grounds, this narrow focus has been unfortunate because there is at best mixed evidence on the performance consequences of autonomous work groups. A recent review (Goodman, Devadas, and Hughson, 1987) concluded that while self managing or autonomous work groups do generally produce a positive effect on productivity the magnitude of this effect is rather modest and may be significantly less than the effects of technical aspects of the production system. Thus while our approach shares some of the features of earlier socio-technical models, for both theoretical and empirical reasons the model outlined below is considerably broader.

The full range of the human resource dimensions that need to be considered can perhaps be illustrated best by reviewing the results of several recent studies of the effects of human resource management innovations and applications of new technology in auto assembly operations. Three different sets of data and analyses will be used: (1) pair-wise comparisons of the performance of several auto assembly plants with different human resource and technological configurations, (2) a cross-national comparison of the performance of 31 assembly plants, and (3) a comparison of the performance of 52 assembly and suppplier plants in the US.

Pair-Wise Comparisons: Learning from NUMMI

The auto industry provides a rich natural laboratory for assessing the effects of human resource systems and new technology. All US based firms have been aggressively investing the development and use of new technologies in their manufacturing operations while at the same time working hard to introduce reforms in their traditional labour-management relations and human resource systems (Katz, 1985). With the growth of Japanese investment in the US in the past decade even greater variation in human resource practices and manufacturing policies has been introduced into American settings with American workers. One of the most highly visible of these new plants and one that has been the subject of a great deal of debate and discussion has been the New United Motors Manufacturing Incorporated (NUMMI) facility located in Fremont, California. This plant is a joint venture between General Motors and Toyota.

Figure 1 positions the NUMMI plant along with several other comparison facilities in a two dimensional space according to the extent of innovation in

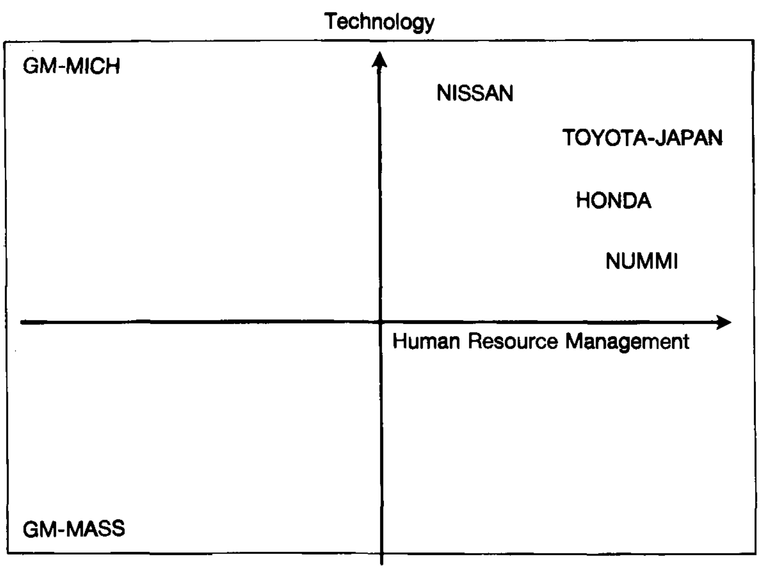

Fig. 1 Comparison of major automobile plants

human resource management systems and the amount of new technology found in each plant. In the lower left quadrant of the Figure is located a General Motors low technology plant with a traditional labour relations and human resource management system. In earlier work (Kochan, Katz, and McKersie, 1986) we characterised this traditional system as one that perpetuated a high conflict/low trust cycle; low trust levels manifest themselves in high levels of grievances which in turn gave rise to demands for specification of more precise work rules and regulations which in turn gave rise to further grievances and mistrust. Our analysis then showed that plants experiencing this high conflict/low trust cycle had significantly lower levels of quality and productivity than plants with fewer conflicts, higher trust relations, and better labour–management relations. Thus the lower left quadrant represents the traditional human resource system operating in a low technology environment. Clearly, we would expect this to be the base or lowest performing mix of technology and human resources.

The upper left quadrant provides a comparison of a plant which invested over $650 million in new information and manufacturing technologies without significant reforms in the human resource or labour-management relations system. The comparison of this plant with the traditional low technology plant provides the best test of a "technology alone" strategy.

Plants located in the upper right quadrant provide different mixtures of human resource management reforms and advanced technologies. The NUMMI plant combines a very moderate technological upgrade – far from the technological frontier for high technology auto plants – with a fundamentally reformed human resource and labour management relationship. While the same local union (and union leadership) was carried over into this plant from a prior traditional GM plant and approximately 80 percent of the workforce of the old plant was likewise carried over, NUMMI is managed by Toyota and has adopted the production and human resource policies that this company employs in its Japanese plant. The NUMMI plant therefore provides the best test of the effect of human resource management changes in the context of a moderate technological upgrade strategy.

The other plants shown in this quadrant differ from NUMMI in several respects. The Nissan plant is a new very high technology plant in Tennessee that introduced a number of human resource management reforms (few job classifications, flexible work organisation, extensive communications) but does not go as far on this dimension as does NUMMI. Likewise the Honda plant is slightly lower on the technology scale but, like NUMMI, has implemented a broader range of human resource innovations. Unlike NUMMI however, both Honda and Nissan plants are nonunion and thereby provide another interesting dimension on which to compare performance. Finally, the home plant of Toyota in Japan is shown in this quadrant and provides a useful benchmark for comparing the performance of these various US plants.

Table 1 presents quality and productivity data for these plants as of 1986. Quality is measured by the number of defects per 100 cars. Only defects attributable to assembly operations are included in this measure. Productivity is measured by the number of work hours required to perform a standard set of assembly tasks after controlling for differences in product size, option content, and a number of other factors (see Krafcik, 1987 for details on the methods used to develop these standard measures).

Table 1 Quality and productivity comparison of major automobile plants

	Productivity (hrs/unit)	Quality (defects/100 units)	Automation Level (0: none)
Honda, Ohio	19·2	72·0	77·0
Nissan, Tenn.	24·5	70·0	89·2
NUMMI, Calif.	19·0	69·0	62·8
Toyota, Japan	15·6	63·0	79·6
GM, Mich.	33·7	137·4	100·0
GM, Mass.	34·2	116·5	7·3

Productivity: standardised number of man-hours to weld, paint and assemble a vehicle.
Quality: defects attributable to assembly operations reported in first six months of ownership.
Automation level: robotic applications/production rate, normalised to 100 for highest level in the group.

The results presented in Table 1 are rather astounding. Indeed they send such a strong message that they have been widely cited and used within the auto industry and in the public press to bring home several important lessons. For our purposes the central messages from these data appear to be the following:

1. High technology strategies, in the absence of significant changes in human resource practices (GM low tech/traditional versus GM high tech/traditional) produces no significant productivity or quality improvements. It took 34 hours to produce a car with an average of 1·16 defects per car in the traditional low tech plant and after an expenditure of $650 million on high technology it still took almost 34 hours to produce a car with an average of 1·37 defects.
2. In contrast NUMMI, with moderate investment in new technology but fundamentally different human resource management and production systems took 60 percent as much time to produce a car with an equally significantly lower defect rate.
3. Comparing NUMMI to Nissan and Honda suggests that union-management relations need not be the barrier to improved performance that many American managers have traditionally believed. NUMMI's performance is equal to Honda's and slightly better than Nissan's, again despite the higher levels of technology found in the Nissan facility.
4. Finally, productivity and quality at Honda and NUMMI approach the levels achieved in Toyota's home plant in Japan.

Thus, taken together these pair wise comparisons suggest that at least in this industry significant improvements in economic performance are achievable in the US, with American workers, and with American unions. But to turn this potential into a reality means a fundamental rethinking and reform of traditional human resource and labour management relations practices and a much more careful or strategic use of new technologies than has often been recognised by American managers and technology specialists.

The Underlying Model: Humanware

While the data presented above are useful for documenting the magnitude of the differences in performance achieved with different human resource and technology strategies, they do not provide a clear theoretical model of the policies that underlie the alternative systems or the specific policies that underlie the Japanese production and human resource management systems that seem to produce superior performance results. Figure 2 presents a model of the Japanese production and human resource management system developed by our colleagues Haruo Shimada and John Paul MacDuffie (Shimada and MacDuffie, 1987). This model is based on a comparative case study analysis of Japanese auto plants operating in North America and was undertaken in part to better understand how human resources and manufacturing policies are integrated in these organisations. Their "Humanware" model shown in Fig. 2 summarises the results of their work.

The "Humanware" concept captures the basic proposition underlying their model, namely, that these production systems do not separate the human dimensions from the hardware dimensions of technological or manufacturing systems. Instead, the central proposition in the Shimada and MacDuffie model is that performance of the system depends on achieving consistently high levels of performance from the human components of the system. Indeed the system's design starts from the premise that workers will have a high degree of skill, motivation, and adaptability to new processes. As shown in Fig. 2 it is these human resource inputs that provide the foundation for the production system and make it possible to (1) achieve continuous process improvements ("giving wisdom to the machines"), (2) embed responsibility for quality control directly within the production teams and work units, (3) build just-in-time inventory control processes into the manufacturing system, and (4) ultimately achieve high quality with low unit costs. Because these systems are highly dependent on their human attributes, Shimada and MacDuffie label these as "fragile" systems, compared to more "robust" manufacturing strategies and systems typically designed by American engineers and managers. A robust system is one that embeds greater control in the technology and the management control systems rather than in the workforce itself. Inventory buffers, quality control inspectors, separation of industrial engineering and technology design from the production workforce, and rigid narrow job definitions are all part of this more robust strategy.

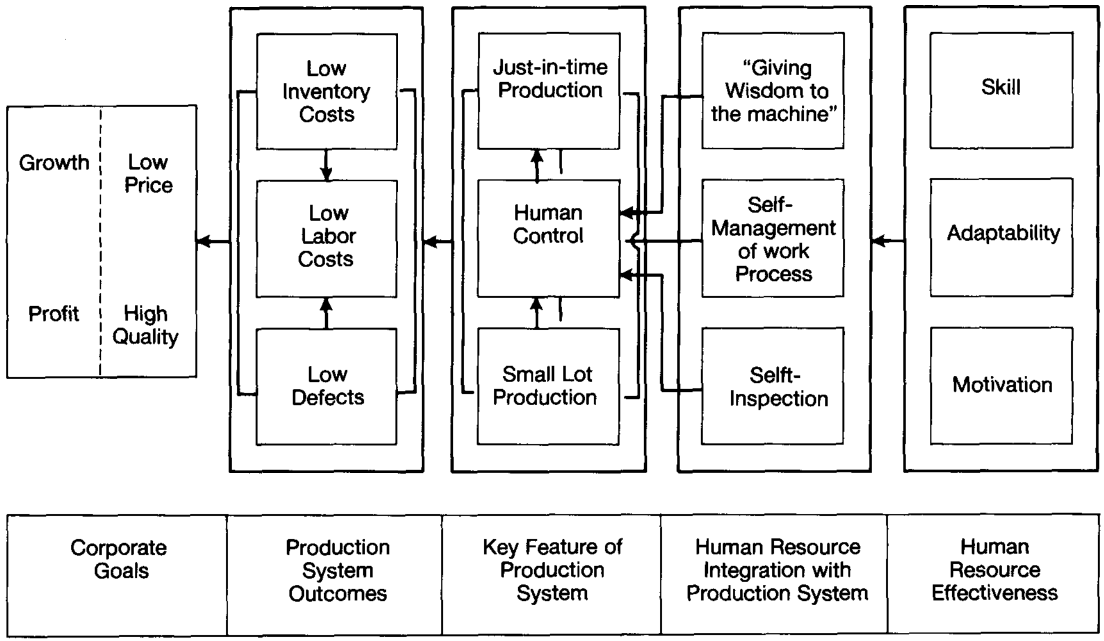
Growth
Low Price
Profit
High Quality
Low Inventory Costs
Low Labor Costs
Low Defects
Just-in-time Production
Human Control
Small Lot Production
"Giving Wisdom to the machine"
Self-Management of work Process
Selft-Inspection
Skill
Adaptability
Motivation
Corporate Goals
Production System Outcomes
Key Feature of Production System
Human Resource Integration with Production System
Human Resource Effectiveness

Fig. 2

Cross National Comparative Data

The Shimada and MacDuffie model provides a theoretical framework for interpreting the results of the pair-wise NUMMI comparisons discussed above. But the question can legitimately be raised: Do these results generalise to a larger and more diverse sample? To answer this question another body of productivity and quality data was collected by John Krafcik (Krafcik, 1988) and subjected to an analysis designed to test the explanatory power of the "fragile" versus "robust" system and to again compare the performance consequences of this strategy against the explanatory power of the pure technology strategy.

The results of this analysis are shown in Table 2. Shown are the correlations between an index of the extent to which the human resource and manufacturing policies in these plants reflected the fragile versus the robust designs. Also shown are the correlations between the level of robotic technology used in the plants – a proxy for the overall technological sophistication found in the plants. Again measures of quality and productivity were used to evaluate the effects of these different factors.

Table 2 Correlations of human resource policy index and robotics index with productivity and quality performance

	Productivity	Quality
Human Resource Policy Index	.61*	.50*
Robotics Index	.29	.38

*Indicates statistical significance at 1% level

These correlations demonstrate that the results of the pair-wise plant comparisons generalise to a larger, international sample of auto assembly facilities. The correlation between the index of human resource and manufacturing practices that reflect the fragile system and measures of quality and productivity are nearly twice as strong as the correlations between these performance measures and the robotics index. The robotics index correlations are not significantly different from zero at this sample size. Finally when these measures are entered into a regression equation that controls for differences in plant size, age, and product complexity, the management index remains statistically significant while the robotics index does not. Thus, we interpret these results as providing further support to the hypothesis that human resource policies are critical to achieving high levels of productivity and quality in manufacturing. High technology, standing alone in the absence of a corresponding set of human resource investments, does not seem capable of achieving comparable results.

American Efforts to Replicate these Results

The major American auto manufacturers have now internalised and accepted the basic message of the findings summarised above. In fact, each of the major American firms has been aggressively seeking to introduce many of these reforms in its plants in recent years. Yet the results of another study we conducted of these efforts present rather sobering conclusions (Katz, Kochan, and Keefe, 1988). We collected data from a sample of 50 US plants of one of the major firms and analysed the results of their efforts to introduce team forms of work organisation, flexible work rules, and employee participation. We found that indeed a number of plants had made considerable progress in introducing these human resource and labour management relations reforms between 1979 and 1986. We also found that work rule flexibility and employee participation did make significant contributions to higher levels of productivity and quality. However, our results also showed that this company had not yet been successful in using team forms of work organisation to improve its quality and productivity performance. Instead, a careful analysis of the data revealed an extremely high variance in the performance of the six out of the twenty-four assembly plants in our sample that had introduced team systems. Table 3 shows the rankings of the quality performance of these six team plants (productivity data were not available for all of these plants). These data are both promising and disconcerting. The promising element lies in that the best plant in the sample of 24 and three out of the top five plants were team plants. However, the worst plant was also a team plant and two of the three worst plants were team plants. Moreover, again it is the high technology team plants that seem to perform worst! Once again, the message is clear: technology alone is a poor predictor of organisational performance.

Table 3 Quality performance rankings of team plants

Team plant	Quality rank*	No. of robots
A	1	24
B	4	187
C	5	26
D	9	162
E	22	270
F	24	216

*Rankings based on 24 assembly plants.

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Notes on the authors

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Ruth Billington is the Manager of the Materials Department at STC/ICL's central laboratory, STC Technology Ltd. She graduated in Metallurgical Engineering from Imperial College, University of London, and has previously been employed by the UKAEA, GEC and Morganite. She is a Fellow of the Institute of Metals and of the Institute of Ceramics and is involved in professional activities in both Institutes. She is also the company's representative on the Women's Engineering Society and has previously been on the Industrial Panels of the Production Engineering Research Association and of Sheffield University.

C.B. Calam

Having gained a degree in Electrical and Electronic from Trent Polytechnic, Chris Calam joined Manufacturing & Logistics at ICL Kidsgrove in 1986. His last two years have been spent implementing advanced testing techniques in various areas. He is currently involved with the competitive analysis of competitors' products.

R.W. Fisher

Ray Fisher joined ICL Ashton as Production Systems Manager in March 1987, following two years with the HQ Information Systems function where he had been involved in formulating the company's future strategy for Manufacturing Systems. Prior to this he had been with Group Information Systems (GIS) and for a period was Manufacturing Operations liaison with the Manufacturing Business Centre, during which time he was responsible for the specification of the MRP and FLOMAC modules of the ICL manufacturing control system OMAC.

A.C. Harman

Tony Harman, a metallurgist by training, worked in various metallurgical/engineering industries from 1964 to 1975 prior to joining the Materials Evaluation Centre (MEC) at STC Technology Ltd (STL). Coupled with the central trouble-shooting role within MEC are various long-term R&D programmes covering all materials-based aspects of the telecommunications/computing industry. Soldering and reliability are two major programs with which he has been closely associated, with particular emphasis in recent years on surface-mount technology. He is currently on the management committee of the British Association of Brazing and Soldering (BABS).

Edwin F. Hill

I am a graduate of Leicester University and joined the research department of LEO Computers Ltd. in 1962, working on a successor to LEO III. Following the merger with English Electric Computers I moved to Kidsgrove in 1964, where I worked on the FORTRAN compiler for the Egdon project on KDF9. From there I moved in 1965 to a newly formed Design Automation department where I worked on computer graphics, wrote a program that wrote simulators for any given designs, and set up a design route for hardware design.

In the mid-1970s (now ICL) I moved into the Terminal Design department and wrote a suite of control programs for the 7502 cluster controllers. While there I was on the Communications Protocols Committee (HDLC as it was then). After another period in Design Automation I moved in the CADES (software design) project, before moving back into the hardware development route for what was then the Distributed Systems Development Division, now called Automation Services, to become responsible for the photo-plotter development route.

G. Jackson

Gayle Jackson gained his Master's degree in Ship Propulsion Technology from Strathclyde University in 1975 and since then has been involved in computer application within manufacture. He worked as part of a team developing a computer based planning and control system at a shipyard on the Clyde before moving to Vickers Shipbuilding and Engineering Ltd. (VSEL) where he first developed structural analysis programs and then moved to the computer services department as a support engineer. During this period he also worked on developing the case for CADCAM at VSEL, a technology that was to be used across a wide range of applications. In 1983 he transferred to the Production Control department as Assistant Manager; computer systems again featured in the work, although people proved the most fascinating part of the job.

He joined CADCentre Consultants in 1984 and for 2½years worked as a senior consultant assisting clients in system selection, staff training and implementation of CADCAM. For the last 18 months he has been working on C-PLAN and related products and on their implementation at engineering sites.

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Thomas A. Kochan is a Professor of Industrial Relations and Chairman of the Behavioral and Policy Science Area at MIT's Sloan School of Management. From 1973 to 1980 he was on the faculty of the School of

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S.M. Lynn

Sarah Lynn graduated from University College Dublin in 1983 with a B.E. in Mechanical Engineering. She went on to receive a Master's degree (M.Eng.Sci.) for a robotics design project. She joined ICL in 1986 and has worked on various activities related to mechanical design. These have included Design for Manufacture, Design for Assembly and Value Engineering. Adopting a more strategic role involved her in co-ordinating the analyses of competitors' products and evaluating Mechanical Computer Aided Design/Computer Aided Engineering tools.

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Shekhar Nagarkar is Principal Consultant in ICL Manufacturing Business Unit. He specialises in Computer Based Solutions and Information Technology Strategies for 'World Class Manufacturing'.

His main role in ICL has been as Manufacturing Systems Manager firstly at the ICL Ashton Plant and later for all Manufacuturing Operations. At the Ashton Plant, he was responsible for development of Project Mercury, which is a unique Computer Integrated Manufacturing Solution. In his 'group' role he developed interests in the application of Artificial Intelligence technology to manufacturing and was responsible for the establishment of the AI Centre.

His career before joining ICL included a period as Research Engineer and later as Lecturer at the University of Salford where he carried out research and consultancy work in Manufacturing Systems.

D.A. Pass

David Pass joined English Electric in 1961 as a technical apprentice and completed an ONC course in Mathematics, Electronics and Physics. He became involved with the first CAD system for the System 4 platter design and with the first engineering database in the Kidsgrove drawing office.

He spent seven years in Engineering Change Control, becoming Change Control Manager at Kidsgrove and Winsford. Since 1984 he has been responsible for the development of Engineering Information Systems, introducing the PPCC, DEMI, PASS and IADB applications into Manufacturing.

R. M. Phillips

Rick Phillips joined ICL in 1984 after graduating from Manchester University with a joint honours degree in Computer Science and Mathematics. He spent three years working as systems engineer in the MIS unit at Kidsgrove, in a user support/consultancy role within the mainframe system section. After working on the project team to implement OMAC VME 1.00 he went on to support OMAC and to be responsible for mainframe tactical developments and some strategic developments.

During 1987–88 he was seconded to the AI Centre and worked primarily on the specification and ultimately the development of the MAES software. After returning from this secondment to the Kidsgrove Information Systems department he has been given responsibility for mainframe systems support and development, along with the ongoing implementation of AI/Expert Systems within Kidsgrove Manufacturing Operations.

B. R. Rudd

Bernard Rudd joined ICL in 1985 from Hawker Siddeley. He has wide experience in Materials and Production Management and was responsible for the implementation of OMAC 29 at Hawker Siddeley. Until 1988 he was responsible for the materials control function within ICL's Kidsgrove plant, and is now responsible also for Information Systems at Kidsgrove.

P.J. Russell

Peter Russell gained a Diploma in Technology with 1st Class Honours in 1961. He has since held a number of positions in the computer industry. He joined the STC group in 1974, initially working on a number of advanced telecommunications developments. More recently he has participated in studies aimed at demonstrating the practical relevance of traditional software analysis and design methodologies to the planning of Computer Integrated Manufacturing (CIM) facilities. He is currently participating in the unique 19-company consortium of CIM users and CIM vendors working on the ESPRIT Project 688 – AMICE – to create and validate an Open System Architecture for CIM.

D. J. Saxl

David Saxl joined ICL from the engineering company Rubery Owen in 1973. As a Manufacturing Systems Consultant he was responsible for the implementation of OMAC 29 and other manufacturing systems, both for ICL customers and for ICL's own use within Manufacturing and Logistics (M & L). During 1987 he was manager of the Artificial Intelligence Centre within M & L and is now responsible for the exploiting of M & L's systems and for the development of strategy.

C.J. Sherratt

Chris Sherratt joined ICL in 1966 and worked for 8 years as a hardware and firmware design engineer. He then spent 4 years in the Kidsgrove Post-Design Services group, identifying and correcting design faults, before joining the Test Engineering group where managed the PCB testability group. He was largely responsible for introducing in-circuit and functional commercial automatic test equipment into Kidsgrove and has produced Manufacturing and Logistics current PCB testing strategy. He is currently identifying advanced contactless testing techniques for designs with high density interconnects.

He is also ICL's representative on the In-circuit Backdriving Sub-committee led by Ministry of Defence, whose task is to produce an industry standard for the safe operating limits for backdriving.

C.G. Tanner

Chris Tanner started work at the British Non-Ferrous Metals Research Association as a Scientific Assistant, in 1964. He then moved to the Central Electricity Generating Board, followed by a brief period at Stone Managanese Marine. He first became involved with soldering processes at his next employment at Fry's Metals, after which he took up a position as Technical Manager of a metallurgical company in Australia. On his return to the UK he worked at the GEC Hirst Research Centre in the electro-chemical department and then joined STC Technology Ltd. in October 1984, where he has remained for a whole four years. Here his interest has been all areas of surface-mount technology. He is a metallurgist by training and has a master's degree in the technology of metal surfaces.

R.K. Westbrook

Roy Westbrook has a B.A. from Leicester University and joined London Business School as a Senior Research Officer in 1980, after eight years in central government as a civil servant in the Department of Health and Social Security (DHSS). He has studied numerous manufacturing operations both in the UK and in the Far East, where he gained first-hand experience of Just-In-Time systems in major Japanese corporations.