SRC TR 86-14

Computer Integrated Manufacturing: Overview and Suggested Stategy

by

Dr. G. Harhalakis and M. E. Bohse

TR-86-14

Computer Integrated Manufacturing:

Overview and Suggested Strategy

by

Dr. George Harhalakis

Michael E. Bohse

Computer Integrated Manufacturing: Overview and Suggested Strategy

Dr. George Harhalakis

Michael E. Bohse

Department of Mechanical Engineering

University of Maryland

College Park Maryland 20742

Abstract

The relatively new area of manufacturing technology referred to as Computer Integrated Manufacturing (CIM) is defined and explored in terms of its current status and future potential. The various components of CIM are described, both those in common use today, such as Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Manufacturing Resource Plannning (MRP II), and those that are in early stages of development, such as Computer Aided Process Planning (CAPP), Artificial Intelligence (AI), and Group Technology (GT). The two most prominent CIM approaches, the single data base and the multiple data base designs, are presented, and their relative merits discussed. It is concluded that at least in the near future, the multiple data base approach is the most practical.

In support of this conclusion, a strategy for CIM implimentation is given in which components are integrated in a gradual process as technology allows. The required exchange of information would be through the use of a central data "bus," linking the various systems. The starting point for this strategy is the integration of CAD and MRP II through part specification data and the Bills of Material. MRP II would then function as the central coordinating "hub" of CIM as other components are integrated into the system.

INTRODUCTION

Manufacturers today are literally inundated with technologies promising improved productivity, reduced costs, and improved quality, all supposedly leading to the automated "factory of the future." These include some of the hottest buzzwords since interchangeable parts: Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Flexible Manufacturing Systems (FMS), Manufacturing Resourse Planning (MRP II), Group Technology, Just In Time inventory control (JIT), Automated Materials Handling, Computer Aided Process Planning (CAPP), Artificial Intelligence, and others. Given the potential benefits of these ideas, it is no wonder that the interest of manufacturing firms, large and small, has been aroused. But too often, out of fear of falling behind in the race towards automation and losing profitability, firms plunge head first into one or more of these techniques without clear goals or long term plans. The result is usually "islands of automation," isolated areas that benefit from the latest technologies, without communicating or interacting with related activities.

In fact, experience has shown that some firms may independently automate as many as 50 different functional areas, often using unique hardware and software for each (3). Over the past several decades, this practice of implementing specialized activities and functions has been commonly accepted as the way to achieve efficiency (13). Recently however, this approach has been questioned. Based on findings of the National Research Council, "In case after case, the absolute necessity of integrating each element of the manufacturing process from market analysis through design, fabrication, and sales to follow-on customer service has emerged as the key to achieving the productivity gains required".

The integration and coordination of the different automation techniques, using appropriate hardware and software configurations is synergistic; the whole is

greater than the sum of its parts. Such an integrated system can be called Computer Integrated Manufacturing, or CIM. Any fragmented or isolated implementation of automation represents a loss of the potential benefit of CIM, through redundant and inconsistent data, extra maintenance, and the reliance o manual procedures.

CIM means different things to different people. To some, it is the combination of CAD and CAM; to others it means MRP II. Traditional thinking has resulted in these restrictive ideas; to be most fruitful, CIM should encompass not just robots and scheduling, but every aspect of a business, from design and manufacture to sales, marketing, and distribution.

CIM has been referred to as a system, a project, a product, a philosophy, a concept, and a program (3). It is all of these; it is both hardware and software, used to provide effective and economical interaction between every business activity using information as the ingredient to hold it all together, information as varied as geometrical design, bills of material, routings, costs, scheduling, testing, tolerances, and so on. CIM is a dynamic system that evolves as business needs change. But most importantly, CIM is a dream. Its potential scope is so grand that it eludes an exact definition.

It is therefore not possible to purchase a CIM system from any vendor (3). And it will be years before technology allows the creation of such a system. In the meantime, several research and development programs, both public and private, are beginning in the direction of CIM. The obstacles are numerous, and include both technical and organizational issues.

One of the major obstacles to integration is the traditional specialization of software and hardware vendors. Like the systems themselves, their creators tend not to communicate; there is perhaps the root of the problem. There are vendors producing engineering and manufacturing packages (i.e., CAD, CAM, Numerically Controlled Machining, rototics), and there are vendors producing operations

management packages such as MRP II and financial packages. Each type of vendor may have achieved some degree of single axis integration, i.e., CAD linked to CAM, or Material Requirements Planning (MRP) linked to shop floor planning, materials movement, and accounting systems, but what is needed now is a "weaving" of these two axes, a link between process definition data and schedule definition data (17). Because of this specialization problem, the few attempts at limited manufacturing integration thus far have relied on user-customized interfaces and extensive trial and error procedures.

Another problem is the lack of standards that would allow users to easily interface systems from different vendors. Progress in this area has been hampered by the complexity and variety of data that must be transferred between systems, and by vendors' fears of releasing proprietary information.

The most significant obstacle, however, is the difficulty of arriving at an acceptable and achievable model for such an extremely complex system. How should integration be achieved? Through the use of a single, all encompassing data base requiring large computing power and upkeep? Or through a series of much smaller data bases, perhaps on separate computers, allowed to communicate and interact freely? Further, where should integration begin? Is it possible to create a full-blown CIM system directly, or will a gradual, modular approach be necessary? And finally, who will develop CIM? Can the expensive and long term research efforts be carried by private industry alone (both software vendors and manufacturers), or should government/university organizations share the work load?

It is the intent of this paper to explore these questions by examining the current state of affairs of several existing computer assisted systems, and reviewing experiences and ideas of systems integration. Key areas requiring substantial effort are identified. Further, a proposed strategy for CIM implementation is presented, along with a suggestion for a logical starting point--the

integration of CAD and MRP II.

EXISTING SYSTEMS PART I: CAD

Computer aided design, or CAD, had its beginnings in the 1960's at large manufacturing companies such as General Motors and Boeing. Its primary use was as an electronic drawing board, capable of creating two dimensional drawings, usually for electronic circuits. By providing designers with the power of a computer, they could more readily create and modify drawings than they could with traditional methods. The result was a measureable increase in drawing productivity, often several fold. The major advantace of these systems was that drawings requiring minor, or even major changes could be easily modified instead of being completely redrawn.

But the first CAD systems, more appropriately called computer aided drafting systems, required a lot of computer power, limiting their use to firms with mainframe capabilities. Once a CAD drawing was created, it was printed, and traditional systems were used for the rest of the production cycle. Though it did save time and money at the drawing stage, CAD did nothing to aid the rest of the organization. And finally, CAD was expensive, with each workstation costing tens of thousands of dollars, and software similarly expensive.

In the intervening years, CAD systems have improved greatly, and their use has become widespread. The growth in computer technology has yielded minicomputers capable of handling CAD systems, at prices within the reach of most midsized firms. Accordingly, most CAD systems are now aimed at minicomputer users. The cost of the CAD systems themselves, especially the hardware, has likewise dropped rapidly. But most importantly, CAD systems are finally beginning to deserve their name. Many of today's systems not only provide traditional drawing capabilities, but also include design features such as automatic mesh generation for finite element analysis, stress and strain analysis,

thermal analysis, and clearance/interference studies. Solid modeling techniques are giving CAD the capability of generating truly three dimensional designs. Once created, a user can manipulate objects on the screen and view them from any angle. The more sophisticated systems provide shading and shadowing for any user-defined "light source," giving drawings a photographic-like appearance more readily visualized by designers.

Unfortunately, a large number of current CAD installations remain confined to drafting only. Gunn (11) estimates that such uses provide only about 10% of the benefits obtainable from CAD systems. As other possible benefits, Gunn includes:

- Establishment of geometric part descriptions in a database accessible to other manufacturing funtions
- Increased productivity, a 3 or 4:1 gain being typical
- Elimination of the need for prototypes
- Reduction in design cycle times
- Provisions for a quick view of parts through the use of zoom, pan, rotate, and section functions.

Recognition of these potential benefits is a first step towards an increased level of CAD utilization.

EXISTING SYSTEMS PART II: CAM

CAM, or computer aided manufacturing, began in the form of numerically controlled machine tools as early as 1949 at MIT, and by the mid 1960's, these systems had achieved relatively widespread use. At that point, the devices used rolls of paper tape, on which holes were punched, that were "read" by the machine to provide the proper tool movement, in much the same way that a playet piano works. The use of the paper tapes made machining much more consistent over a batch of parts than manual techniques, and reduced the time of machining over the tracing method also common at the time, but it did have its problems. The creation of the paper tape was not a simple task; it required an experienced programmer to manually create a complex program in a specialized, cumbersome language for each part to be machined, limiting its usefulness to parts with fairly high production volumes. And the required machinery was big, expensive, and often unreliable.

In some respects, little has changed in NC machining since the sixties. Paper tape continues to be the most common data input media, and about half of the programming is still done manually, albeit with more advanced NC languages, such as APT, and other computer aides. Most significantly, the size and cost of the NC machinery has decreased due to the development of the integrated circuit. For the same reason, the reliability has increased.

The potential for advancement, however, is much greater as can be seen in a few of the latest systems. The decreased cost of computer power makes it possible to eliminate paper tape altogether, having a computer directly feed the machine with instructions. And further, instead of the single machine tool concept, it is possible to control an entire machining center, with lathes, bores, etc., capable of generating almost any cylindrical or prismatic shape.

Anderson, Solberg, and Paul (1) describe a future NC machining system in

which the machine's traditional task of simply playing back preprogrammed movements is supplanted by the much more complex role of interacting intelligently with its surroundings. The machines would require high level commands only, from which they would gather the necessary resources, determine the sequence of basic tasks, monitor performance, and correct errors. Such a system greatly reduces human involvement, and makes possible the Flexible Manufacturing Cell (FMC) concept, which allows the machining of any number of different parts in large or small batches economically with a single machine set up, or cell, and with little intervention.

CAD, CAM, AND CAD/CAM

One of the first steps towards integration of manufacturing systems was the idea of integrating CAD and CAM, the link between the two being the part geometry. The goal was to design and manufacture parts from a common data base. A designer could sit at a CAD workstation and create a part. Once the geometry was determined, the system could analyze the part for loadings, stress and strain or thermal behavior and any other design consideration, pointing out any potential weaknesses. Once the part was determined to be acceptable, an NC program could be generated, optimized, and verified automatically (or other process instructions for non-machined parts), and then fed to a machining center, which would produce the part.

Progress in this area has already brought some success. Northrop Aircraft Division in Hawthorne California has developed a system linking its NCAD (Northrop Computer Aided Design) three dimensional system to several manufacturing systems (20). From the design specifications of hydraulic tubing, their T-bend program will automatically create instructions for an automated tube-bending machine. Similarly, NCAD part data can be converted to programs for five axis machining centers to produce parts, via their NCAM program. The system also interacts with Northrops Quality Assurance program NQA.

AT&T Technologies, at their Richmond Works, have interfaced CAD and CAM such that design data for their printed wiring boards, generated at a remote Bell Laboratories location, and transmitted to Richmond, can automatically generate NC instructions for drilling, routing, and testing, plots of router cutter paths, points to be tested, drill hole locations, and artmaster plots on mylar film (2). These capabilities require that the new design fit into a predetermined family of similar parts, as defined by the use of group technology. For their efforts, the Richmond Works was awarded the 1983 LEAD (Leadership and Excellence in the Application

and Development of CIM) by the Computer and Automated Systems Association of the Society of Manufacturing Engineers.

As a final example, General Electric's Aircraft Engine Manufacturing Division in Evendale, Ohio runs 115 NC machines using instructions downloaded directly from the facilities network of minicomputers without the use of punched tape (14). The system, thought to be the largest distributed numerical control system in the world, had, by 1982, improved productivity by 15%.

The weakest area in each of these systems, and therefore the area most in need of research, is the generation of process plans. Computer Aided Process Planning, or CAPP, is a system that will eventually provide the link between CAD and CAM. Generally ignored in discussions of so called "CAD/CAM," it is CAPP that will convert the geometry produced by CAD into viable process plans for use by CAM. Specifically, CAPP will:

- Select tools and processes
- Determine process sequencing
- Determine cutting conditions and times
- Identify non-machining elements and times
- Select jigs and fixtures

CAPP systems are generally divided into two classes: Variant and Generative. Variant CAPP systems utilize Group Technology (GT) to classify parts into families with common geometries, machining requirements, and so on. Process plans for new parts are then generated based on variations from existing plans for similar parts. Generative CAPP systems, still in the experimental stages, attempt to create process plans from a clean sheet of paper for each new part, using a set of rules as the basis for decision making.

As long as companies attempt to directly link CAD and CAM without due consideration of CAPP, the "missing link," the concept of an automated linkage between design and manufacturing will remain unfulfilled, and an extension to the ultimate goal of CIM will be impossible.

EXISTING SYSTEMS PART III: MRP AND MRP II

One of the first uses of the computer in the manufacturing industry was the tracking of inventory. Back then, in the late 1950's and early 1960's, the high cost of computing facilities made them prohibitive for all but the largest companies. For those that could afford them, their power made inventory ordering more efficient, and helped to introduce several of the popular inventory control techniques.

But these techniques had problems that limited their usefullness (9). First, only past history was considered, and the future was arbitrarily assumed to be similar. Second, the relationships between individual parts and their parent assemblies were not acknowledged by the system. These relationships result in dependencies between the quantities of various parts required to which the early systems were blind.

By the late 1960's, great improvements were made as inventory control systems gave way to Material Requirements Planning, or MRP. Instrumental to the birth of MRP were the development of better integrated circuits that lowered the cost of computing, and the introduction of powerful software such as data base management systems. Also instrumental were the several men dedicated to using computer technology to improve production and inventory control: Joseph Orlicky; Oliver Wight; George Plossl; to name a few.

With MRP, users use static part information, bills of materials, and production forcasts to determine gross and net requirements, and scheduling of production and ordering. Because it recognizes the relationships between parts, i.e., the bill of material, and because it is based on the best estimate of future activities, MRP has revolutionized inventory and material control. Used properly, it can decrease inventory levels, increase inventory turnaround, improve productivity, and reduce

lead time. As computers became more powerful and affordable, more companies were able to share in its benefits. And software firms, sensing the need, have responded with numerous "off the shelf" MRP packages that eliminate the need for expensive, custom-built software, further increasing the MRP user base.

But MRP, for all of its improvements over the original computer inventory control methods, still falls short in several areas of production control. Its primary shortcoming is that its major function is only to release orders. It ignores other important aspects of production such as: Are the forecasts in line with marketing trends? Is the necessary capacity available in the plant to meet the forecasts? Is the scheduling process realistic enough?

To help analyze these questions, material requirements planning has expanded into manufacturing resource planning, or MRP II, of which the original MRP is but a small part. MRP II aims to achieve planning on a corporate scale, incorporating more acitvities and control, while maintaining a broad perspective. To do so, MRP II begins with the business plan, detailing the overall objectives of the company. From these objectives, sales objectives are generated for each product line, and then translated into top level item production forcasts.

From the plans input to the system, MRP II explores their feasibility using rough cut capacity planning techniques. Bills of resources for each product are examined, and the necessary resources compared with the resources available over the term of the plans. If it is not possible to meet these plans, the system alerts the user that either the plans must be modified, or additional resources must be sougnt.

The function of translating corporate plans into production plans is carried out by the Master Production Schedule (MPS). In addition to setting up a schedule of production activities to meet the needs of the forecasts, MPS also has the role of modifying the forecasts to better suit business conditions. Forecasts of slow selling products can be decreased to free resources for those that are selling well.

Production may be increased to cover unanticipated orders. Once a workable master schedule has been generated, this information is used as an input to the material requirements portion of the system, which serves the same purposes described before; to determine the quantities of components necessary to meet the production plan, and the time these components should be bought or made.

As the MRP II generated plans are being implemented, the Capacity Requirements Planning (CRP) function monitors the loads on the various work centers, pointing out those that may be overworked or underworked. This provides the feedback necessary to close the MRP II loop. While this represents a major improvement over the original MRP systems, it relies on after the fact measures; one of the goals of CIM is to allow for forward capacity planning.

The step from MRP to MRP II has enabled manufacturing software to grow from fairly simple order generation and inventory control systems into responsive, closed loop planning and information tools. To the functions already described, MRP II adds financial features, such as sales order entry, cost accounting, accounts receivable, accounts payable, and general ledger maintenance

This combination of functions provides numerous benefits for companies that take advantage of MRP II. Primarily, it allows managers to get an accurate view of what is currently happening and what the future holds. Problems with particular components, vendors, or processes can be discovered and steps taken in advance of a crisis. Expediting is minimized. Inventory falls more in-line with production, and it is generally reduced to allow for higher stock turns.

In the limit, a well designed and implemented MRP II system should allow for a Just in Time (JIT) inventory philosophy, in which minimal, or even zero, inventory is maintained; just the right number of parts are delivered just as they are needed. Thi successful use of JIT requires a perfectly timed MRP II implementation.

But like CAD and CAM, MRP II has yet to fully mature. A major area of concern is the inflexible scheduling provided by MRP II. The typical MRP II generated

schedule is determined by working backwards through the bills of material from the desired completion date, using leadtimes for each activity to find the necessary start and completion dates for each. But this means that the dates are "late dates," and any delays that may occur will delay the final completion date. This is a particulary serious problem in a make to order environment, where delays are inevitable, and lead times are long.

A solution to this problem is to view the bill of material as a network (12), with each component representing an activity and each leadtime a duration. By applying traditional Critical Path Method (CPM) analysis techniques to the BOM "network", one can identify both critical activities, and those with "floats" available. As a result, the flexibility of the MRP II schedule is increased; schedules can be modified as necessary to improve resource allocation or due to delays with a minimal effect on the overall completion date.

THE MISSING LINKS

The systems just described, CAD, CAM, CAPP, and MRP II, will be the primary functional areas of CIM, at least as it is currently envisioned. But in order to link these and create an intelligent, efficient system, there are many more "transparent" systems that augment individual systems or provide the links between two or more systems. These systems include, in addition to Computer Aided Process Planning, which was previously discussed, Automated Material Handling, Robotics, Artificial Intelligence, and Group Technology. By the time CIM becomes a reality, more technologies are likely to join this list.

Computer Aided Process Planning, (CAPP), will help to link CAD and CAM by developing tooling and process plans. In addition, CAPP will feed routing data to MRP II for scheduling. Automated Material Handling, (AMH), will provide the physical movement of material through and between the activities beginning with delivery from vendors and ending with the finished product. Current AMH systems include Automated Guided Vehicles (AGV) and Automated Storage and Retrieval Systems (ASRS). AMH will link MRP scheduling with inventory activity and with CAM processing. Robotics will serve primarily to enhance CAM capabilities by automating maching, welding, assembly, and other processes. This form of automation is especially important in activities that are either dangerous, high precision, or tedious.

The final two systems to be discussed here may be of benefit to each of the CIM components. Artificial Intelligence (AI), now a technology in its infancy, will eventually allow a system to make rational decisions based on the given circumstances and a set of guidelines, or rules. AI is sure to play a role in CAPP, and will also be applied to other systems requiring decision making capability.

Group Technology (GT) will likewise benefit each component of CIM. GT

classifies parts into "families" based on common geometry, function, manufacturing process, or other parameter. This is done to exploit the commonalities between parts that may allow for cost or time savings. To benefit CAM and CAPP, GT allows the generation of familty NC programs for use by variant CAPP systems. On the shop floor, GT can be used to identify parts requiring common machine set ups; those with equal priority can be scheduled sequentially, reducing overall set up time. GT is currently used in various forms primarily for mechanical parts; the technology is not at all well developed for electronic components.

It is these technologies (and probably others as well) that will make CIM run smoothly. Without them, and effictive CIM system is impossible. Some of the technology is already available in one form or another, e.g., AMH equipment and early robotics systems, but much work remains, especially in the areas of CAPP AI, and GT.

TOWARDS CIM: A STARTING POINT

Kutcher and Gorin (17) have rightly pointed out that no part of the manufacturing process is an island. Development engineering, manufacturing, sales, and distribution are all unseparable components of what they call the "product enterprise system." Though developments in individual systems will continue, it is now time to concentrate on uniting the various technologies. The ingredient that binds the parts together in the system is information. Gunn (11) stresses the importance of this information by simplifying manufacturing to a "series of data processing functions" involving creating, sorting, analyzing, transmitting, and modifying both alphanumeric and geometric data. It is the goal of CIM to automate this system in a unified and coherent manner, providing control and management of the information that is one of a firm's most important and vital resources.

CIM is not an easy goal to achieve, however. Anderson, Solberg, and Paul (1) consider the science of manufacturing to be in its infancy, given how far we are from "reaching the theoretical limits of efficiency." They continue by calling the commonly held attitude that "the technology is available now--all that remains is to apply it," "dangerously shortsighted." Revolutionary changes are required in product design, material handling, processing, assembly, and management. Much of the fundamental research necessary to achieve CIM has yet to be undertaken. Some areas requiring effort include machine tool technology, programming languages, hardware and software architectures, robotics, and geometric modeling.

But if CIM is ever to be achieved, a starting point must be found, and integration must begin. The only practical approach to integration is to begin with a manageble combination of two systems, integrating and testing these, and adding on other systems gradually as technology allows.

The first two systems to be integrated should be realtively mature, and should have a well defined interaction, such that efforts can be focused on the integration aspect rather than the individual techology. Of the systems mentioned so far, only CAD and MRP II come close to meeting these criteria. Each is still maturing, but the interaction, or overlap, between the two is well developed. Note that CAM is specifically excluded from consideration, even though it is commonly lumped together with CAD as CAD/CAM. As indicated previously, CAD/CAM is really still an unfulfilled ideal, and the integration of the two will have to wait for technology to catch up.

Though CAD/MRP II integration may appear to be the choice by default, it is, in fact, a quite logical starting point for CIM. Because CAD and MRP II exemplify two of the three major areas to be united by CIM, design/development and operations management, it is advantageous to form links between these systems early in the development of CIM, i.e., begin "weaving the two axes." And with its project- and operations management capabilities, MRP II is best positioned to take the role of the "hub" of CIM (9). Eventually, CAM and the other systems will likewise be located around the MRP II core. Figure 1 shows this concept in the completed CIM system.

Though they are the best candidates for integration, CAD and MRP II have not been integrated in any commercial system, for many reasons. As noted by Burgam (6), each "technology is moving too fast for the systems integrators to follow." Keeping up with the changes has made it nearly impossible for software firms to break away from their traditional specialties in order to address the more global concerns of CIM. To complicate the problem, MRP and MRP II systems have traditionally been designed for mainframe computers, while most CAD/CAM systems have been intended for minicomputers, with their different internal architectures and programming languages, and data representations. This trend seems to be changing, however, with the introduction of several MRP II systems

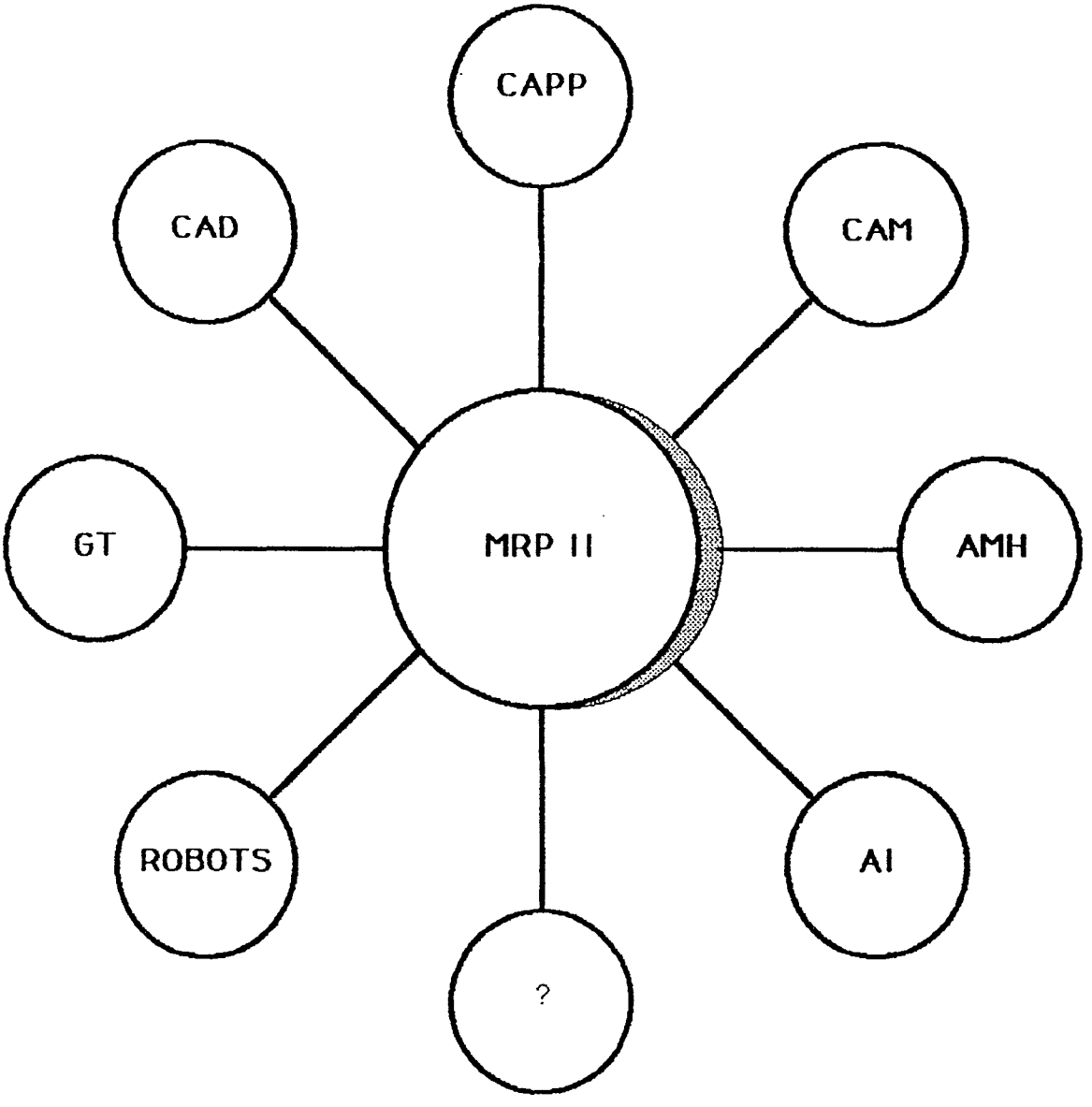


Figure 1. Functional CIM Model with MRP II as the "Hub".

for mini- and even microcomputers.

Another problem is the reluctance on the part of CAD advocates to get involved with MRP II while the latter has a success rate of only 25% (6). MRP II users are often categorized into four classes (23), A, B, C, and D, based on their degree of success with the system. Class A users, only 2% of all MRP II users, have the highest level of success, maintained by a closed loop system used throughout the business and well supported by top management. Class B users, about 4% of all users, often have hardware and software similar to Class A users, but the support by top management is not as great.

Class C users have open loop systems, essentially first generation MRP software, and account for the majority of users (55%). Finally, Class D users run MRP in the data processing deparment, minimizing the users' involvement. This arrangement, a waste of MRP II's capabilities, is used by about 40% of MRP II users, who may spend as much as 80% as much on implementation as Class A users. The primary reasons for failures such as these are (12) insufficient education of users, inadequate implementation strategy, and lack of top management commitment.

Interestingly, as mentioned earlier, the majority of CAD implementations also fail to live up to their full potential (11), though this is less often realized, since CAD systems generally are not complete failures.

DEFINING THE INTERSECTION OF CAD AND MRP II

As seen by Gallagher (10), there are four elements common to MRP II and CAD/CAM; to these, one more is added--engineering change control--to make the list more comprensive:

- Part Specifications
- Bills of Material
- Engineering Changes
- Routings
- Group Technology Coding

These pieces of information serve different purposes in CAD and MRP II; to the designer, they represents documentation of the part created and its manufacturing processes. To the production control and materials department, they serve as the guide to production activities and material purchases.

Accurate and timely communication of the shared data is essential; traditional methods do not allow this to occur. Typically, the part specifications and bill of material for each part are maintained independently by both systems. A designer creates the part and corresponding documentation, stores it in the CAD system, and generates either paper output, or in a few cases, a disk or tape, containing the necessary information. The data is then either manually entered into the part master record and bills of material files of the MRP II system, or occasionally read by the system from the disk or tape in a batch mode. Such data redundancy wastes not only time and computer storage, but it also leads to inconsistent and error prone data.

Engineering changes are likewise complicated by redundant data. Changes entered into the CAD system must be reentered into MRP II to update the bills of

material. Automatic links would eliminate this problem altogether, giving both systems access to the same information, and would provide the additional feature of allowing the designer to determine the best effective date based on current inventory/order levels available from MRP II.

Because routing data is maintained by CAM and the shop floor control and capacity requirements planning modules of MRP II, but not by CAD. For this reason, routings will not be a part of CAD/MRP II integration, but will have to wait for the addition of CAM and CAPP.

Group technology, as previously discussed, is also a common element to both CAD and MRP II. However, it functions less as a link than as a tool within each system. Group technology applied to CAD will allow new parts to be designed form similar existing parts, and will provide for the classification of all-new parts as well. The family relationships established by GT would then be maintained as the data is transferred to MRP II.

THE EXTENT OF CAD/MRP II INTEGRATION

Having identified the major elements common to CAD and CAM, and eliminating routing data and group technology for the time being, one is left with the integration of CAD and MRP II through part specification, bills of material, and engineering change control. This starting point is both practical and manageable, involving what has been called the "intersection" of the two systems (22).

Conceptually, this form of integration is easy to understand, and is shown in Figure 2. The Part Specifications (PS) input to CAD would automatically update the Part Master Record (PMR) and Bill Of Material (BOM) of MRP II. The same data would thus serve both systems' users. In addition, the geometrical information originating in CAD could be viewed (with no maintenance capabilities) on a high resolution monitor (not a CAD terminal) by MRP II users such as shop floor personnel, as the need arises.

Engineering Change (EC) control would also be simplified. Changes made to the part specification in CAD or the part master record or bills of material of MRP II would be transferred between the systems, keeping each accurate and consistant. CAD users would have instant access to inventory information when determining effective dates for changes. Further, effective dates are then instantly available to MRP II for changing or cancelling of orders. Some type of "flagging" system would be used to alert users of each system to changes that originated from the other. This concept is especially important in the event of design changes made necessary by MRP II constraints, such as a change in a supplier's part.

The goal of this system is to achieve accurate and timely exchange of information between CAD and MRP II. The use of paper for information transfer could be virtually eliminated, reserving paper only for permanent record keeping.

As other components of CIM develop to the proper technological level, they,

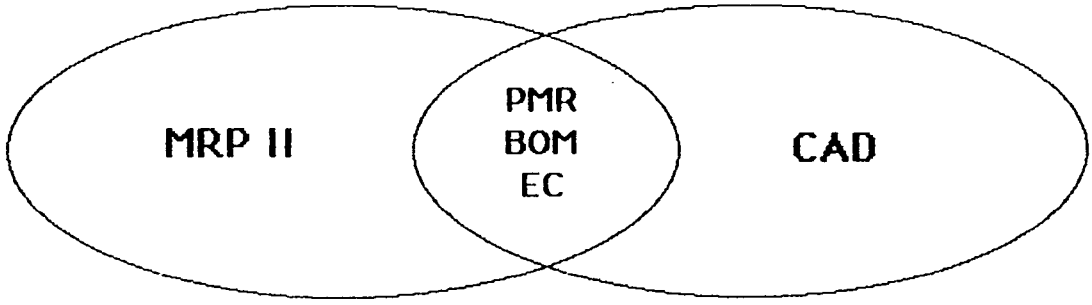


Figure 2. The Intersection of CAD and MRP II

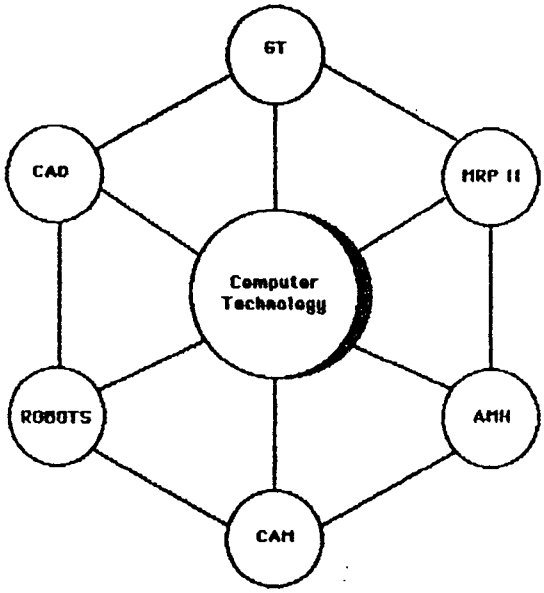
THE DATA BASE PROBLEM

Conceptually, CAD/MRP II integration, and even CIM, is easy to grasp; information is shared between all related functions form design to manufacturing to finance and so on. But physically, the integration of these systems presents many problems, the most apparent of these being the data base structure.

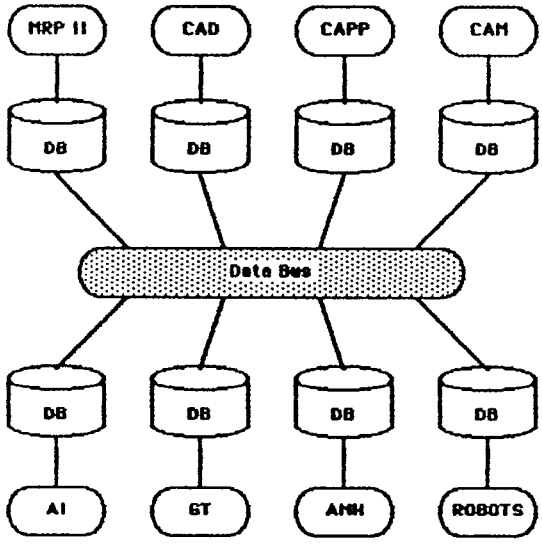
There are two primary shcools of thought on the issue: the use of a single, central database for all functions; and the use of multiple data bases with some form of linkage between them. Each thought has its advantages and disadvantages, and the final choice will have to provide the best compromise between these.

A single data base for all CIM functions would provide the most efficient means of communication; all data would be stored once and only once, thouhg it would be accessible for reading and modification from a variety of functions. No duplication of data would occur. A typical CIM model, as conceived by Arthur D. Little, Inc. (11), utilizing a single data base, is shown in Figure 3. The various CIM functions surround a central core, which represents not only the data base, but all of the hardware, software, and telecommunications necessary to integrate the diverse functions.

But many data base experts, including Melkanoff (18), point out that the development of "a single integrated CIM system data base could very well create a monstrous monolith so large and complex that it would require enormous efforts to utilize and to maintain, and might well yield unacceptably slow results." A second alternative combining the existing data bases from each system into a single data base, is said to be just as formidable, "generally requiring millions of dollars and dozens of man-years." A modular approach to CIM, most practical at this point, complicates this problem, since design considerations would have to be made in the data base design for future systems of unknown form. These and other



a. A Single Data Base CIM Model.



3b. A Multiple Data Base CIM Model.

Figure 3. The Two Most Common Physical CIM Models

difficult challenges to the creation of a CIM data base are largely responsible for the current fear of integration among manufacturing firms.

The second alternative is to use multiple data bases linked by some form of communication. While this is less efficient than a single data base, in some respects, it is considered by many to be the only real alternative. Bridging different data bases, which will have some redundant data, requires custom programming, and special care to insure that updating will automatically be done to all relavent data bases. Another complication is the diverse range of data to be interfaced, including textual, numerical, and geometrical. In tandom to this problem is the diverse range of users and requirements for data formats. Some of the major data base concerns, both specific to multiple data bases, and data bases in general, are summarized (18) in Figure 4. The key to the successful creation of CIM is that regardless of the particular structure of the data base, ie., single or multiple, the user should be aware only of a single, all encompassing data base.

The major advantage of the multiple data base concept is that functions can more readily be added to CIM in modules without disturbing the existing system. Becuase it accomodates the modular approach, the multiple database concept is supported by the authors.

In light of these conclusions, the CAD/MRP II integrated system can use the bridged data base concept, as shown in Figure 5. The initial bridges to be built revolve around the bills of material, part specification, engineering changes, and geometry. Such a form allows for the use of currently available packages, and would even allow the two systems to operate on separate computers.

The means for exchanging data now under study by the authors is a data "bus," a hardware/software system that would serve as a temporary vehicle for transporting information between each database in a standard format. All future CIM components would likewise be interfaced with the data bus.

DATA BASE CONCERNS

Multiple Data Bases:

- Heterogeneous Hardware
- Heterogeneous Software
- Heterogeneous Models
- Data Conversion

General Data Base Concerns

- Size
- Heterogeneity of Data
- Heterogeneity of Users
- Update Difficulties
  - Integrity Constraints
  - CAD as an Update
  - Automatic Update Propagation
- Performance Requirements
- Graphic I/O Requirements
- Ease of Modifying Data Base
- Control of Security, Integrity, and Privacy
- Distributed Data
- Integration of Text and Graphic Information

Figure 4. Some of the Major Data Base Concerns Facing CIM

To avoid customized interfaces between each specific set of CAD and MRP II Packages, communications standards would be used for all types of data passing through the bus. "Translators", specific to each sofware system, would be developed to convert data to and from the standard format from whatever format the system itself requires. Eventually, software manufacturers would supply the translators as front ends to their systems, allowing them to maintain the internal data format of their individual systems (Figure 6). Users would then be free to select the best packages for their needs without regard to vendor or fears of incompatibility.

The functions of the data bus will make its development complex, and undoubtedly time consuming. Its primary role will be to handle the exchange of different types of data between different CIM functions, possibly spread over different computers, in different physical locations, at rates fast enough to satisfy a large, busy system. At the same time, it must be able to accept new or modified data from any system and transmit that data to every other relevant system, all while working within the framework of the data integrity constraints of each system. To make matters worse, in the case of engineering changes, the system must be able to either propagate the changes to every affected system, or at least alert the proper users so that the necessary modifications can be made and verified.

The approach given by Melkanoff to minimize these hurdles is to "start developing a CIM system data base to the extent that it is convenient and feasible today and keep adding to it without distrubing what we have already developed." The proposed integration of CAD/CAM and MRP II as a starting point for CIM utilizes the same philosophy.

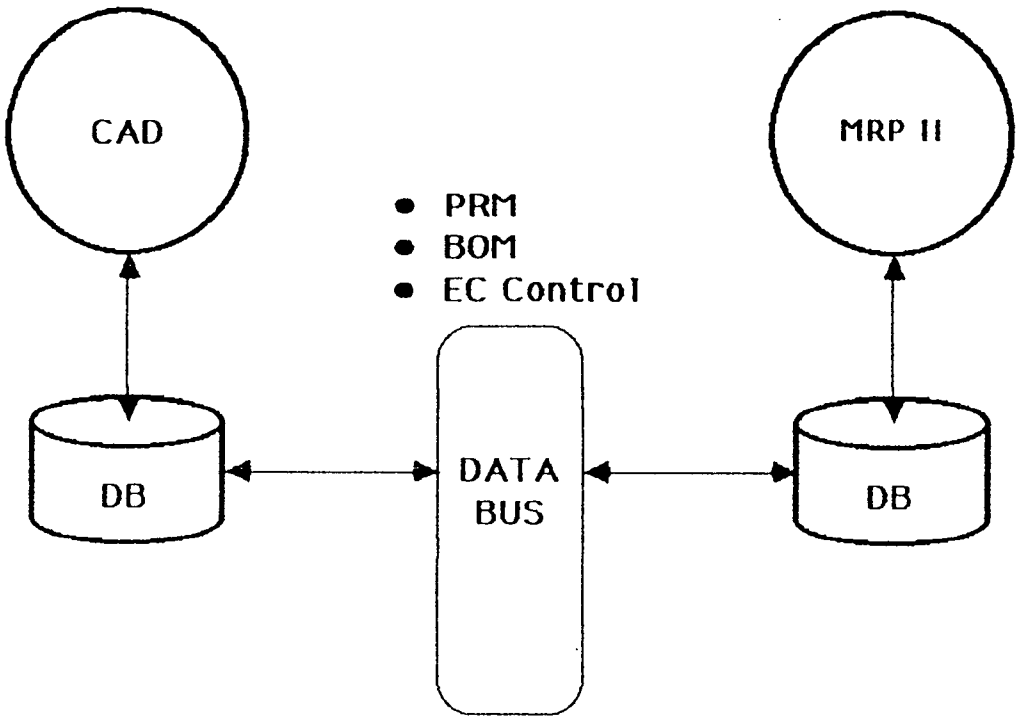


Figure 5. CAD/MRP II Integration Using Multiple Data Bases and a Data Bus.

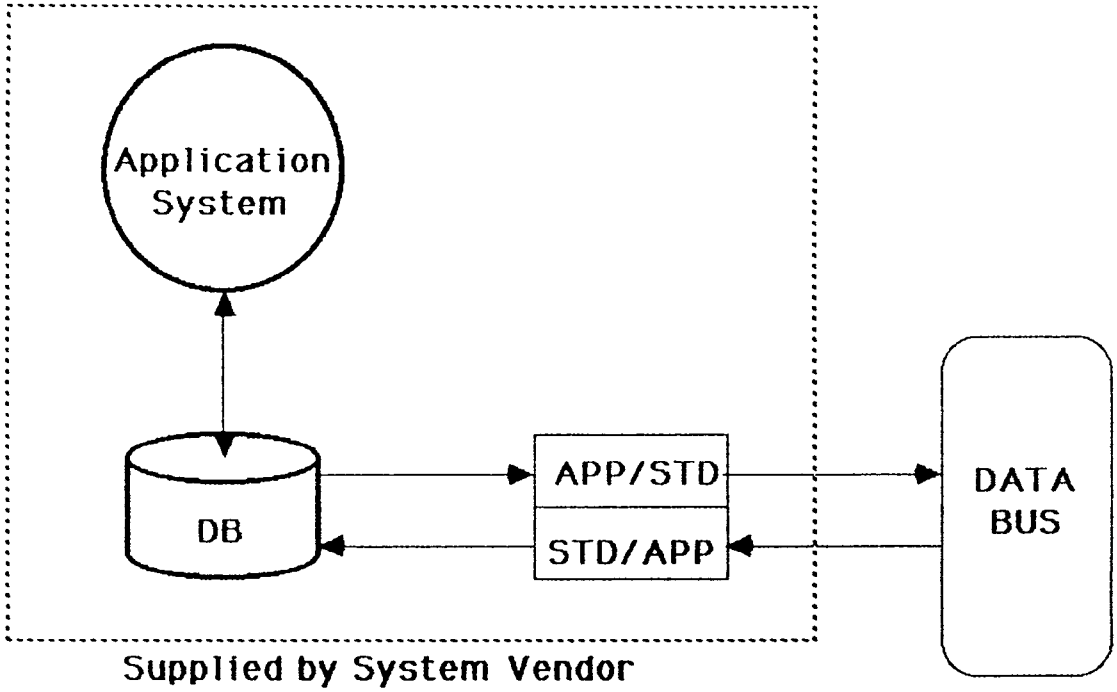


Figure 6. The Use of Application Specific Translaters to interact with Data Bus.

STANDARDS: A PREREQUISITE TO CIM

The most crucial requirement for such a system is a set of standards for the communication of data, be it textual, numerical, or graphic. With the enormous number of software vendors producing manufacturing systems of one form or another, it is apparent that this is not an easy problem. The use of a data bus, however, minimizes the difficulties, since each individual system can retain its internal communication system.

The Initial Graphics Exchange System (19), IGES, created to permit the exchange of geometric information between different CAD systems, is an example of the type of standard needed. IGES now claims many supporters, especially large firms such as General Motors, who may have many different CAD systems scattered around their offices and plants, and would benefit greatly from the communication capability.

General Motors is also involved with the Manufacturing Automation Protocol (MAP) specification for local area networking in manufacturing. Originally developed by GM to allow communication between different computer systems, MAP may become an international standard.

Finally, GM is currently working with Robotics researches to develop Numerical Control standards which may eventually be used to update the IGES standard. It is obvious that such a huge firm as GM would benefit greatly from these standards; the sooner they are developed and accepted, the sooner the goal of integration can be achieved.

THE NEED FOR COMMITMENT

The implementation of any type of automation is bound to disrupt an organization for a period of time, and CIM is no exception. If it ever becomes a reality in its envisioned form, CIM will require major changes in virtually every aspect of a company's operation, especially at the management level. Communication between departments will have to be improved, and the whole business must learn to function as a team, instead of separate, antagonistic groups. In effect, CIM should be a model of the actual structure of the company, a series of diverse functional areas held together by the communication of the information needed to achieve its goals. Accuracy is essential, for any wrong data is instantly transferred to all the relevant users, with possibly disasterous results. For these reasons CIM delelopment creates not only phsical problems, but "people problems" as well.

Given the technical complexities, high price tag, and long term nature of CIM development, it is no wonder that most firms have taken a "wait and see" attitude. As long as there is no fully operational CIM system to demonstrate its benefits, it will be difficult to convince these companies to proceed with integration.

Another group of firms seek quick solutions to their production problems, embracing the ideas of MRP II, CAD, CAM, and CIM, but are unwilling to provide the necessary time and resources, both financial and human, to see projects to their successful completion. Too often, they have unreasonable expectations of the quantitative benefits, and don't recognize the amount of time, education, and modification to company procedures, that must precede and accompany such a large undertaking. As a result, they may spend millions of dollars on a project such as MRP II, and then abandon it when they discover that the same performance measurements they intended to improve have actually been degraded, or at best,

unchanged.

A third and growing class of firm is the most likely to eventually succeed at CIM. These firms have an enthusiasm for integration projects that is balanced by their acknowledgement of the obstacles slowing them down. The management of these firms, which tend to fall in the mid to large size range, look beyond the traditional return on investment calculations to the real long term, though hard to quantify benefits of integration, such as (16) responsiveness, productivity, quality, lead-time, design exellence, flexibility, and work-in-process inventories. Also, management is willing to involve all affected levels of personnel in the effort during design, and especially during the training process.

Planning for integration is crucial to success for these companies. Analyzing needs, arriving at a conceptual model of information flow through the organization, and developing an implementation plan may take anywhere from four to 20 months (18). French (8) provides a list of various considerations to be explored during this phase; some of the most important are as follows:

- First, the potential impact on every functional area of the organization should be examined and likely problems, penalties, and benefits, both short-term and long-term, should be identified.

- Second, the leaders of each functional area should be allowed to share their concerns and ideas with those in charge of planning, so that a consensus can be reached as to why the project should proceed from the viewpoint of a given function.

- Third, company-wide concerns and opportunities should be identified, and a single list made of these, as well as those specific to each functional area.

With the list just described, a plan can be developed, to include funding needs, manpower, and time requirements; inevitable delays and mistakes should be allowed for. Once generated, it is important that the development and

implementation plans be discussed with each of the areas so that their involvement can be made clear.

The actual implementation of the plan may again extend from several months to several years. The most important factor for success is that implementation be done gradually, and with minimal distrubance of existing operations. For those areas to be altered drastically, the current system should be maintained until trouble-free operation has been attained by the new system.

As portions of the system become operational, continual evaluations should be made to uncover any problems and determine the effectiveness of the system. Potential changes should be carefully studied before any alterations are made.

CASE STUDIES

Many of the attempts at integrating manufacturing systems are worth noting at this point. Most of those receiving attention in the literature have involved large firms with enough capital to invest in a large-scale project taking many years to complete. The thrust of these projects tends to be toward integrating CAD and CAM, but some MRP II functions are occasionally accommodated, albeit not integrated.

Probably the most comprehensive and most often cited example of an integrated system currently in use is at Ingersoll Milling Machine Company of Rockford Illinois, winner of the 1982 LEAD award. Begun in 1979, Ingersoll decided to integrate their systems when they realized their systems were headed for chaos with 1300 different computerized applications, and 225 master files containing redundant and uncoordinated data. Ingersoll produces large milling machinery, customized for each customer's application, with lot sizes averaging less than three. The plant uses 25,000 different parts each year, of which 70% are in lots of one, and 50% are never made again. Most engineering efforts therefore cannot be reused, and there are no provisions for prototypes or models.

Ingersoll's system encompasses, in one form or another, the following functions (15):

- Master Scheduling
- Engineering Design
  - Assembly and Piece Part Drawing
  - Bills of Material
- Production Planning and Control
- Inventory Control
- Purchasing and Accounts Payable
- Routings and Process Planning
- Numerically Controlled Programming and Post Processing

CASE STUDIES

Many of the attempts at integrating manufacturing systems are worth noting at this point. Most of those receiving attention in the literature have involved large firms with enough capital to invest in a large-scale project taking many years to complete. The thrust of these projects tends to be toward integrating CAD and CAM, but some MRP II functions are occasionally accommodated, albeit not integrated.

Probably the most comprehensive and most often cited example of an integrated system currently in use is at Ingersoll Milling Machine Company of Rockford Illinois, winner of the 1982 LEAD award. Begun in 1979, Ingersoll decided to integrate their systems when they realized their systems were headed for chaos with 1300 different computerized applications, and 225 master files containing redundant and uncoordinated data. Ingersoll produces large milling machinery, customized for each customer's application, with lot sizes averaging less than three. The plant uses 25,000 different parts each year, of which 70% are in lots of one, and 50% are never made again. Most engineering efforts therefore cannot be reused, and there are no provisions for prototypes or models.

Ingersoll's system encompasses, in one form or another, the following functions (14):

- Master Scheduling
- Engineering Design
  - Assembly and Piece Part Drawing
  - Bills of Material
- Production Planning and Control
- Inventory Control
- Purchasing and Accounts Payable
- Routings and Process Planning
- Numerically Controlled Programming and Post Processing

- Flexible Machining System
  - Parts Storage and Retrieval
  - Automatic Transportation
  - Part Identification and Tracking
  - Direct Numerical Control (DCN)
  - Automatic Inspection (QNC)
  - Tool and Fixture Management
  - Process Data Management and Support
- Assembly
- Job Cost and Management Reports

Integration is achieved through two data bases, one alphanumeric and the other geometric, which Ingersoll hopes to eventually combine. In order to reduce the previous chaotic data situation to only two data bases, considerable rewriting of software was necessary, and a moritorium placed on all other software development.

The major integration successes at Ingersoll are in the area of flexible machining. The CAD/CAM geometrical data base and NC programming capabilities have allowed Ingersoll to use six machine set-ups to replace 17 old machines. A second set of six machines will replace 23 more machines. Drawings created with the CAD system are the driving force for not only NC programming, but also for routing and quality control inspection.

Ingersoll's use of MRP II is also impressive, incorporating purchasing activities, shop floor control, material needs, and scheduling, all in real time.

In the area of CAD/MRP II interaction, Ingersoll has achieved a limited interface between the two systems. When an assembly is drawn on the CAD system, its component parts are found in the bills of material file, and their part numbers and descriptions are retrieved. When the assembly drawing is completed, the component data is downloaded to the bills of material, where it drives the rest of the manufacturing process. The CAD module, as of yet, cannot automatically generate a bill of material for a new part, nor does the interface handle

engineering changes.

Ingersoll considers its system a great success, and plans to continue on the road to complete integration. George Hess, Vice President of Systems and Planning, credits the commitment of management and their willingness to be a leader in automation instead of a follower. Each system, such as CAD and CAM, was developed as soon as it was practically available.

Another example of integrated systems can be found at the Boeing Commercial Airplane Company, of Washington, currently implementing their second such system. Their first system, the CAD/CAM Integrated Information Network, or CIIN, was used in the design of the 757 and 767, and is still in use today. Because of CIIN, both these planes were delivered ahead of schedule and under budget.

The CIIN network is used to provide communication between the various data bases and applications that already existed at Boeing; the concept is demonstrated in Figure 7. The primary goal, according to Beeby (4), was to interface the key geometry and graphics systems, including several Boeing lofting programs (which generate descriptions of lines and contours of an airplane). These functions were interfaced via translators to and from a "neutral" data base format, and the data stored in a geometric data base, as shown in Figure 8 (5). The network allows, for example, lines to be extracted from master models, translated to a graphics system, stored, and then retrieved by manufacturing for use in tool design and part manufacture.

While the geometric functions at Boeing are well interfaced, if not integrated, non-geometric functions do not fare as well. The geometric data base management system of CIIN does have access to other data bases, such as marketing and manufacturing, but not in an integrated sense; only certain information processes are interfaced, and those only at the data level.

Though it has been instrumental in saving time and money, Beeby (4) points out several shortcomings of CIIN, such as its complexity, lack of user-friendlyness,

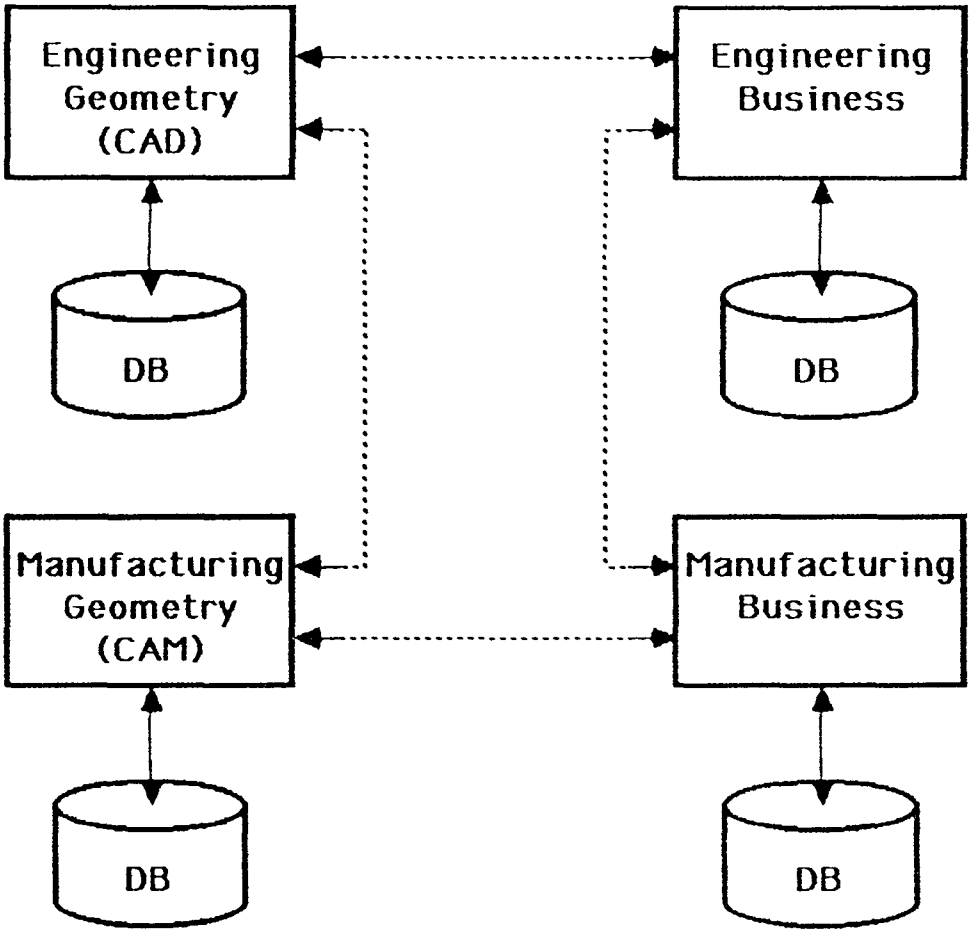


Figure 7. The Current CIIN System at Boeing, which provides interfaces for certain information proceeses, but not true integration.

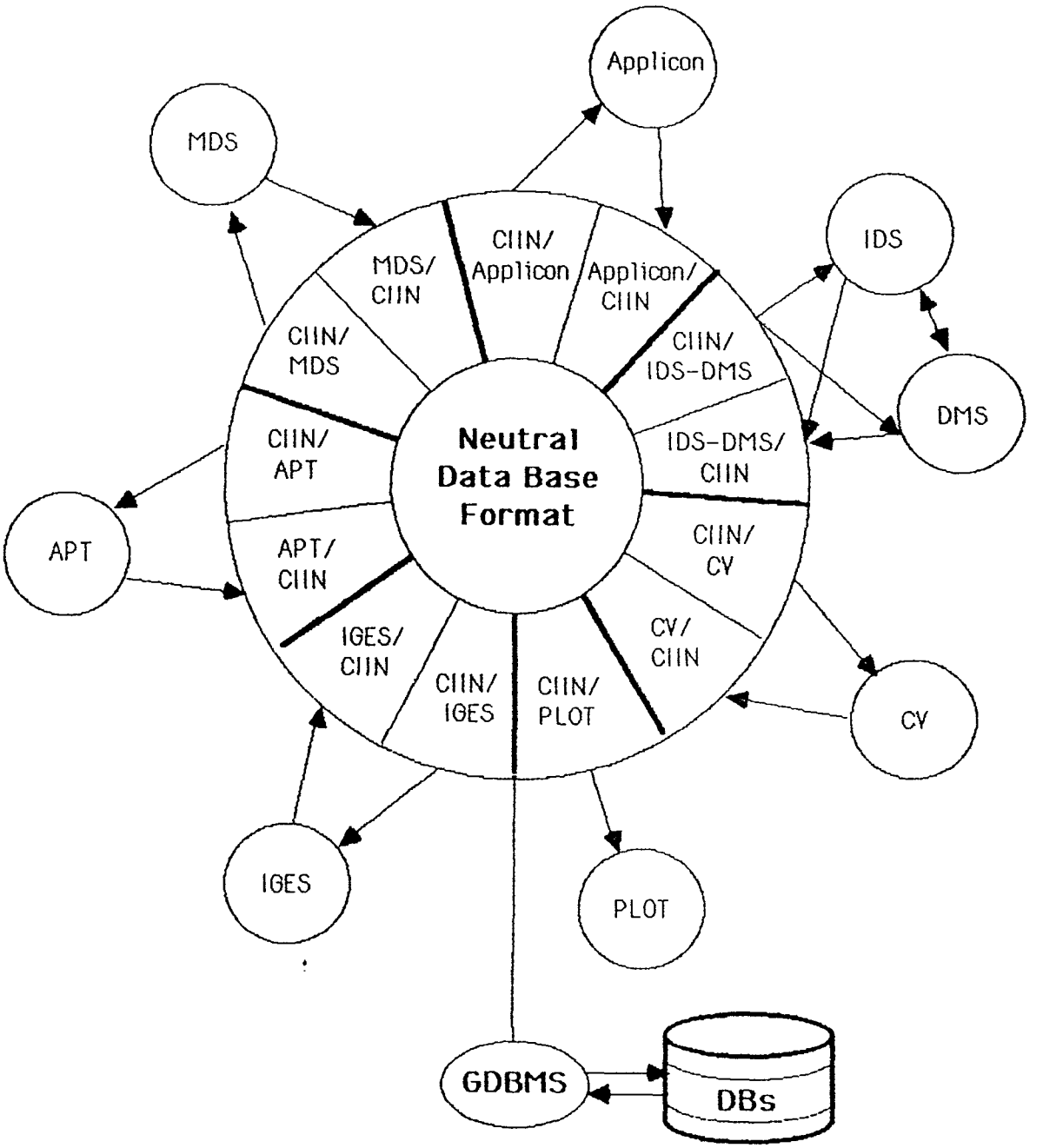


Figure 8. The Physical Arrangement of Boeing's CIIN.

and its high price tag. The use of so many heterogeneous hardware and software systems, each with different user interfaces and a unique set of translators, makes the system large and inefficient, and makes it difficult for people to move around the organization without being retrained.

With the problems of CIIN surfacing, Boeing began planning their next system, hoping to achieve the integration that CIIN did not. The new system, which took four years to plan and will take 10 years to implement (1985-1995), is centered around the Boeing Computer Support System (BCSS). The goal is a single data base handling all engineering and manufacturing funcions, as well as finance, sales, marketing, and customer support. Instead of translators customized for each function, a single data structure will be used for all product data. A special core data manager will be disigned to verify and enforce all of the data base system constraints. Boeing is likely to find the development of this single data base to be its most difficult, if not impossible, chore.

According to Beeby (4), BCSS will use a structure emphasizing the logical relationships between functions corresponding to the structure of product development. Therefore, high on Boeings priorities is the integration of product definition data (eg, geometry, analysis data, bills of material) and planning and control data (eg, inventory management, production scheduling). Development will occur gradually, with applications being integrated one at a time.

When completed, the functions of BCSS will cover the entire spectrum of manufacturing activities, serving everyone from designers to process planners to financial personnel. Boeing has committed the full time efforts of 100 professionals to the development effort, a promising sign for success.

In addition to private industry, government agencies are also highly interested in the potential benefits of CIM, and have undertaken several projects related to aspects of integration. The National Aeronautics & Space Administration (NASA), for example, has determined that CIM developments will be essential to the

achievement of two of NASA's major goals: to launch a Manned Space Station by 1992 with an $8 billion budget; and to be "a leader in the development and application of advanced technology and management practices which contribute to significant increases in Agency and National productivity" (16).

To help in their efforts, NASA established the Integrated Program for Aerospace Vehicle Design (IPAD). Originally intended to encompass the development of a broad range of design software for use in the American aerospace industry, NASA later decided to narrow the scope to two areas: data management and networking between heterogeneous machines.

Their efforts in the data management area have produced a prototype Data Base Management system (DBMS) called IPIP, that improves on the way information is managed and shared. IPIP is a multimodal, multiuser, multilevel-schema, concurrent-acces DBMS, and includes data data definition and data-manipulation languages for the solving of engineering problems. It can also support multiple data models (ie, relational, hierarchical, and networked).

Through the communication capabilities of the IPAD network system, IPIP can exchange data between heterogeneous equipment. The key to this exchange is the multilevel-schema approach. Three schema are used in IPIP (7): logical, (or user) schemas, which organize information appropriate for each user; internal schemas, which reflect the way information is stored in a particular machine; and mapping schemas, which connect the various logical and internal schemas. This process allows a virtually limitless number of easily modified formats for meeting specific needs, yet allows information to be stored only once on one particular computer in a distributed network.

The IPAD network system's communications capabilities correspond to Levels 3 through 6 of the International Standards Organizaion (ISO) communications model, which has seven levels (16). Levels 1 and 2 (process to process communications) can also be obtained with Network System Corp.'s Hyperchannel

between different computers with different operating systems. These advancements in networking and data management are likely to have a significant impact on the future development of CIM.

A second, more production oriented effort is underway in the Air Force: the Integrated Computer Aided Manufacturing (ICAM) program. ICAM personnel began by examining the state of the art in manufacturing systems, and determining the barriers that were preventing more effective integration. Their goal was, through industry/university consortia, to discover and demonstrate ways to overcome these obstacles.

ICAM has included many projects under its umbrella, essentially providing "seed money" to interested firms willing to share the results of their work. One of their most significant projects deals with the transfer of geometry and instructions across the interface between design and production. To explore this problem, the Product Definition Data Interface (PDDI) project was established (16). The goal of this project is to provide the foundation for the exchange ofdigital product definition data to serve the functions of traditional engineering drawing. It is expected that the interface will provide product information to process planners, NC programmers, quality control personnel, tool designers, and all other members of the organization that use blueprints today. Using IGES, which allows a limited product deifintion data interface, as a starting point, PDDI is likely to greatly advance the applicability of this standard.

When it is demonstrated in the near future, PDDI will interact with both an advanced NC programming system, and an advanced process planning system. And to prove its widespread compatibility, it will be operated with two different commercial CAD systems.

Like NASA's IPAD, ICAM has been intentionally narrow in scope, focusing on only a few of the key areas in CIM. But the forthcoming results of these projects promise to dramatically improve the knowledge of the most fundamental aspects

of integration.

CIM: NOT IF, BUT WHEN

There is no doubt that CIM is coming; it is just a matter of time before development and implemention begins in most manufacturing facilities. Those firms not willing to udertake an integration program will soon find themselves falling behind their competitors in productivity, quality, and, as a result, profits. Small firms will probably have to wait for the development of lower cost, turn-key CIM modules, but then they too will be able to share in its benefits.

Before its use can be practical, CIM requires significant research and development efforts. Specifically:

- A better understanding of the relationships between and information flow among the various departments and functions of a company is required, to provide a unified model on which to base CIM.
- Improvements and extentions are needed of each CIM component.
- Research in group techonlogy and artificial intelligence, which are crucial to the success of CIM, must be stepped up.
- Work on the data sharing system, be it a single data base, or inter-connected multiple data bases, must continue until a satisfactory design can be found.
- Creation of standards for communication and data formats are required so expensive customizing of systems can be avoided.

Work in these areas will undoubtedly occur both in private industry and governmental agencies. The proprietary nature of many firm's research, however, limits the transfer of technology to industry in general. Hence the importance of projects such as IPAD and ICAM, which are specificially created to provide technology and help to the industrial community. University research will

likewise be important, assuming that industry is willing to help sponsor the efforts.

The actual implementation of CIM will occur gradually, and most likely in the modular approach previously outlined. New functions will be added to the system as theys become practical. The use of standards will allow users to pick their individual component systems from whatever vendor they choose and "plug them into" the central control system.

As for the specific order of integration, the proposed links between CAD and MRP II offer a convenient and logical starting point. The two technologies have a well defined overlap, the Bill Of Material, Part Master Record, and Engineering Change control, which will be maintained regardless of the changes that will inevitibly occur in both systems as they continue to mature. Though it is conceptually an easy linkage, the task is complicated by numerous realities; heterogeneous software and hardware, lack of standards, and technical barriers in data management and exchange are just a few of the factors that hinder even this modest step towards CIM. Efforts by the authors are now underway at the University of Maryland to develop this initial integrated system. And, once developed, the CAD/MRP II system can form the nucleus for future CIM growth.

Once a CIM system is created, it will be possible for firms to link their system to those of their suppliers, extending the benefits of CIM to purchased, as well as manufactured, parts. Development will continue, and with faster computers and cheaper mass storage, it may someday be possible for CIM to evolve into a single data base system, maybe even produced as a single package.

As for the potential affects on a typical factory of the future, consider the admittedly idealized image of Anderson, Solberg, and Paul:

> First, we expect to see around-the-clock operations, with only brief stoppages for diagnostic checks, preventive maintenance, and so forth. Very small lot sizes, even down to single item jobs, will not only be

economically justifiable but also the norm. The normal time span from product concept through delivery will be measured in hours instead of weeks or months. For relatively simple products, such as pumps or gear boxes, the customer will specify his requirements one day and take delivery the next. There will be little or no labor by humans at the point of production. (The deciding factor, by the way, will be the limited capabilities, not the high cost, of human labor.) Moreover, the white-collar functions of design, engineering, and management will require far less human attention.

While this scenario may never come true, it demonstrates the type of changes that will definitely occur as CIM prevades industry. All it will take is time, effort, and commitment.

Acknowledgements

We wish to acknowledge the Systems Research Center (NSF Grant NSFD CDR-85-00108) of the University of Maryland for partial funding of this research, as well as the National Science Foundation for their direction contributions (NSF Grant NSFD DMC-85-04922).

References

1 Anderson, D. C., Solberg, J. J., and Paul, R. P. "Factories of the Future: How will Automation Research be Integrated?," Computers in Mechanical Engineering, Vol. 2 (1984) 31-36.

2 Anonomous. "Automated Factory Update," Production Engineering, Vol. 31 (1984) 66-70.

3 Appleton, Daniel S. "The State of CIM," Datamation, Vol. 30 (1984), 66-72.

4 Beeby, William. "The Future of Integrated CAD/CAM Systems: The Boeing Perspective," IEEE COMPUTER GRAPHICS AND APPLICATIONS, Vol. 2 (1982), 51-56.

5 Beeby, William D. "The Heart of Integration: a Sound Data Base," IEEE Spectrum, Vol. 20 (1983), 44-48.

6 Burgam, Patric. "Marrying MRP and CIM," CAD/CAM Technology, Vol. 2 (1983), 25-27.

7 Fulton, Robert E. "Using CAD/CAM to Improve Productivity: The IPAD Approach," Mechanical Engineering, Vol. 103 (1981), 64-69.

8 French, Robert L. "Managements Looking at CIMS Must Deal Effectively with These Issues and Realities," Industrial Engineering, Vol. 16 (1984), 70-77.

9 Fox, Kenneth A. "MRP II Providing a Natural 'Hub' for Computer-Integrated Manufacturing System," Industrial Engineering, Vol. 16 (1984), 44-50.

10 Gallagher, Gerald R. "The MRP Crusade Meets CAD/CAM," APICS 26th Annual International Conference Proceedings, (1983), 151-153.

11 Gunn, Thomas G. "CAD/CAM/CIM: Now and in the Future," I&CS, Vol. 58 (1985), 59-64.

12 Harhalakis, George, An Integrated Production Management System for Engineered Equipment, PhD Thesis, University of Manchester Institute of Science and Technology (1984).

13 Hazen, David C. "The Engineering Research Centers as a Tool for Change in the

Culture and Attitudes of Acedemic Engineering," Presentation at the Second Meeting of the Steering Group on Systems Aspects of Cross Disciplinary Engineering, August 8, 1985.

14 Hegland, Donald E. "Putting the Automated Factory Together," Production Engineering, Vol. 29 (1982), 56-64.

15 Hess, George, "Computer Integrated Flexible Manufacturing (CFIM)," Presentation to Autofact 6 Conference, Anaheim CA, October 2, 1984.

16 Jablonowski, Joseph and Wengler, John. "The Interface Challenge," American Machinist, Vol. 129 (1985), 95-102.

17 Kutcher, Mike and Gorin, Eli. "Moving Data, not Paper, Enhances Productivity," IEEE Spectrum, Vol. 20 (1983), 84-88.

18 Melkanoff, Michael. "The CIMS Database: Goals, Problems, Case Studies, and Proposed Approaches Outlined," Industrial Engineering, Vol. 16 (1984), 78-92.

19 National Bureau of Standards. Initial Graphics Exchange Specification (IGES), Version 2.0 (1983).

20 Rosenbaum, Jacob D. "A Propitious Marriage: CAD and Manufacturing," IEEE Spectrum, Vol. 20 (1983), 49-52.

21 Schaefer, Thomas J. "Modular Approach to CIM: Integrate your Factory in Pieces," Production Engineering, Vol. 32 (1985), 102-104.

22 Warmack, Hardy. "CAD/CAM Coexistence with P&IC Software," APICS 26th Annual International Conference Proceedings, (1983), 161-164.

23 Wight, Oliver. MRP II: Unlocking America's Productivity Potential. O.W. Ltd. Publications, 1981.