United States Air Force
Computer-aided Acquisition &
Logistics Support (CALS)

November 1988

CAD/CAM/CAE
Technology Assessment (1988 - 1998)

Version 3.0

FINAL DRAFT

Prepared By

U. S. Department of Transportation
Research and Special Programs
Administration
Transportation Systems Center
Cambridge, Ma 02142

Prepared For

U. S. Air Force Systems Command
HQ AFSC/PLXC
AF CALS MIO
Andrews AFB, DC 20334-5001

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1988

3. REPORT TYPE AND DATES COVERED
Final Draft

4. TITLE AND SUBTITLE
CAD/CAM/CAE Technology Assessment (1988-1998)
Version 3.0 FINAL DRAFT

5. FUNDING NUMBERS

6. AUTHOR(S)
Information Integration Division of Transportation Systems Center

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Departement of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, MA 02142

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Air Force Systems Command
HQ AFSC/PLXC
AF CALS MIO
Andrews AFB, DC 20334-5001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
No software developed per Dan Turner AFSC/[illegible] 10/30/91 [illegible]

12a. DISTRIBUTION/AVAILABILITY STATEMENT
unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report is part of a larger effort to assess the current status of CIM technologies and to project their development over a ten year time horizon. It concentrates on assessing commercial Computer-Aided Design/Computer-Aided Manufacturing/Computer-Aided Engineering (CAD/CAM/CAE) software and hardware offerings. Source material for the assessment was garnered from trade publications, government sponsored studies/reports, industry sponsored studies/reports, and telephone/personal interviews with government personnel and major software and hardware vendors.

14. SUBJECT TERMS
CIM
CALS

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C	- Contract	**PR**	- Project
G	- Grant	**TA**	- Task
PE	- Program Element	**WU**	- Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

DOD - See DoDD 5230.24, "Distribution Statements on Technical Documents."
DOE - See authorities.
NASA - See Handbook NHB 2200.2.
NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - Leave blank.
DOE - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
NASA - Leave blank.
NTIS - Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*.

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

Table of Contents

List of Figures

1.0 Introduction

This report is part of a larger effort to assess the current status of CIM technologies and to project their development over a ten year time horizon. It concentrates on assessing commercial Computer-Aided Design/Computer-Aided Manufacturing/Computer-Aided Engineering (CAD/CAM/CAE) software and hardware offerings. Source material for the assessment was garnered from trade publications, government sponsored studies/reports, industry sponsored studies/reports, and telephone/personal interviews with government personnel and major software and hardware vendors.

A parallel report, entitled Evolution of CIM Technologies, was prepared on technologies such as flexible manufacturing systems, group technology, and MRPII. Additionally, a companion to the present report, CAD/CAM/CAE Current and Future Environment, describes the current and projected Air Force and contractor CAD/CAM/CAE environments. The results of these studies will be utilized in developing realistic technology scenarios for development of the product definition data future state.

2.0 Commercial CAD/CAM/CAE Market

The CAD/CAM/CAE market posted total revenues of $4.6 billion in 1987. Of this $4.6 billion market, the mechanical segment accounted for 60% of the revenues, the electrical segment 21.7%, the architectural engineering segment 16.7%, and miscellaneous 1.6%. It is a market undergoing structural change as mergers and acquisitions increase. Over the past four years, revenue growth rates of 23.7%, 16.8%, 10.3%, and 13.4% were recorded along with generally decreasing hardware and software prices. In the following subsections, the major software and hardware technologies currently impacting or projected to impact on the mechanical and electrical/electronic segments will be discussed first from a software and then from a hardware perspective. Note that the major focus of this study is on software aspects.

2.1 Software

Software will be discussed under the following headings: mechanical design, mechanical computer aided engineering, electronic/electrical computer aided engineering, and manufacturing. Current technology will be presented first, followed by a discussion of trends in future technology over a ten year time horizon.

2.1.1 Mechanical Design

Current Technology

Mechanical design can be characterized as spanning a spectrum from automated drafting to geometric modeling (2D and 3D wireframe, surface, and solids). Automated drafting systems typically run on either mini or micro computers and are used most often for 2D applications. Color and 3D to 2D conversion capability are also available. Functionally drafting systems usually offer:

- automatic dimensioning for drawing reference lines and dimensions
- pattern filling, including cross-hatching
- zoom and pan to enlarge pictures of a drawing for detail work

- availability of symbol libraries
- ability to work with a number of different layers
- hidden line removal
- rotation of an object to view it in any perspective
- presentation of an object in several different perspectives at once

A two to six-fold increase in productivity has been found with installation of automated drafting systems, largely through the automation of the revision process.

Geometric Modeling

The starting point for virtually every function in CAD/CAM is the geometric model, representing part size and shape. Once the geometric model has been created, it can be used to assist with other tasks, such as creating a finite-element model for system analysis or generating NC code for making parts on automated machine tools. Functionally, the CAD modeling system provides many features to speed the design process, including:

- line construction based on user specified points and commands
- similar automatic construction of curved lines, circles, corners, and splines
- automatic projection of views
- detail duplication
- line deletions
- temporary line erasure
- model enlargement or reduction

Wire Frame Models

Generally, the simplest type of models to create are wireframe models which provide precise information about the location of surface discontinuities on the part. They can be ambiguous in representing complex structures because they contain no information about the surfaces, nor do they differentiate between the inside and outside of objects.

Surface Models

Surface models define outside part geometries precisely and are created by connecting various types of surface elements to user-specified lines. CAD systems typically include the following surface types:

- o planes
- o tabulated cylinders
- o ruled surfaces
- o surfaces of revolution
- o sweep surfaces
- o fillet surfaces
- o sculptured surfaces

Where the definition of structure boundaries is critical, such as for NC machining, surface models are extremely important.

Solid Models

By combining elementary cubes, spheres, and other solid primitives, solid models are able to define the external and internal geometry of a part. Solid models are commonly constructed in two ways: constructive solid geometry (CSG) or boundary representation (B-REP). In CSG, the user positions elementary shapes (e.g., blocks or cylinders) as required and generates a new shape by utilizing Boolean logic (union, difference, intersection). In the boundary representation technique, two-dimensional surfaces are rotated around an axis to trace out volumes. Components with complex contours are more easily modeled using B-REP techniques, while other parts are readily modeled using CSG. Most CAD systems today combine the two techniques in a unified hybrid package.

Systems embodying these technologies typically are segmented and priced according to the hardware that they run on. Typical costs quoted in a presentation given early in 1988 (Ref. 12) were:

- o mainframe and mini-based CADD system - $90,000 (average price per seat)

- distributed workstation based CADD system - $30,000 (average price per seat)
- microcomputer based CADD system - $12,000 (average price per seat)

The State-of-the-Art survey prepared by the Geometric Modeling Applications Interface Program (GMAP) assessed a number of modeling software systems for their ability to address the data classes needed to support the design and analysis, manufacturing and inspection, and product and logistics support of complex structured components. The systems surveyed had specific voids in the implementation of the following data classes:

- topology - laminate representations
- features - section defined features, replicate features/feature patterns, compound feature representations
- tolerances - projected tolerance zones, tolerance function, statistical process control tolerancing, airflow tolerances
- assembly - non-shape information

The study found that complete integrated product modelers were not yet available. They also found that system users indicated difficulties with modeling and application of free-form curves and surfaces, as well as an inability to efficiently model objects with multiple transitional surfaces or other complex geometries. Note that at least one relatively new mainframe CAD/CAM system claims to have bridged most of the aforementioned deficiencies.

Future Technology

Interviews were conducted with major vendors in order to supplement information collected during the literature search. Based on an integration of the prevailing views embodied in these two sources, the major trends impacting the future of mechanical design software appear to be:

- continued significant decreases in hardware price vs. increasing hardware performance.

- a trend toward distributed work stations in combination with PC-based systems.
- acceptance of UNIX as an operating system.
- significant improvement in user interfaces.
- improved software performance through development of more efficient modeling algorithms, e.g. Nonuniform Rational B Splines (NURBS).
- integration of surface modeling and solid modeling.
- improvement in solid modeling implementation (functionality and performance).
- migration from proprietary databases toward relational/object-oriented databases and eventually to a common data model (PDES).
- development of feature based design modeling.
- integration of CAD and CAM.
- evolution from part design to product design (e.g., design for manufacturability; design for assembly).
- integration of expert systems into the design process.
- design of open systems architectures.
- acceptance of parametric and variational modeling.
- automatic conversion of wireframe and surface models into solid models.
- a major thrust into the distributed data management arena.

Probably the most significant trend is that related to the incorporation and integration of features into solid models. A feature is a higher-level, more-intelligent description of a portion of a workpiece that allows for the communication of data, both geometric and non-geometric, between different design and manufacturing organizations. Some of the major reasons driving the implementation of features are:

- features offer a mechanism for a friendlier and more efficient user interface upon which to build a model.
- features allow for increased editability of the model, thanks to their explicit storage.
- features provide a mechanism whereby the intention of the designer may be easily captured and stored.

- features, in conjunction with other information found in the CAD model,will improve the level of communication between design and manufacturing.

Implementation of features should assist in the automation of:

- process planning
- numerical-control programming
- part inspection
- manufacturability checks
- assembly modeling

There are two instances of true feature based modelers noted in the trade journals at the present time, developed by small start-up "niche" firms. Experience with these systems has mostly been on a prototyping basis. Large turnkey vendors are entering this arena cautiously. Therefore, it would seem that this technology would be available on a general basis in the 5-10 year time frame.

It is difficult to project the direction of software prices as software and hardware are unbundled. One school of thought predicts a relatively stable or increasing price with greater software functionality. The other school predicts decreasing prices driven by the decreasing prices offered by the hardware sector.

An article written by one of the new solid model vendors (Ref. 2) provides some further insight into the issues of CAD system price, performance, and future trends. Referring to the chart (Figure 1) depicting the progression of high end, mid-range, and low end systems, the author makes the following points:

- A high end system's cost is about the same as the annual burdened rate of a design engineer; a mid-range system is about one-third of this cost; while a low-end system is about one-tenth the cost of a high end system.
- The majority of production users are likely to be five years behind the chart predictions.

Progression of CAD systems

	1970	1975	1980	1985	1990	1995
High end	Flat bed plotter, 2D graphics routines	Shared 16-bit mini, wireframe geometry	Shared 32-bit mini, surface geometry	1 MIPS workstation or share of CPU, limited solids	10 MIPS dedicated, assemblies of solids	Desktop supercomputer, complex simulations
Mid range		Turnkey seat, 2D geometry	Turnkey seat, wireframe geometry	Workstation seat, surface geometry	5+ MIPS workstation, parts-oriented solids	Super workstation, assemblies of solids
Low end	Drawing board etc.	Drawing board and microfilm system	8-bit microcomputer, 2D digitizer	16-bit wireframe geometry	Workstation, surface geometry	5+ MIPS workstation, parts-oriented solids

MIPS = Millions of instructions per second

Figure 1. Trends in CAD Systems, 1970-1995

Source: "What Do Solid Models Need?", Machine Design, March 12, 1987

- The progression of systems with specific functional qualities tends to move from the high to low end over about 10 years. Users generally take about five years to understand and apply each new generation of modeling tools.

Another interesting perspective on the future of CAD is provided in Reference 30. The Congressional Office of Technology Assessment (OTA) conducted an analysis of a number of programmable automation technologies for a study published in 1984. Key problem areas and projections of the timing of their solution were compiled as a result of interviews with technology experts. Figure 2 presents an extract of a table developed for the CAD area. It is interesting to note the pace of development since 1984. Most of OTA's projections seem to be realistic with two exceptions. OTA seems to have been optimistic with regard to extensive design/manufacturing integration (Problem Number 6) and too pessimistic with respect to Problem Number 2b.

2.1.2 Mechanical Computer Aided Engineering (MCAE)

Current Technology

Major CAD/CAM vendors have provided access to engineering capabilities by providing interfaces or data converters to third-party software capable of assisting with finite element analysis, kinematics, and mechanical simulation. These analysis programs have typically required large amounts of computing power (supercomputer, mainframe, minicomputer) depending on the size of the problem. Today, certain size problems can be run on workstation and even PC based machines. MCAE systems have an average cost per seat of approximately $40,000.

A growing number of vendors of solid modelers are offering integral solvers so that no translation is needed to a third party package. Automatic 3D mesh generation is also being offered by a few vendors. However, most handle only linear static analyses. Note that some developers of analysis software now also offer solid modelers.

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. High-resolution, color display of designs, with rapid generation of images[a]	▲	●	■		
Both hardware and software:					
2. Low-cost, powerful microcomputer-based workstations for:[b]					
a) electronics design	▲	●	■		
b) mechanical design		▲	●	■	
3. Independent CAD workstations linked by network, with access to supercomputer for powerful analysis and simulation	▲	●	■		
Software:					
4. Three-dimensional solid modeling systems, resulting in:[c]					
a) more realistic images	▲ ●		■		
b) enhanced ability to connect with manufacturing equipment	▲		●	■	
5. Comprehensive, powerful computer-aided engineering systems[d] for mechanical design			▲	●	■
6. Extensive design/manufacturing integration[e]		▲	●	■	

[a]While color displays are currently available, they tend to sacrifice either resolution (the fineness and clarity of the picture) or the speed with which the images can appear on the screen. New techniques for displays, such as the use of dedicated microprocessor chips (sometimes termed "silicon engines") to generate images, promise to *improve* this situation.

[b]Microcomputer-based workstations for CAD are now being marketed, but in the judgment of technical experts consulted by OTA, *they are either not powerful enough* and/or not inexpensive enough to be useful in a wide variety of applications.

[c]CAD experts report that many systems for 3-D solid modeling are available now, but they are not being used because of their large appetite for computer power, and because their capacity to link design data to manufacturing equipment is inadequate. Part (b) of this entry refers to this ability to store and manipulate design data about the physical characteristics of a part in such a way that *it can be transmitted to manufacturing equipment* with only *minimal intermediate* steps.

[d]This entry refers to modules powerful enough to allow extensive interactive testing, simulation and refinement of designs in a wide range of applications. Such systems are strongly product-dependent; while they may be near available for certain products now (e.g., integrated circuits, certain portions of aircraft and motor vehicles), they are much less advanced in other industries and applications.

[e]*This entry denotes the "window from design to production"* which would, for instance, allow designers to examine the production implications of design choices. These include the costs and necessary production processes, as well as the history of manufacturing similar items at the plant. Such comprehensive connections would allow much more substantial integration of CAD, CAM, and computer-based management.

▲ = solution in laboratories

● = first commercial applications

■ = solution widely and easily available (requiring minimal custom engineering for each application).

SOURCE: OTA analysis and compilation of data from technology experts.

Figure 2. OTA Projections for Solution of Key CAD Problems

Source: Computerized Manufacturing Automation, OTA, April 1984

Future Technology

MCAE as a distinct technology emerged in 1987. In the future, it will become a specific market area, distinct from CAD or CAM. In response to the belief that 85% of the cost of a product is committed by the end of the conceptual design phase, MCAE systems are geared toward providing the engineer with the tools necessary to optimize the design prior to the drafting or verification/prototyping stage. The tools embodied in MCAE systems will be able to determine the following types of design data: mass and section properties, interferences, clearances, stress levels, forces, temperature distribution, path motion, and manufacturing cost. Expert system/AI techniques will also play a major role as vendors attempt to provide the generalist mechanical engineer with specialized knowledge.

There also appears to be a growing integration between solid modeling and finite element modeling. Loads and restraints will be applied directly to the geometric model. The entire system (geometry, materials, mass properties, and finite element modeling, analysis, and post processing) will operate on a common database and use a consistent user interface.

2.1.3 Electronic/Electrical Computer Aided Engineering (ECAE)

Current Technology

Electronic design/engineering is commonly addressed under the single heading of electronic computer aided engineering. ECAE tools today address the entire electronic product design cycle from initial concept to production. Figure 3 presents a simplified diagram of the design cycle with no attempt to show all the decision points and loops.

ECAE is considerably more advanced than MCAE. Powerful digital circuit design tools for electronic engineers first emerged commercially in the early 1980's. Today, ECAE has grown to a market of over $500 million a year. It has even adopted leading edge artificial intelligence techniques in connection with silicon compilers as well as with the design of Application-Specific Integrated Circuits (ASIC).

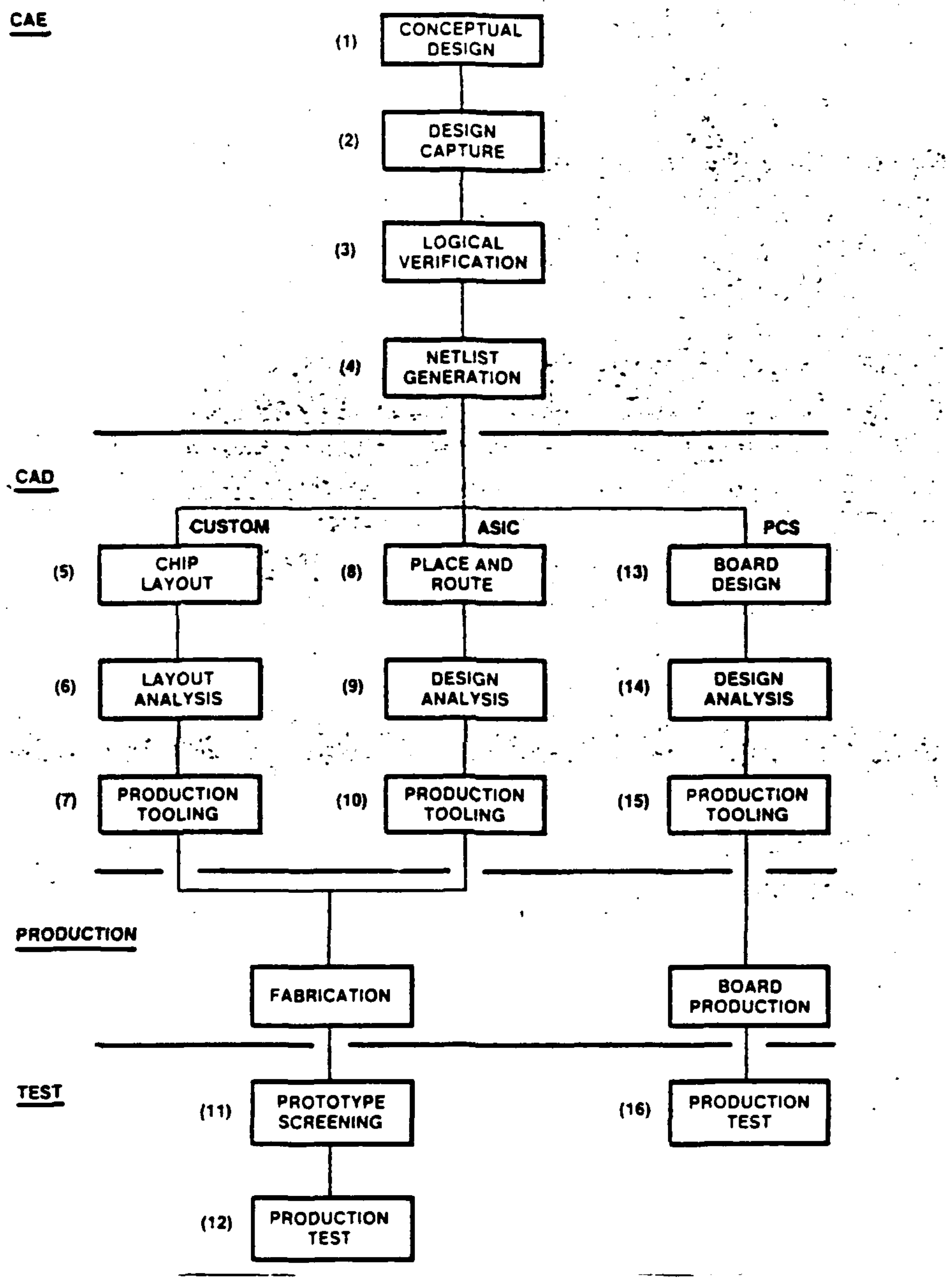

Figure 3. Simplified Diagram of Electronic Circuit Design Process

Source: "Software for Defense and Aerospace", Journal of Electronic Defense, May '88

Major elements of ECAE today include: printed circuit board design (schematic capture, netlist extraction, automatic placement and routing); integrated circuit design (semi-custom logic design, full-custom VLSI design, standard cell design, gate array design) and analysis (logic simulation, fault simulation, circuit simulation).

ECAE vendors have recently brought automation to the task of electronic system packaging, integrating mechanical engineering with electronic design. Tool sets for packaging analysis are projected to have the following capabilities: 3D geometric modeling, drafting, thermal analysis, electromagnetic analysis, cabling design, and interface software for mechanical designers developing subsystem and system enclosures, PC-board cages, and integrated circuit packages.

Future Technology

ECAE technology is projected to evolve along the same lines it has followed over the past seven years, further integrating the process of automating the electronic design to production cycle.

Areas where gaps exist or automation is currently lacking will be addressed. These areas include:

- application of AI technologies to board design in the areas of routing and placement.
- data handling architectures.
- automatic documentation updates and package generation.
- improved analog simulation.
- evaluation of cell designs.

Advances in electronic technology will also force ECAE vendors to react. Tool sets will have to be developed to address problems unique to surface mount technology, analog design, high-frequency design, hybrid devices, and others. Hybrid devices, a middle ground between integrated circuits and printed circuit boards, will force vendors to support a front-to-back solution. Another generation of ECAE tool, called logic synthesis, is beginning to be marketed. Logic synthesis is intended to help convert a high level design specification into a low-level logic network. Within a few years, board level synthesis tools that can map high-level descriptions into standard parts will probably emerge.

2.1.4 Manufacturing

Under the topic heading of manufacturing, numeric control and process planning will be discussed. Other topics included in this area (e.g., group technology, MRPII, etc.)have been addressed in a separate report.

Current Technology

Numeric Control (NC)

Numeric control commonly refers to a microprocessor-based control system that accepts a set of program instructions, processes output control information to a machine, accepts feedback information from transducers placed on the machine, and based on both instructions and feedback, assures that proper motion, speed and operation occur. An NC system today may be characterized in terms of three major elements: hardware, software, and information.

NC software can then be segmented into two major domains and characterized as follows:

Control Software
- o operating systems
- o system control
- o I/O control
- o servo control
- o computation
- o communications

Application Software
- o specialized function
- o NC programming languages
- o NC graphics systems
- o CAM interface
- o CAD interface

This discussion will concentrate on the application software side.

Today, NC programming is usually coupled with CAD systems. However, there are a significant number of NC system vendors which interface with the major CAD systems. There are four distinct techniques commonly used to generate NC instructions.

- manual NC instruction definition
- computer-assisted NC part programming
- computer graphics-based systems interfaced to CAD
- solid modeling systems

The first two techniques are the most widely used at present, but should be displaced by graphics based systems over the next couple of years. Computer-assisted NC part programming involves the use of NC languages, and the processors and post processors that translate languages into instructions.

APT and COMPACT II are generally considered to be the most widely used NC programming languages. Each statement in an NC program is translated and analyzed by a program called a processor to produce generic tool path information called a cutter location file (CL). The CL file is then commonly passed to a post processor that converts the generic data into controller specific NC blocks.

In graphics based systems, the part programmer retrieves a component geometry from the CAD/CAM database and describes the relevant geometric elements and the tool path pictorially on a screen using interaction devices. NC software then makes all the calculations to define the tool path and display the same. After verification of tool motion and position, an NC program is generated automatically and the NC processor and post processor are invoked.

A growing number of solid modeling systems provide NC programming capabilities, particularly for more complex machining operations. Because manufacturing relies on the production and manipulation of solids, solid modelers have provided the basis for the automation of NC code generation. Solids can also provide NC verification by simulating an actual operation, in which cutter tool path data is used to "cut" (simulate cutting) a solid model. Interferences or gouges are clearly shown.

Future Technology

There are a number of trends which could have a significant impact on the numeric control area. The BCL Standard (RS494-1983. "32 Bit Binary CL Exchange (BCL) Input Format for Numerically Controlled Machines"), is an attempt to provide a standardized machine-independent format that permits different machines of similar capability in the same class to operate from the same part program. The proposed BCL exchange format requires that the following guidelines be followed to achieve part program exchangeability (Ref. 19):

- o The machine tools should be of like configuration but not necessarily the same model or built by the same manufacturer.
- o The machine should have the requisite size, rigidity, accuracy, spindle horsepower, speed, etc., to produce the parts to which the data is intended to apply.
- o Fixtures required to hold the part in the proper manner should be available for the alternative machine or for transfer with the part assignment to the alternative machine.
- o The clamp arrangement and location of clamps should be the same for the principal and alternative machines when making the part in question.
- o Tooling for the alternative machine should be available and suitable for production of the intended part.
- o The N/C units must be capable of responding correctly to BCL data format and commands as specified and as they apply to the particular machine type.
- o If a portable input medium is used for input of BCL data, the medium format must be considered.
- o If a data link is used for input of BCL data, the electrical characteristics, line control protocol, and user language must be considered.

Feature based modeling in combination with solid modeling and expert systems are the other major technologies which should impact the further automation of NC. Prototype systems currently exist which largely automate the generation of NC code for select small families of parts. Some of the major elements necessary for automated NC include:

- o feature machining rule databases (for selection of the correct machining and cutting operations)
- o machine tool libraries
- o cutting tool libraries
- o machine technology databases (for recommended cutting speeds and feed rates)

Figure 4 presents the OTA assessment of the solution of key problems in the NC machine tool area. Most of the projections presented in this figure seem reasonable with the exception of item No. 7 (widely applicable 3-D verification of NC programs using CAD-based simulations). Commercial applications of this technology have begun to appear, which should decrease the time period required for the technology to be transferred.

Computer Aided Process Planning (CAPP)

Current Technology

Process planning is defined as the process of establishing:

- the sequence of machines through which a part must be routed for manufacturing.
- the operations that should be performed on the part at each machine.
- tool, jig, and fixture selection.
- documentation of time standards associated with each operation.

Ideally, the process plan is a single document which specifies the most cost and/or time-efficient method for making a given part.

Automation of process planning has occurred because of a shortage of trained process planners, and the need for consistent routings in order to promote efficient production schedules. CAPP is touted to possess the following benefits:

- user experience level requirements are reduced
- reductions in process planning time
- standardization of manufacturing process
- improved accuracy and less troubleshooting
- increased manufacturing productivity

Concepts of group technology, discussed in the companion assessment on CIM are usually an integral part of a concerted process planning effort.

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Systems which can automatically and reliably remove a wide variety of metal chips produced in cutting[a]			▲	● ■	
Both hardware and software:					
2. Reliable, widely applicable adaptive control to optimize speed of metal removal	▲		●	■	
3. Tool wear sensors applicable to wide range of cutting tools	▲	●		■	
4. Systems for measurement of parts of a variety of shapes and sizes while the parts are being machined		▲	●	■	
Software:					
5. Controllers to accommodate ties to robots	▲	●		■	
6. Model-based machining in which the machine tool operates substantially automatically based on data about metal processes and the part to be produced		▲	●		■
7. Widely applicable 3-D verification of NC programs using CAD-based simulations ..		▲		●	■

[a]Systems currently exist for automatic removal of metal chips, but despite much interest and research, they are neither very reliable nor generically applicable (i.e., they can only be used for certain kinds of metals or cutting processes).
▲ = solution in laboratories.
● = first commercial applications.
■ = solution widely and easily available (requiring minimal custom engineering for each application).
SOURCE: OTA analysis and compilation of data from technology experts.

Figure 4. OTA Projections for Solution of Key NC Problem
Source: Computerized Manufacturing Automation, OTA, April 1984

There are currently essentially two categories of CAPP - variant or generative, with a third category being a combination or hybrid of the two. The vast majority of systems currently in use are variant, which means they are based on a library of standard plans for different part families that a process engineer retrieves and edits, creating "variants" of basic plans. There is no attempt to generate an optimum plan each time a variant is developed. When the library contains only standard plans, new part input will be close to that of manual process planning.

Generative process planning systems attempt to generate an ideal routing and associated information for a part based on information about the part and sophisticated rules about how such parts should be handled and the capabilities of machines in the plant. Generative planning systems use decision tree logic, decision table logic, or an expert system approach to arrive at an optimum plan. Generative systems based on expert systems are still in the prototype development stage.

Hybrid planning systems are generally variant at the part and production planning levels and generative at the operations planning, tooling methods, and detail levels. There is at least one firm pursuing this hybrid approach to process planning technology.

Future Technology

Feature based modeling together with development of expert system technology should have major impacts on CAPP in the coming years. Once design features have been mapped into manufacturing or process-oriented features and then into a geometry database, they can be adjusted during an analysis process in order to make optimum use of resources.

Optimized CAPP will then be able to serve as one of the principal tools for programming factories. They will interface and provide inputs to shop floor control systems and MRPII systems.

2.2 Hardware

The debate over whether hardware or software is driving the pace of development in CAD/CAM/CAE technology persists. Nevertheless, it is clear that there is a synergy between the advances being made in both areas which produces considerable momentum. This section will present a brief overview of the hardware technologies embodied in engineering workstations and NC machine tools.

2.2.1 Engineering Workstations

Current Technology

Engineering workstations are display terminals combined with significant computing power, most often in the form of 32-bit microprocessors. A typical workstation today is a machine with a 32-bit CPU, 4M to 8M main memory, 40M to 80M on-line hard disk storage, a 1024 by 800 resolution display, 10 megabyte per second networking capability and a demand paged multitasking virtual memory operating system (Ref. 6).

Several trends are clear in the workstation market:

- definite segmentation - low end (1-2 MIPS competitive with personal computers), high end (8-10 MIPS) and graphics supercomputers (16 + MIPS, $80,000). Figure 5 presents an overview of market offerings.
- push toward standardization - standard operating systems (UNIX), open architectures, standard communication facilities and interfaces (e.g., X windows)
- quantum leaps in performance/price ratios - MIP ratings have been increasing by a factor of 2 every 2 to 3 years
- increasing use of RISC (reduced instruction set computer concepts) and multiple parallel processors
- 64 bit architectures are appearing in the super class machines

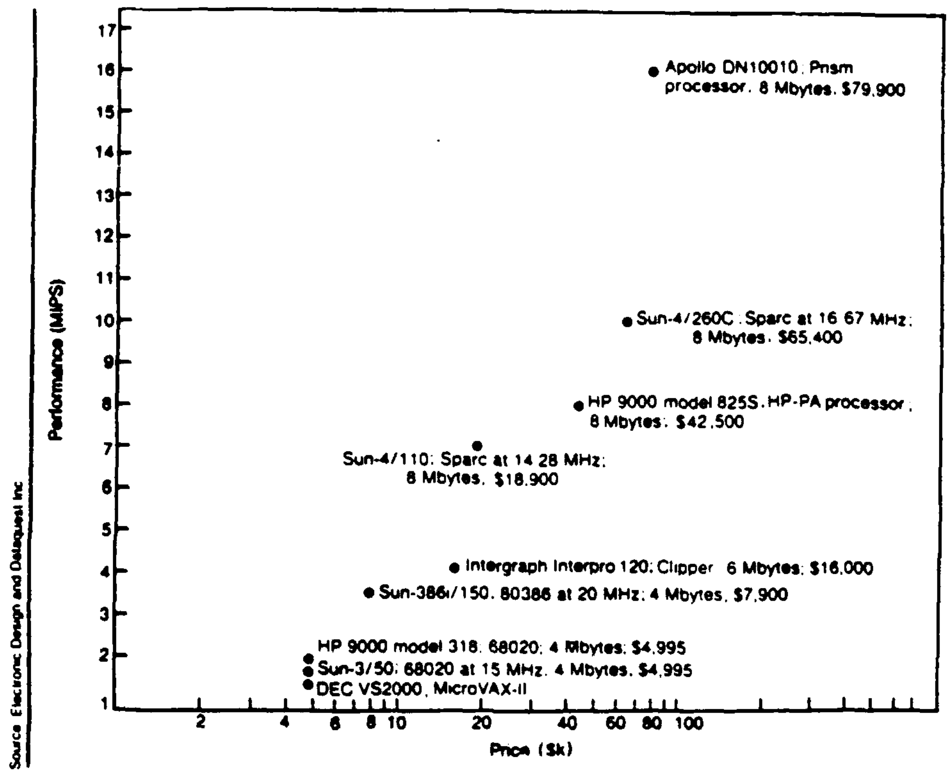

Figure 5. Workstation Price ($K) vs. Performance (MIPS)

Source: <u>Electronic Design</u> - June 9, 1988

The newest niche players in the workstation market are those vendors offering machines which couple the computational speed of a supercomputer with high performance graphics, but are priced and packaged like technical workstations.

Future Technology

The trends enumerated in the current technology section are expected to continue. In addition, there will be a growing use of specialized hardware (e.g., dedicated accelerators, graphics processors, memory management units, high-speed system buses). Projections have been made of 100-MIPS workstations by 1992.

2.2.2 Numeric Control Machine Tools

Current Technology

Considered to be a mature technology, Numeric Control (NC) machines combine electronic hardware with increasingly sophisticated software to span a number of application areas, from machining of metal parts, to placement of integrated circuits, to inspection of mechanical and electronic components. NC machines are comprised of a microprocessor based control system, a servo system that includes transducers to measure speed, motion, etc., activation devices for accurate positioning and motion; and application specific mechanical and electronic peripherals. Most NC systems today are computer based, termed Computer Numerical Control (CNC). However, there is no typical hardware architecture for a CNC machine. With the development and growth of local area networks within factories, numeric control has progressed into the distributed realm - termed DNC (direct or distributed numeric control), with a CNC system forming a node on the network.

There are currently two general classes of machine tools - machining centers and turning centers. Machining centers generally operate with a stationary workpiece and a rotating tool. Drilling, milling, and boring operations are primarily performed on these machines. Turning centers typically have rotating work and a stationary tool. They are primarily used to do internal and external turning, drilling, and threading.

Both classes of machines can be equipped with automatic tool-changing devices, automatic work loading, operating condition sensors and measuring devices. NC is also being applied to special cutting and finishing processes (e.g., gear cutting, shearing, punching, etc.) and is beginning to appear in punch presses and other types of presses used for sheet metal fabrication. Several new cutting technologies are also beginning to impact on NC technology, including electrical discharge machining and lasers.

Future Technology

The future of NC machine tools will be impacted by parallel development in materials, tooling, fixturing, sensors, communications and artificial intelligence. The major trends in the materials area include:

- increased use of warm and cold formed steel parts with emphasis on near-net-shape processes
- increased superplastic forming in aerospace manufacturing
- continued progress in development of metal matrix composites
- increased use of high-technology ceramics

Niche machines may evolve to accommodate the properties of different groups of materials. Tooling is also being impacted by development in material science. As combinations of materials and coatings produce more tooling options, the variety and volume of tooling requirements can be expected to grow. With this growth, tool changing and management remains a problem. Coolant and chip management are also areas receiving increased attention as increases in accuracy and productivity are demanded.

Fixtures hold and locate a part being worked during machining and assembly operations. Characteristics of a fixture depend on the process being performed, the shape of the part, and the tolerances required. The need for a large number of fixtures remains a problem even for flexible manufacturing systems. Although there are a number of research efforts devoted to solving the problem of flexible fixturing, none seems to offer the flexibility needed in terms of variety of applications, the types and sizes of parts that can be held, and expense.

Sensor technology is also a very active area of research. Research areas holding promise for manufacturing include: micromechanics, three-dimensional vision for depth sensing, and development of intelligent sensors capable of processing and interpreting data. Immediate attention is being devoted to sensors which monitor the workpiece, tooling, and machine to prevent failure.

Future CAM architectures, through developments in communications and controller technology, will integrate NC data with other manufacturing information. NC will evolve from a stand-alone device to one component in an intelligent manufacturing cell. Note that a major government sponsored research program is being launched to develop a next generation controller which will incorporate major advances in artificial intelligence. During the interim, controls are becoming less hardware sensitive and much more software sensitive.

3.0 SUMMARY

Figure 6 presents a summary of the major findings of the technology assessment.

3.1 Software

Mechanical Design

Current mechanical design systems provide capabilities in automated drafting, geometric modeling, wire frame modeling, surface modeling, and solid modeling. The future of mechanical design systems will be significantly influenced by the integration of features into solid models, along with the migration of vendors from proprietary databases toward relational/object-oriented databases and eventually to a common data model (PDES). Feature based modelers will be available on a general basis in the 5-10 year time frame. These trends will assist the integration of CAD and CAM, while development of expert systems decreases the skill level and amount of manual effort necessary.

Mechanical Computer Aided Engineering (MCAE)

MCAE systems are geared toward providing the engineer with tools necessary to optimize design prior to the drafting or verification/prototyping stage. Still in its infancy as a distinct technology, MCAE systems are attempting to bring specialized knowledge and capabilities to the generalized engineer by utilizing expert system/AI techniques. Although commercial systems have been developed to assist with finite element modeling and manufacturing cost estimation, the pace of development in this area appears slow. OTA projects comprehensive, powerful systems widely and easily available only after the year 2000.

Electronic/Electrical Computer Aided Engineering (ECAE)

ECAE tools are considerably more advanced than MCAE today. Tools exist to address the entire electronic product design cycle from initial concept to production. ECAE technology is projected to evolve along the same lines it has followed, further integrating the design to production cycle. Advances in electronic technology will force ECAE vendors to develop tool sets in the areas of: surface mount technology, analog design, high-frequency design, hybrid devices, and others.

HARDWARE/SOFTWARE	CURRENT TECHNOLOGY	FUTURE TECHNOLOGY
	DESIGN	
o MECHANICAL	o WIREFRAME/SURFACE MODELS	o FEATURE-BASED PRODUCT MODEL o INTEGRATED SOLID MODELS
o ELECTRONIC	o PCBs, ICs, ANALYSIS	o TOOLSETS (SURFACE MOUNT/HYBRIDS)
o ENG. WORKSTATIONS	o 32 BIT CPU o LOW END = 1-2 MIPS o HIGH END = 8-10 MIPS	o STD OP. SYSTEM, ARCHITECT, INTERFACES o ↑ MIPS ↓ PRICE (100 MIPS-1992)
	MANUFACTURING	
o NUMERIC CONTROL (NC)	o LITTLE INTEGRATION o CONSIDERABLE MANUAL EFFORT	o FEATURE-BASED/SOLID MODELS o GRAPHIC-BASED EXPERT SYSTEMS
o COMPUTER-AIDED PROCESS PLANNING	o GENERATE VARIANTS OF STANDARD PLANS o MINIMAL CAD/CAM INTEGRATION	o GENERATE PLANS TO OPTIMIZE RESOURCES o FEATURE-BASED MODELING/EXPERT SYSTEMS
o NC MACHINE TOOLS	o MACHINING AND TURNING CENTERS o CNC	o NEW MATERIALS-COMPOSITES, o CERAMICS, ETC. o DNC

Figure 6. CAD/CAM/CAE Technology Assessment
Summary of Major Findings

Numeric Control (NC)

NC programming is usually coupled with mechanical design systems today. Graphics based systems along with solid modeling systems are decreasing the amount of manual effort required to generate numeric codes. The further automation of NC code generation is dependent on development of feature based modeling in combination with solid modeling and expert systems. OTA projects model-based machining to be widely and easily available only after the year 2000.

Computer Aided Process Planning (CAPP)

Touted as a necessary bridge between CAD and CAM, computer aided process planning can take essentially one of two forms - variant or generative. The vast majority of systems currently in use are variant, which means they are based on a library of standard plans for different part families that a process engineer retrieves and edits, creating a "variant" of a basic plan. The second form of planning systems, termed generative, will become more widely available as feature based modeling systems appear. Generative systems attempt to optimize the use of resources by generating efficient routings. These systems are principal tools for programming factories.

3.2 Hardware

Engineering Workstations

A typical workstation today is a machine with a 32-bit CPU, 4M to 8M main memory, 40M to 80M on-line hard disc, 1024 by 800 resolution display, 10 megabyte per second networking capability and a demand paged multitasking virtual memory operating system. Trends in the workstation market point to: increasing performance/price rations (MIP ratings increasing by a factor of 2 every 2 to 3 years); increasing standardization (operating systems (UNIX), open architectures, communications and interfaces (X windows); increasing segmentation (low end, high end, and graphics supercomputers). Projections have been made of 100-MIPS workstations by 1992.

Numeric Control Machine Tools

Numeric Control (NC) machine tools span a number of application areas from machining of metal parts, to placement of integrated circuits, to inspection of mechanical and electronic components. Most NC systems today are computer based. NC machine tools technology will be impacted by parallel development in materials, tooling, fixturing, sensors, communications, and artificial intelligence.

References

1. Herskovitz, S., "Software for Defense and Aerospace", Journal of Electronic Defense, May 1988

2. Marks, P., "What Do Solid Models Need?", Machine Design, March 12, 1987

3. Mills, R., "Sorting Out Solid Modelers", CAE, May 1988

4. "CAD/CAM Accelerates", Managing Automation, May 1988

5. "CAD/CAM Reference Issue", Machine Design, June 19, 1986

6. Killmon, P., "Technical Workstations", Government Computer News, February 5, 1988

7. Costea, I., "The Interaction of Computer Graphics and Artificial Intelligence/Expert Systems", National Computer Graphics Association Conference Proceedings 1988 (NCGA '88)

8. Villers, P., "Computer-Aided Engineering for Mechanical Engineeers, Applying New Technology", NCGA '88

9. Atkinson, A. & J. R. Lindberg, "CAPP Enables Concurrent Design and Manufacturability Analysis", NCGA '88

10. Loughlin, C., "Feature-Based Modeling", NCGA '88

11. Hogan, J., "The Marriage Between Solid Modeling and Finite Element Technologies", NCGA '88

12. Orr, J., "Mechanical CADD for Beginners", NCGA '88

13. Chasen, S., "Integrating CAD/CAM/CAE/CIM, "The Organization-Strategies, Experiences, Benefits", NCGA '88

14. Lerner, E., "Linking Islands of Automation", Aerospace America, February 1988

15. McLean, C. and P. Brown, "Process Planning in the AMRF", CIM Technology, August 1987

16. Mills, R., "Linking CAD and CAM", CAE, September 1987

17. Martin, J., "CIM What the Future Holds", Manufacturing Engineering, January 1988

18. Schaffer, G., "Autofact: "More CAD/CAM than CIM", January 1988

19. Bacheler, A., "EIA and ISO Numerical Control Standards for Automated Manufacturing Systems", ASTM STP 862, L.B. Gardner, Ed., American Society for Testing and Materials, Philadelphia, 1985.

20. Bhalla, S. and E. Williams, "DEC Connects CAD to CAM", CAE, October 1987

21. Murray, J., "CIM - Plan Top Down, Implement Bottom Up", Control Engineering, April 1988

22. Lyons, E., "Solids and Surfaces", Computer Graphics World, June 1988

23. Ketabchi, M., "A Matrix of CAD Applications Requirements/DBMS Capabilities", Dept. of Electrical Engineering - Santa Clara University, Santa Clara, CA 95053

24. Shah, J. and M. Rogers, "Functional Requirements and Conceptual Design of the Feature - Based Modeling System, Computer-Aided Engineering Journal, February 1988

25. Milne, B., "Design Automation Comes to Electronic System Packaging", Electronic Design, February 4, 1988

26. Anastasi, R., "An Overview of Trends in Computer Aided Design", Electronic Manufacturing, March 1988

27. Goering, R., "Logic-synthesis Tools Forge Link Between Behavior and Structure", Computer Design, June 1, 1988

28. Rapid Acquisition of Manufactured Parts (RAMP) Test and Integration Facility (RTIF) Technology Assessment Report, November 26, 1986

29. United Technologies Corporation, Geometric Modeling Applications Interface Program - State-of-the-Art Document, March 1987

30. U.S. Congress Office of Technology Assessment, "Computerized Manufacturing Automation, April 1980

31. Manufacturing Studies Board, Toward a New Era in U.S. Manufacturing, 1986

32. National Academy of Engineering, Design and Analysis of Integrated Manufacturing Systems, 1988