NEW DIRECTIONS THROUGH CAD/CAM

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This book is dedicated to
Ernest V. Fenn
a champion in every sense of the word.

Foreword

Those of us who are active in manufacturing today have both a real privilege, and a real challenge facing us. We are witnesses to, can participate in, and may contribute to the most rapid evolution of a technology in history. Never before has a technology made such rapid growth as the growth made by CAD/CAM. This book provides a solid foundation of CAD/CAM information for those involved in the field or those who will be involved in CAD/CAM in the near future.

William D. Beeby and Phyllis K. Collier have collected in one volume the current state of the art, a discussion of its management and justification, and examples of its use.

I know of no one better qualified to speak on this subject than William Beeby. He joined Boeing Aircraft after service in the Air Force during World War II, to become lead engineer for B-47 liaison. By 1956, he was senior group engineer at Boeing Wichita, supervising production design of the Bomarc missile structure. When it came time to make the transition from design to production, Beeby's experience in both design and production made him the choice to head the project.

The 1956 era was also the time when numerically controlled machine tools were being introduced to the world of aerospace manufacture, and that too was assigned to Beeby at Boeing. He has been one of the leaders in the introduction of computers into manufacturing. And, as we now know, NC tools proved that computers could survive on the shop floor, that they could control machinery, and that manufacturing engineers could control them. From this beginning, data processing technology spread to many corners of the manufacturing world, and concurrently to the world of design. By a curious inversion, NC became a part of CAM, rather than its parent; and CAM and CAD have become so closely intertwined that they are—in reality—one. William Beeby has witnessed and contributed to this integration of the science of manufacturing through the medium of data communication.

To recognize this diversity of background, this wealth of knowledge, and this rich list of achievements, *American Machinist* magazine presented William D. Beeby with the 1981 AM Award. Now retired, he has taken time to share his wisdom with the rest of us.

New Directions Through CAD/CAM first provides us with an introduction to CAD/CAM—what it is, what its history has been, and how it developed. The book looks ahead to what it may contribute to American industry. It then presents a richly documented and clearly explained statement of just what it is all about—the tools, the technology, and the standards. The authors cite examples to illustrate their points, with names, places, and accomplishments. The reader begins to feel more comfortable with the terminology and the fields of application.

Then in three fact-packed chapters, the book discusses the computer-aided design side of the subject, then the computer-aided manufacturing side of the subject, and third, the vital tie between the two sides. I found the many concrete examples, documented with information on the equipment used, the problems encountered and solved, and the increases in productivity achieved, to be particularly interesting. It is clear that the authors have been there themselves and know whereof they speak.

The subject of computer-integrated manufacturing lies close to my heart, and I am honored that Bill Beeby and Phyllis K. Collier see eye to eye with me that the integration of the many parts of manufacturing is the element of greatest significance, and the one fact that holds the greatest import for the future. The science of manufacturing is a tremendously complex structure, every part connected to and interacting with every other part. The single common thread running throughout the whole is the fact that everything done in manufacturing, from design concept straight through to field support of the product, may be expressed in the form of data that may be handled on a computer. Add to this the exponential rate of growth of our data processing capabilities, and it is easy to see why this evolutionary explosion is taking place at this time.

But *New Directions Through CAD/CAM* tells us something more about integration. It points out the importance of people in this field, and the need to integrate them, too, into the structure. They must be carefully selected, trained, and provided with a working ambience suited to the new kinds of work that they are to do. And they must be managed in an appropriate manner. This means that the managers, too, must change their methods of thought as well as their methods of leadership. This widens our mental horizon to a wholly new level of integration, the interaction of humans and computer technology, for indeed they do have to interact. The authors have the experience to tell us, clearly and quantitatively, how this is to be accomplished.

We hear a great deal these days about how the Japanese are running away with the ballgame. Are their methods applicable to our people, our products, and our technology? I am happy to say that we are not invited to copy the Japanese doctrines. In their final chapter Beeby and Collier discuss what our proper goals and directions should be, the concerns which face management, the impact of corporate strategy on CIM and vice versa, and the immediate tasks before us.

Old or young, experienced or novice, craftsman or supervisor, labor or management, we can all find this book valuable. To paraphrase the American Express Card motto, "Don't start into CAD/CAM without first reading this book."

Joseph Harrington, Jr., Sc.D.

Preface

For nearly a decade, computer-aided design and computer-aided manufacturing have been touted by industry as the phenomena that will overcome the productivity stagnation that has been blamed for hampering the ability of American industry to stay competitive. CAD/CAM technology, which was pioneered and developed in the U.S., has rocked industry and caused profound change both here and in other countries.

In this book we have attempted to define and depict the techniques, advantages and rudiments of CAD/CAM and to delve into its brief but fascinating history and its impact on the American factory.

How are companies using this revolutionary newcomer that has made its way into the hard-nosed and usually conservative arena of the American factory? What kinds of companies have embarked on CAD/CAM projects, and to what extent and level? How are the people affected? What are CAD/CAM's beginnings?

Insofar as it is possible to develop an anthology of companies' work with CAD/CAM and despite the fact that no "typical" company exists, we have addressed the foregoing questions so that any serious student of CAD/CAM technology might gain a greater insight into the trials and errors, the lessons learned, and the required steps to achieve success with CAD/CAM. We hope that the final benefit that those planning to use CAD/CAM may derive from this book is the confidence, courage, and knowledge they will need.

Based on these objectives, the book has been organized to include a history of the various aspects of CAD/CAM, a description of the tools and the companies using them, the people who use them and how their work-lives have changed, and how-to guidance for getting started and continuing with a CAD/CAM system.

Although many books and trade journal articles have focused on individual areas within CAD/CAM, and although bringing together all of the many facets of CAD/CAM into one descriptive volume looms as a herculean task, our hope is to put away the idea that CAD/CAM is any one of its individual efforts, such as graphics, numerical control, or robots alone. Rather, the book's more ambitious goal is to shed some light on all of its most interesting and absorbing activities.

William D. Beeby
Phyllis K. Collier

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The Phenomenon of CAD/CAM

Competition among American and foreign industries has accelerated to a rapid rate, as has competition among makers and vendors of computers. Trying to keep up-to-date with the blitz of information regarding equipment, capabilities, processes, and software development of computer-aided design, computer-aided manufacturing, and the integration of both disciplines—for they have evolved into a maxidiscipline—is akin to trying to keep pace with a meteor.

Along with the blitz of information a new vocabulary has arrived, a unique language of high-tech jargon and acronyms. Neophyte users of CAD/CAM must first learn to break down the acronym list in order to know what OEM, CIM, CAE, CAPP, DEC, CDC, CV, VAX, CADAM, CAQA, CAD, CAT, and MRP mean. And unless newcomers have worked around a CAD/CAM user group and have picked up terms such as turnkey, solid modeling, picojoule, peripheral, refresh, pixel, and raster, they keep a glossary close by. The first job of the describer is to demystify CAD/CAM. The exercise of selecting a system or systems to use in a design or manufacturing milieu is complicated enough without fancy and confusing descriptions. Unfortunately, in the past, circumlocution has been one of the bywords of much of the literature. (Over the past few years, many companies and groups have attempted production of glossaries which have usually met with disagreements because of the varied and changing definitions of terms.)

A History

Thirty-five years ago when ENIAC, the first digital computer, performed ballistics calculations for the Army at 300 multiplications per second, no one could have predicted computers that could operate at four-and-a-half million multiplications per second, or 15,000 times faster than ENIAC. Nor could one have predicted the rise in semiconductor growth from 100 devices per chip in 1970 to more than 100,000 in 1980, with an intelligent prediction of one million in 1985.

The emergence of the microprocessor business has served as the prime contributor to CAD/CAM's growth. One million microprocessor units were sold in 1975; in 1983 that unit number increased to 295 million. In 1982, total revenues for turnkey CAD/CAM systems in the United States passed the $1 billion mark; revenues exceeded

$1.7 billion in 1983. As recently as 1979, total revenues amounted to only $330 million—and this, after sales were made relatively soft due to the recession. U.S. industry revenues advanced a mere 44% from 1981 to 1982, down from a 68% growth rate during 1980. The market saw another decline in growth rate down to 37% in 1982, before revenues climbed again to a 40% growth in 1983.

CAD/CAM is not only big business for the present, but is a business that continues to grow, at least for the foreseeable future. But just what, exactly, are companies getting for this heavy capital expenditure? What is the scope of the proliferation of CAD/CAM equipment across the country? Examples within this book will answer these questions. Consider, however, the following.

If we were able to view a map of the United States, with tiny red lights that would glow, one for each CAD/CAM work station in use, our faces would take on a rosy glow from the 20,000-plus lights burning. At the end of 1979, we would have reflected a pale pink by comparison from the 7,500 work stations at that time, growing, by the end of 1985, to 75,000. Keep in mind, however, this illustrates activity rather than productivity (which varies from application to application).

The major businesses that use CAD/CAM are aerospace, automotive, and architectural businesses, but they are by no means the exclusive users. It could be said that they have performed a pioneering role in its development. CAD/CAM is used in such industries as diamond cutting, plant engineering, nuclear physics, geological sciences, architecture and mapping, metals processing, electrical batteries, molded plastics, motion pictures, needlework, microwave integrated circuits, farm and lawn machinery, piping design, municipal planning, and shipbuilding, just to name a few. And, manufacturers of CAD/CAM equipment use CAD/CAM themselves. Examples of CAD/CAM use in the aerospace and automotive industries are the shuttle tile analysis program that calculated stresses and deflections based on orbiter/tile geometry, loads data, and material properties; and General Motors' Fisher Body Cadillac design, which was produced in 29 months—about a third less than the time usually required for development alone.

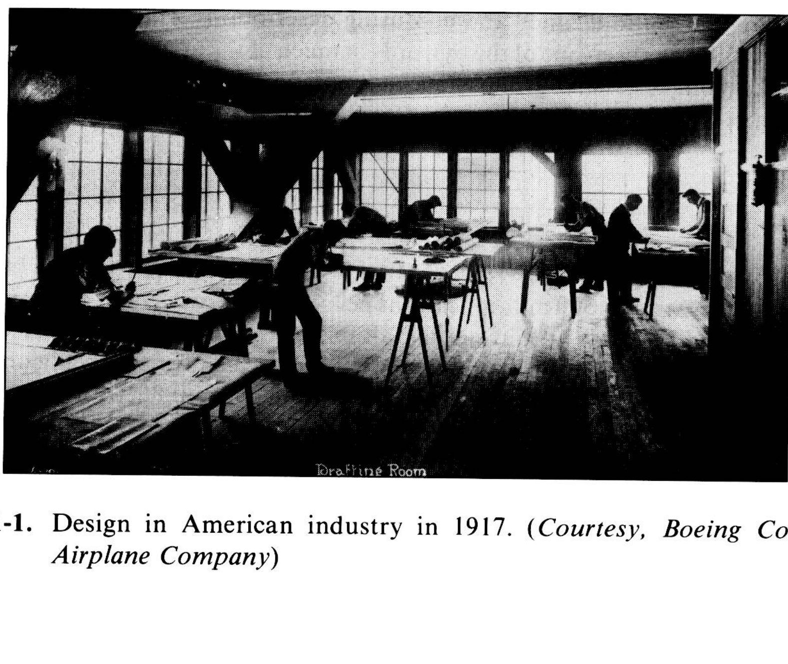

Figure 1-1. Design in American industry in 1917. (*Courtesy, Boeing Commercial Airplane Company*)

Figure 1-2. Design environment in the 1960s. (*Courtesy, Boeing Commercial Airplane Company*)

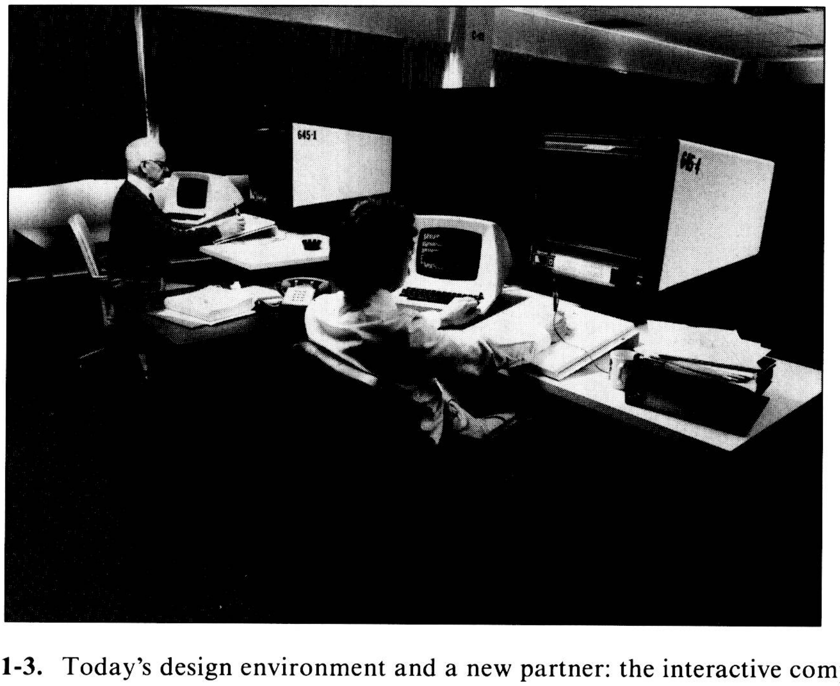

Figure 1-3. Today's design environment and a new partner: the interactive computer. (*Courtesy, Boeing Commercial Airplane Company*)

What CAD/CAM Comprises

Although such continuous-process industries as petroleum refining, paper-making, steel-making, and plastics use computers in their design and manufacture, by far the greatest users are the makers of discretely processed products, such as computers and components of computers, aircraft, automobiles, furniture, and electronic instruments. In making such products, the same techniques for designing, analyzing, cutting and assembling can be applied. The major problem has rested in coordinating the various disciplines, from preliminary design to final assembly, in the flow of information, not in the processes themselves.

Figure 1-4. Building the mockup for the Boeing 757 and one of the greatest users of CAD/CAM for discrete-process production: the aerospace industry. (*Courtesy, Boeing Commercial Airplane Company*)

Definitions

A series of processes, CAD/CAM is more than one kind of a computer, or even one system. These processes encompass designing, drafting, analyzing, tooling, cutting, assembling, and keeping records on a product.

CAD/CAM is defined elsewhere as "the application of computers to design where the designer converses directly with the computer by using a graphic or nongraphic console in such a manner that problem-solving processes are highly responsive and essentially uninterrupted." But then, the whole process of batch CAD, which is distinctly noninteractive, is neglected.

CAD/CAM is a broad term encompassing the use of computer systems for design and manufacturing purposes, and for communicating design and manufacturing information. All CAD/CAM applications use (to varying degrees) the three special computer functions of interaction, graphical visualization, and large-scale data communication. Most add the special attributes of batch programming for families of parts, lofting processes, and numerical control (NC) programming.

The CAD/CAM Process

Trying to describe a typical CAD/CAM system is similar to describing a typical human being. Although certain similarities in flow of data and uses of processes and equipment exist, there are many variations in information flow, component parts, and process integration. To make an understanding of the CAD/CAM process clearer, this book has been organized more or less in the order that factory processes occur, from the earliest stages of product conceptualization to the delivery of process information, dividing the processes into the two major divisions of computer-aided design and computer-aided manufacturing.

Though each of the various systems in the network may have its own method of representing data, eventually all must pass the information along to the next system in the process. Often, autonomous systems exist whose data must be translated before they can be transmitted. Manual systems often stand between automated systems. The ideal computer-integrated system shares common languages and achieves a smooth flow between and among all processes.

But this ideal has been achieved by few companies. The process of data flow typically begins with master dimensions data captured from surface parametric drawings based on the product design requirements. These definitions prepare data that are called on for subsequent definitions of the individual parts of the product. Ideally, this process supplants the need for physical master models. Using application programs created with high-level languages such as automatically programmed tool (APT) or FORTRAN, parts that have been entered into the system can be displayed and manipulated using interactive graphics devices to display and plot the parts. The next step converts the part geometry into machine-sensible data for numerical control processing in the factory. It is this step that crosses the line from CAD to CAM and that has been the most difficult transition to make efficiently. Once transferred, the geometry can be used for tooling, template making, machining, fabrication, and assembly of the product.

Other peripheral systems come into play: cost, inventory, and order entry systems; online planning; plant engineering; materials handling; electrical wiring schematics, and so forth, using data generated by the design group and revised and updated all along.

Ideally, the data are available on a central database management system for all who need to access them.

Development

On an individual level, the computer has greatly affected our lives. Over the past 20-plus years, we have progressed from using pencils, slide rules, and unwieldy mechanical calculators to hand-sized calculators to do our desk mathematics, from the drawing table and ink to the graphics computer to do much of our design and drafting work, and from the manually operated template and parts-maker to automated machinery to cut out templates, parts, and tools.

The Beginnings

The term computer-aided design became recognized following work on multiaccess computing activities at MIT in the late 1950s. Structural design and part programming for NC machining were explored in aerospace applications in the 1960s. The digital computer and the aerospace industry are, in fact, contempories and both have played an important part in their mutual development. This dual technological development brought about a total re-evaluation of relationships within the aerospace industry, and more recently among competing aerospace companies and among the companies who use CAD/CAM.

An example of early use came about in the 1960s when Landis Tool Division of Litton Industries developed the master cams used in grinders for internal-combustion engine crankshafts. Machinists tooled parts from figures supplied by the customer and inserted them in a program that produced an NC tape. The tape then operated a jig grinder to produce the master cams. No drawing was produced in the process.

The history of machine tools goes back as far as the 14th Century, when Giovanni DeDondi proposed a mechanical-weight-driven clock. During the industrial revolution, James Watt, with his development of the steam engine, and Eli Whitney, with his modular-built musket, contributed to the evolution of machine tools.

But it was not until the late 1940s, when John T. Parsons devised an automatic machine control method that would cause a milling cutter to make a smooth curve that numerical control began. Parsons conceived that if coordinate points along a curve could be coded onto punched cards that were fed into a controller, the milling machine would move along that path incrementally. The servomechanisms laboratory at MIT used a system based on Parson's idea to develop a workable NC system for the U.S. Air Force in 1949.

The aviation industry was one of the first serious pioneers to use numerical control in a production mode. Each advancement in aircraft design demanded ever-increasing complexity of shapes and fabrication tolerances. In August 1957, after two years of study and preparation, the Boeing Airplane Company began using the new technology at the Wichita, Kansas plant. Boeing assembled a team of engineers, mathematicians, machine planners, tool designers, and computer programmers to develop the first of the company's programs for the new numerical system. If the airplanes designed and built today were to be built without the use of NC, they might be so expensive as to preclude their practical use by commercial airlines. Likewise, if the original NC pioneers had not achieved early success in the application of this technology, the aircraft industry would have missed the window through which to competitively enter the commercial market.

One user of numerical control in the early days described the bizarre flow of data through the NC processes. "Precautions had to be taken in shipment of the magnetic tapes from Wichita. Static from the airplane could cause a depolarization of the tape, which would cause delays and questions of NC's merit. There were no standards; each manufacturer could create its own control system."

Another early NC pioneer remembered: "Today NC is one almost indistinguishable step in a highly sophisticated integrated system known to us as CAD/CAM. It was not always so. At one time, the task looked nearly impossible to these people. The largest computer they had to work with was scarcely more powerful than a good microcomputer today."

By 1957, NC was used in production, but the programming method had many flaws. In the late 1950s, the Illinois Institute of Technology Research Institute, or IITRI, perfected a process, which MIT developed, called automatically programmed tool, or APT, to expedite input to the cutter. APT is a symbolic language by which the programmer can specify mathematical relationships of parts. In the 1960s, APT programming began widespread use in industry.

In 1961, Boeing tooling began using APT to make punched tapes to cut tools. The language is still called APT. Cutting instructions are recorded on a paper or mylar tape with tiny holes, (such as those on the rolls of a player piano). The end result is a numerical control-produced part. The APT language could instruct the cutter which direction to go, how far, and exactly how to cut the part. But, initially, the machining capabilities of APT were limited to two-dimensional circles and straight lines.

The evolution of numerically controlled production of parts using APT continued along a rocky path, taking a long time to gain acceptance by shop and management personnel. This innovative system required such a heavy outlay of capital funds that many managers had to be shown, beyond all doubt, that it would work in a real time, production environment. The process itself, unlike the noise and clangor of the shop, was quiet, an atmosphere that caused potential users to view it with skepticism. Managers who had been accustomed to the smash-and-bang environment of a machine tool shop found it difficult to wait for a computer to perform. But early productivity gains, though small compared to those achieved more recently, eventually won over the skeptical.

NC Improvements

All the time that NC users were improving the performance of programs, hardware was being improved on a parallel path. Hardware technology focused on improving systems and machine tools. By 1965, sophisticated NC machines and control systems were available for every major machine tool configuration.

Software development saw even greater progress, adapting the APT language to other applications, branching out to other disciplines such as creating drawings, and crossing over the line between shop and design.

In the late 1960s, it was found that APT could be used to make calculations, saving workhours in writing mathematical formulas. Then in 1973, Boeing engineers borrowed from manufacturing to convert the capabilities of APT programming to create a variation of the language that they could use to produce drawings. Using a pen instead of a cutter for a tool, this crew of programmers began building a database of APT programs. Such pioneers in the APT programming realm designed wing inspar ribs, leading edge ribs, and body frames. These programs were the ancestors of a family of computer-drawn parts that designers for later models of airplanes would adopt and borrow.

One of the discoveries made in this early venture was that computer aid could produce the most accurate tooling any production program had ever experienced. Computer-defined geometry allowed prototype assemblies to be built without the use of unplanned shims.

Lofting

In ancient times, the Vikings designed their ships full size on loft floors, as later aircraft loftsmen did their airplanes using long, flexible splines. Woodworkers in the airplane factories then carved a wind tunnel model in mahogany, asked the project engineer to check it, then blended and faired it by hand to fit the spline. It was a feel that was once manual, and has now gone into a computer.

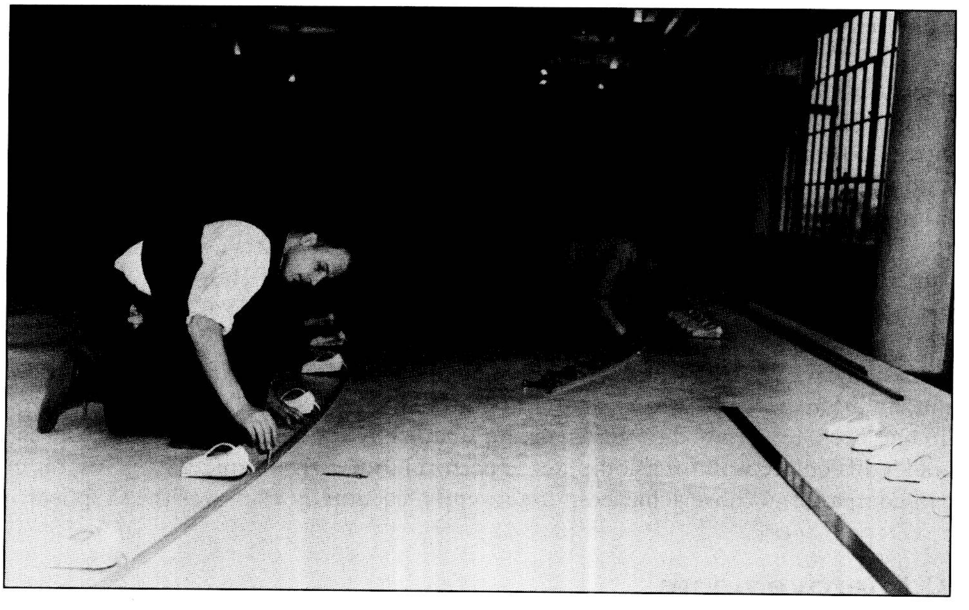

Figure 1-5. With "ducks" and splines, loftsmen drew full-size contours of airplanes in the late 1930s. (*Courtesy, Boeing Commercial Airplane Company*)

In 1961, industry began developing and using automated mathematical surface geometry systems. These systems amounted to a collection of computer programs that helped users create a mathematical model defined in geometric shapes from which a variety of detailed data could be derived. These systems, sometimes called "master dimension," simulate the two-dimensional graphic approach of traditional mathematical lofting techniques.

Enhancements to the APT language and to the process were gradually added, including a Boeing-developed supplementary capability called APT-loft (APTLFT), which has become, like its parent language APT, an industry standard. The APT-loft program reads master dimensions geometry directly into the APT system, bypassing another manual step of entering points extracted from a drawing.