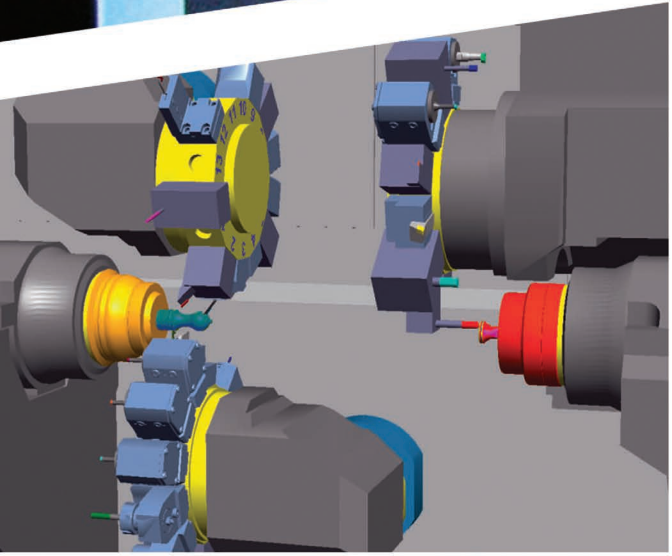

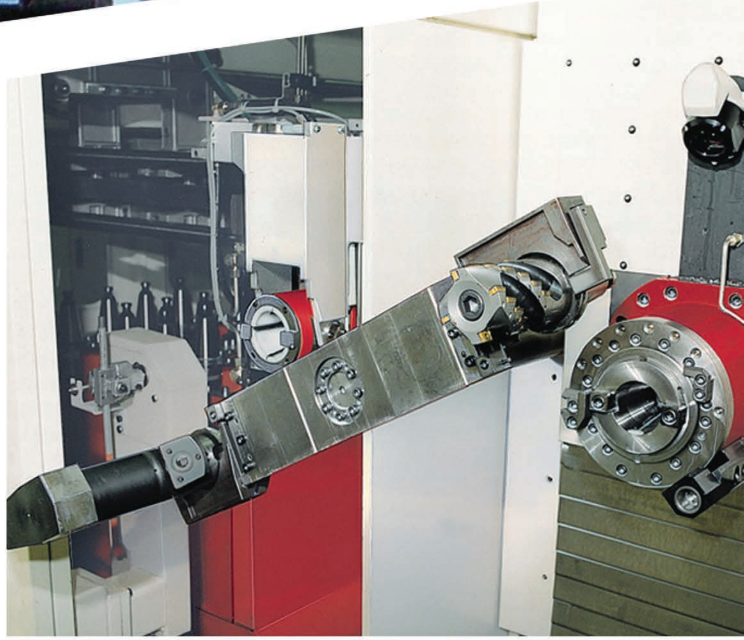

CNC HANDBOOK

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McGraw Hill

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Preface

Since 1976 the German *CNC Handbook* has kept pace with the rapid transition from NC to CNC and the emergence of new technologies. Each new development has been described as it appeared. As a result the range of topics covered by the book has been expanded more and more. In order to meet the needs of readers with various levels of existing knowledge, the introductory chapters have been tightened up, the contents of the chapters on punching/nibbling, laser technology, and generative manufacturing methods have been updated, and the subject of energy efficiency has been added.

NC/CNC: Both terms are used in industry and in the literature. Today, up-to-date products are all CNC systems, CNC hardware, or CNC machines. It is still common, however, to speak of NC technology, NC programs, and NC programming—as we have done in this book.

CNC machines and mechatronics: Machine tools are in themselves already highly developed mechanical systems. CNC machines, flexible manufacturing systems, and robots are based on the close interaction of mechanical, electronic, and IT elements. As such, they are typical examples of highly complex mechatronic systems. In addition, there are process measurement technologies, CAD/CAM programming, and data network technology. Computers and CNC systems are command centers for automated production processes. They contain intelligent functions in the form of software that costs almost as much as the hardware.

People: When it comes to digitally controlled manufacturing systems, human beings—from mechatronics technicians to managers—are still essential to perform important and responsible tasks. It is also vital for them to know the functions of the individual mechatronic components and to understand how they interact in a complete functioning system.

Thanks to our contributors: It is no longer possible today for any one author to master all of the specialized areas related to CNC in detail and to describe them at a basic level as well as at a highly sophisticated technical level. We therefore would like to thank all of our contributors for the excellent support they have provided in developing new chapters and illustrations. It is our goal not only to give our readers an overall survey of the wide field of digital manufacturing technology, but also to provide them with the necessary fundamental knowledge.

We also thank all of our **reviewers and critics** for their suggestions. These have enabled us to make continual improvements in each new edition.

Hans B. Kief *Helmut A. Roschiwal*

About the Authors

Hans B. Kief is acknowledged as one of the world's leading experts in the fields of CNC manufacturing and computer-controlled flexible manufacturing systems (FMS). He has worked as a consultant in the manufacturing industry, having developed CNC reliability software for the aircraft and automobile industries, and has traveled widely in his professional capacity through the United States and Europe. Mr. Kief has a degree in electrical engineering, founded the German NC Society, and has held memberships of the Society of Manufacturing Engineers (SME), the Computer and Automated Systems Association (CASA), and the American NC Society.

Helmut A. Roschiwal began his career as an apprentice to a toolmaker. He went on to earn his mechanical engineering degree and start his own mechanical engineering product development company: Roschiwal+Partner offers development services and design engineering to customer specifications (especially in the area of CNC machine tools) and has subsidiaries in Germany and Romania.

Part 1

Introduction to CNC Technology

1. Historical Development of Numerical Control Production

A look back on the introduction and development of numerical control (NC) technology shows that it was not just technical aspects that played an important role. Correct and incorrect management decisions, the beginning of globalization, and especially the Japanese challenge also were major factors influencing the overall changes in the market and the manufacturing field as a whole.

1.1 Germany after World War II

1945–1948: All manufacturing facilities in Germany were destroyed or unusable and in some cases dismantled and sent abroad as war reparations. Production was completely crippled.

The inner cities had been devastated and were largely uninhabitable; millions of tons of rubble blocked the streets and other transportation infrastructure. Electricity, gas, and water supplies were barely functioning, and with a few minor exceptions, industrial production was impossible.

1948 (currency reform)–1955: The machine tool and manufacturing industry was rebuilt, primarily on the basis of previously existing concepts. During the war and shortly thereafter, the development of new machine concepts was not possible.

Most machines were designed for manual operation, but there was a lack of experienced, skilled workers. The few machines that were still available were busy producing urgently needed mass-produced articles.

The demand for goods was practically unlimited. The existing machines operated in two or three shifts. New jobs were created, but there were not enough workers. Over 2 million German men had been killed in the war, and over 6 million were wounded, sick, or still held as prisoners of war (POWs).

The solution was "guest workers." They came from all the countries of Western Europe. There was plenty of work to be done.

The goal: To rebuild the destroyed cities, factories, bridges, houses, streets, and other infrastructure and to provide urgently needed transportation capacity. To do this, all kinds of machines and vehicles were needed, especially construction machinery, cranes, backhoes, and trucks.

The main focus of industrial manufacturing was on **mass production** using manual production machinery, transfer lines, and mechanical automatic machines. The life cycle of the products being manufactured was at least 10 years; there was no need for rapid production changeovers.

The cumulative result of this enormous demand, clever policies, and energetic workers was the German **"economic miracle."**

1.2 Rebuilding the German Machine Tool Industry

Thanks to the conditions just described, within a few years **(by about 1960–1970), Germany** had the newest stocks of machinery of any developed nation: The average age of the machines was five to six years. But there were too few of them, and the statistics were lagging behind. Furthermore, some of the new machines were still using prewar technology.

During this period (approximately 1960–1975), American machines were about 15 to 17 years old. Renewal was brought about through the use of NC machines (i.e., turning, milling, machining centers) in the automotive and aerospace industries. The NC technology developed in the United States was implemented much more quickly there than it was in Europe. Many projects were subsidized by the government, for example, in defense industries.

American manufacturers of NC machines were very successful in selling their machines worldwide, but they neglected to systematically pursue further development.

This led to a continuous rise in imports of inexpensive Japanese machines.

The rapid series of improvements in numerical controls had major effects on all types of machinery and demanded new, adapted designs. These were not forthcoming, which led to the bankruptcy of many American manufacturers.

At the beginning of the 1970s, Japan made large investments in machine tool production. These were simple, inexpensive NC machines, but they were constructed according to the latest principles. Soon Japan was able to supply machines off the shelf and for heretofore unbelievably low prices. These machines were built according to a different set of requirements: series-produced standard machines without any major modifications, reliable, with standard NC, and no choice of controller, but inexpensive.

While German manufacturers continued selling to their traditional European market, the Japanese based their strategy from the very beginning on the global market, with a focus on the United States and later also on Europe. Customer-specific modifications were systematically refused.

By the middle of the 1980s, Japan had caught up with Germany in its share of the global market. One sign of German manufacturers' diminishing competitiveness was the constantly increasing percentage of imports: From 1973 to 1981, imports increased by 11.9 to 33.3 percent, and, by 1991, to 41.2 percent.

1.3 Worldwide Changes

In many **developed nations,** obsolescent machines were being used for production even 10 to 15 years after the end of World War II. While at first these were entirely sufficient, as competition and the pressure to reduce costs increased and buying practices changed, it became essential to modernize the machinery in many manufacturing firms.

Moreover, the **1970s** saw the beginning of a worldwide trend toward a **buyer's market;** that is, quicker product changes and shorter life cycles became the rule for almost all products.

The result: A shift away from mass production and toward **smaller lot sizes**. Instead of rigid mass production on automatic machines and transfer lines, increasing use was made of more flexible NC machines. However, the increasing complexity of products owing to greater use of computer-aided design (CAD) systems necessitated the deployment of up-to-date machine tools with seamlessly integrated data for quicker NC programming.

New potential users of NC machines appeared, such as

- The German defense industry for tanks, armored fighting vehicles, transporters, etc.
- The German aerospace industry, with manufacturing under license of the Starfighter, Phantom, helicopters, and weapons and later with the Airbus, MRCA Tornado, Alpha Jet, and Dornier Do 27 programs.

The aerospace industries in France (i.e., Dassault, Aerospatiale, and Snecma), the United Kingdom (i.e., Hawker and British Aerospace), and the United States (i.e., Boeing, McDonnell Douglas, Fairchild, Lockheed, Sikorsky, etc.) also were looking for new machine concepts. What was wanted were high-precision machines that could be reconfigured quickly, new machine sizes (i.e., surface milling machines and large drilling machines), and machining centers.

Small and medium-sized subcontracting firms were a large potential market that was as yet undeveloped.

1.4 Typical New NC Machines

From **1968** onward, the reborn German aerospace industry and the German automotive industry provided a major boost to the country's machine tool industry:

- Large-surface milling machines and machining centers with a high degree of automation
- Three- and five-axis milling machines with simultaneous interpolation in all axes
- Gantry-type milling machines for large milling widths with up to eight parallel main spindles
- Electron-beam welding machines, flexible manufacturing cells, and a very high degree of automation in workpiece and tool handling, as well as machining
- High-speed cutting machines for tool and die making
- New programming and machining strategies (e.g., APT, CAD, CAD/CAM) brought in large contracts for many European manufacturers.

In the course of just a few years (1970–1980), Germany became the world's largest exporter of machine tools.

At first, any number of new features were simply added to the old "tried and true" machine concepts without modernizing their basic design.

The result: Too many parts.

Machines too heavy.

Machines take too long to build.

Excessively complex designs.

Machines too expensive.

And

Commissioning takes too long.

Machines break down too often.

There is excessive downtime.

Consequently, these machines were not cost-effective for "normal" industries. The urgently needed breakthrough into the general mechanical engineering industry became possible only when reworked, less expensive concepts became available.

1.5 The Japanese Influence

The Japanese standard NC machines, which in the meantime had undergone continuous improvement, made ever-greater inroads into the German market. The initial "psychological resistance" on the part of purchasers against Japanese products was broken down by their low prices, constantly improving quality, and reports of generally positive experiences with them.

These machines were built in large volumes, had unusually short delivery times, and featured very reliable numerical controllers (e.g., FANUC, Mitsubishi, Okuma, Mazak, etc.). What's more, the Japanese firms provided service and support on a grand scale. Soon more and more German machine manufacturers were adding Japanese controllers to their machines and used the international availability of service and support, for example, from FANUC, to sell machines worldwide.

1.6 The Crisis in Germany

After the boom years from 1985 to 1990, **from 1992 onward** the German machine tool industry was faced with its most serious crisis since World War II. By 1994, production had fallen by almost 50 percent and the number of people employed by 30 percent. At that point the machine manufacturers' structural and financial difficulties took on particularly serious dimensions.

This rapid decline was the cumulative result of a number of problems. The German machine tool industry entered into a crisis for similar reasons to those of the American industry in the 1980s. Instead of marshalling their resources to take on the Japanese competition, German manufacturers tried to fend them off by means of price reductions—a tactic that could not succeed in the long run. Furthermore, German manufacturers worked against each other instead of working with each other to develop new ideas to defend against the ever-stronger Japanese competition. Some good approaches might have been uniform tool holders and changing systems, uniform pallet changers, and coordinated table heights. Such an approach, for example, would have made it much simpler, cheaper, and thus more attractive to introduce flexible manufacturing systems by combining machines from different manufacturers. But there was no money to develop new, less expensive machines.

The competitive atmosphere made it impossible to find common, coordinated, complementary strategic solutions—the kinds of solutions that many major users were looking for.

The result: The contribution margins, which had shrunk to less than 5 percent, did not allow for any large-scale future-oriented development projects. Many German machine manufacturers had either no strategic concept or no money to realize it. Instead, almost all of them tried to escape "upward" to the field of special and custom machines. But this niche policy had no prospects for success because the special machines were too expensive, and the production of standard machines did not use enough of the manufacturing capacity. Moreover, potential buyers demanded extensive, detailed plans from multiple manufacturers without bearing the associated costs.

Many highly respected manufacturers headed into bankruptcy or were taken over by competitors in subsequent years.

1.7 Causes and Effects

German managers asked the question quite openly: What is it that the Japanese are doing better than we German machine manufacturers, who have become so accustomed to success? Was it their lower prices owing to lower production costs? Or their better technical ideas? Or their delivery time?

But that was only part of it! What was much more serious was the fact that the Japanese had better business ideas, produced in larger quantities, and had a **global market strategy!** German manufacturers were looking for **purchasers** for special machines, whereas Japanese manufacturers were looking for **markets** for standard machines!

The Japanese machines were of high quality and made do with about 30 percent fewer mechanical parts. Purchasers were impressed by their advantages, advantages that became even more pronounced as time went by.

Even hard-core German traditionalists bought more and more Asian products. For the price of one German "super-special custom machine" with a long delivery time, it was possible to buy two or three Japanese standard machines off the shelf. Truly convincing!

It was only toward the **end of the 1980s/beginning of the 1990s** that the surviving German machine manufacturers finally understood that they had to build "different" machines in order to once again attract buyers and be successful. The niches for the German special machine manufacturers had become too small.

For many German manufacturers, the solution was mergers—often forced on them by banks. Today, many of these manufacturers have become competitive once again and use as a selling point the fact that they have reduced the number of parts in their modernized machines by 30 to 35 percent. These companies have finally comprehended that neither outmoded ideas nor "technical overkill" with a niche strategy would put them on the right track. But purchasers also have accepted the fact that German machines have comparable specifications to those of Japanese machines without a large number of customer-specific special functions.

Not to be underestimated is the role played by the new, high-performance, dialog-oriented **NC programming systems,** which were available both as a programming stations and also directly on the machines.

The revival of the German machine tool industry also was helped by **new technological processes** and completely new types of machine, such as high-speed cutting, high-power lasers for welding and cutting, additive manufacturing methods such as rapid prototyping systems, and machines for hard machining of metals and ceramics. Most recently, machines with parallel kinematics (i.e., tripods and hexapods) have become ready for market introduction, but potential purchasers are still holding back. However, universal machines for complete machining in a single setup are attracting more and more interest.

Furthermore, the use of new, highly dynamic drives has been making these machines faster and faster.

1.8 Flexible Manufacturing Systems

In the 1970s, large American companies such as Caterpillar, Cummings Diesel, General Electric, and a number of machine manufacturers (e.g., Cincinnati Milacron, Kearney & Trecker, Sundstrand, etc.) started designing and installing the first **flexible manufacturing systems** (FMSs). These consist of several **self-replacing** (identical) or **complementary** (different) NC machines and a common workpiece transport and control system. Such systems can be used profitably to produce either single parts on an order-by-order basis or in small to medium-sized lots. In special cases, FMSs also can be used for large-scale series production.

During this time, the first FMSs were tested successfully in Japan and marketed internationally. Visitors came from all over the world and were astounded by the unmanned production in unlit factory shops.

In Germany, demand for FMSs was at first very guarded. The main factor in this reluctance to buy was the extensive engineering required, that is, the customer-specific planning and dimensioning of such systems at the customer's location and the very involved time, unit cost, and investment calculations generally required by the customers. All this led to high costs and prices. It was only when the fantastic visions of "factories without workers" gave way to "manufacturing with reduced personnel" based on affordable manufacturing concepts that German users started to take more interest in such systems.

In 1974, the Getriebe Bauer Company of Esslingen, Germany, installed one of the first FMSs in Germany. It was composed of nine identical machining centers (made by BURR) with Bosch/Bendix controllers, a recirculating pallet system for automatic workpiece transport, and pallet transfer stations at each machine. The decisive factor here was that at that time, the first NC systems using program memory instead of punched-tape readers had become available. In the following years, Bauer expanded this system to include 12 machines and in 1988 upgraded them with higher-performance computer numerical control (CNC) systems. More than 20 years of two- and three-shift operations have met the user's technical and economic expectations—and then some! Finally, it was possible to produce goods to order—to reduce warehouse stocks and still deliver on short notice.

After the first positive reports, other FMSs followed in many other manufacturing firms.

In **Japan, the United States, and Europe,** FMSs designed according to the latest state of the art are being installed at a steady rate. The positive experience gained with these systems and their cost-effectiveness has led to better FMS-compatible machines that are unproblematic to combine and operate. The integration of robots for tool and workpiece handling also has led to improved system concepts. For early detection of planning errors, powerful simulation and production planning systems (PPSs) were developed.

FMSs have been used in **Germany** for many years now, and the trend is increasing. Because of the unavoidably rapid intervals between updates and modifications of workpieces, flexible manufacturing systems are often more cost-effective than rigid, inflexible transfer lines, even in mass production.

1.9 Situation and Outlook

Manufacturing technology and automation are undergoing continuous worldwide development with new ideas and concepts. Today, the primary role is played by **NC machines and integrated robots,** which are available in a wide variety of designs and combinations for all types of applications. Highly dynamic linear drives, position-measuring systems with extremely high resolution and precision, and fundamentally new machine concepts have made NC machines the dominant type of manufacturing system—and not just for machining.

Also with regard to **robots,** Japanese industry initially responded faster than all other developed nations, developing economical standard robots that subsequently served as a basis for gaining valuable experience worldwide. They won acceptance quickly almost everywhere.

Today there is a great demand for robots worldwide. All developed nations have built up their own production and offer special robots for manufacturing, handling, and assembly.

Computer-integrated manufacturing systems (**CIM systems**) as they were originally conceived are now outdated. The plan was to use interlinked computers to implement factories without workers and to control all the processes fully automatically, from purchasing to manufacturing and assembly. But experience soon showed that implementation of these ideas was too expensive and therefore unrealistic. Rather, users came to the realization that processes should be automated only when to do so would reduce the price of products while maintaining high quality. CIM quickly developed a bad reputation—a reputation that it did not deserve!

So a new term was coined—**digital manufacturing**—to express almost the same concept. This has attracted renewed interest based on the following proposition: **Automate? Yes, but not at any price!** Otherwise, profitability will remain a mere pipe dream.

In contrast, FMSs are in greater demand today than ever before. The much-praised flexibility of such systems no longer resides in centrally controlled machines with an extremely high degree of automation and a host computer but rather in a decentralized, clearly organized arrangement of the system components. Specially adapted workpiece transport systems and, in particular, a seamlessly integrated data network are essential, however. With reliable monitoring systems for tool breakage, measuring probes with automatic measurement logs, corrective interventions and fault messages, monitoring systems for torque and feed force, and absolutely error-free data transmission, **temporary unmanned operation** of these systems is possible. This great potential for greater efficiency was quickly recognized and exploited.

And one should not forget very high performance industrial computers and well-tested software for (almost) all requirements. Much of the more **recently developed software** has further **reduction of times** as its main goal.

Current technical literature shows that the speed of production is becoming more and more important. **Wasted time** is coming under increasingly close scrutiny when looking for efficiency improvements. It is not just shorter and shorter tool changes or faster rapid traverses that are being demanded, but also more intelligent machining itself. To achieve this, existing NC programs have to be reworked and finely adjusted. Today's **simulation systems** are perfectly suited for this, both technically and economically, and they make it possible to save millions of euros per year.

In this area, the largest users of NC machines have exerted their influence on the software producers in order to bring about practice-oriented solutions.

Simulations also can be used to satisfy requirements for quicker **market introduction** of new products—with time savings of more than 50 percent in some cases. Production lines for new products often have to be planned and ordered at a point in time when the final form, size, and machining of the parts have not been finalized. With support from production planning systems (PPSs) and simulation systems, today it is possible to determine and plan with great precision the complete scope of all investments required for production. It is also no problem to incorporate later product modifications into such machinery.

Simultaneous engineering methods provide a perfect supplement to this accelerated pace.

Finally, it is important to mention **rapid prototyping development (RPD)** manufacturing methods, which in the meantime have become an established practice. Depending on the specific tasks, various methods and processes are available to create physical test workpieces from CAD models using special numerically controlled machines. Especially the tool and die industry is already making very heavy use of these options. Most machines for **rapid prototyping manufacturing** use laser beams as a universal tool with completely new manufacturing methods. Many German and other European manufacturers are active in this field, with great success.

1.10 Conclusions

In the course of about 40 years, NC technology has brought about major transformations not only in the machine tools themselves but also in entire manufacturing plants, the people who work there, and beyond. Manufacturers and users have learned not to strive for 100 percent automation on a purely theoretical basis but rather, when performing manufacturing and automation analyses, to include all the departments involved in the process. Only in this manner can one achieve technically and economically viable solutions. Working together, machine and controller manufacturers have developed technically sophisticated manufacturing concepts at market-oriented prices and have managed to contain the initial Japanese success.

Today's manufacturing industry would not be possible without such high-performance components as computers, new machine concepts, automatic transport and handling systems, reliable controllers, and intelligent monitoring systems. And that is certainly not all!

In order to exploit the benefits of this technology profitably, highly educated and trained personnel is absolutely necessary—all the way from the management suite to the shop floor. Only such personnel will be able to plan, implement, operate, and maintain these complex systems competently.

Since 2008, the topics of environmental protection and energy efficiency have been attracting more and more public discussion. Implementing these requirements also will have an effect on the mechanical engineering and manufacturing technology industries. Machine tool and controller manufacturers are already considering how they can optimize auxiliary drives, work processes, and NC parts programs for greater energy efficiency.

In the international machine tool industry, the trend is toward the shifting of markets to Asia since business is still booming in countries such as China and India.