Chapter 9
Major Technology 3: CAPP, CAM and NC Technology

Executive Summary

This chapter deals with the following topics:

- Basics and advanced techniques of Computer Aided Process Planing (CAPP), Computer Aided Manufacturing (CAM) and Numerical Control (NC)
- Providing insight into how engineers benefit from using CAPP, CAM and NC technologies
- Describing functioning, benefits, and limitations of CAPP, CAM and NC technologies in practice.

Quick Reader Orientation and Motivation

The intention of this chapter is:

- to give an overview of CAPP, CAM and NC technology in Virtual Product Creation as driver and enablers for Digital Transformation in engineering
- to present CAPP, CAM and NC technology as part of Virtual Product Creation from a practitioner's point of view to analyze the need and usefulness for day-to-day industrial work practice
- to give instructions on how to use CAPP, CAM and NC technology
- to explain models, frameworks, and representations that help to grasp the internal working modes of CAPP, CAM and NC technology.

This sub-chapter explains all *Virtual Product Creation* technologies which are essential to transform the digital delivery of product development (represented by CAD models) into digital artefacts which can formally and completely describe the working elements to eventually realize the physical shape of the product as part of the digital manufacturing process. The explanation starts with Computer-Aided Process Planning (CAPP) and is followed by Computer-Aided Manufacturing (CAM) and Numerical Control (NC).

R. Stark, *Virtual Product Creation in Industry*,
https://doi.org/10.1007/978-3-662-64301-3_9

9.1 Computer-Aided Process Planning—CAPP

Computer-aided process planning (CAPP) is the generic term for software tools that assist in the planning of manufacturing processes. CAPP serves as a bridge between CAD and CAM. CAPP is used to determine how a design will be manufactured in a production system via digital planning methods. Without a successful CAPP, it is impossible to transform complex design information into manufacturing.

9.1.1 Engineering Understanding of CAPP

The following subsection will explain the basics of CAPP. For this purpose, the functionality and benefits of CAPP in Virtual Product Creation are demonstrated.

9.1.1.1 Why Does an Engineer Use CAPP?

Process planning of manufacturing operations takes place organizationally between product design, manufacturing engineering and operational production. In process planning, the manufacturing processes, their sequences and the manufacturing conditions are determined. Process planning for production is a complex task with many variables from different areas and departments such as component design, manufacturing engineering, task sequence determination, ergonomics, material supply and logistics. All of those aspects need to be considered as part of process planning. The goal is to convert the virtually designed product (assemblies with individual components), in economic and competitive terms, into a physical component with minimum resource investments and high delivery robustness and quality of the product itself.

Process planning is traditionally associated with high manual effort and requires substantial heuristic knowledge. CAPP is used to assist manufacturing engineers in process planning and to make decisions as objective as possible instead of just relying on the knowledge and experience of individual experts. CAPP, therefore, allows engineers to systematically develop appropriate methods for the manufacturing of single components and/or full products with a reduced manual effort and to fulfill efficiency targets of the manufacturing process, the production system or even the entire factory.

9.1.1.2 What is CAPP Doing for an Engineer?

Engineers, in general, and Manufacturing planners, in specific, use CAPP for tasks like:

- Process selection
- Operation sequencing

- Machine and tool selection
- Process scheduling
- Manufacturing condition determination
- Manufacturing time and cost estimation.

Two of the most complex challenges in manufacturing planning are *process selection* and *operational sequencing*. CAPP, therefore, engages algorithms to optimise process sequencing via mathematical methods [1].

By using CAPP, constraints such as the technical priority graph and capabilities of resources can be automatically checked and problems and restrictions in the production system can be displayed. Through simulations in the virtual production system, engineers can secure and optimize the manufacturing of new products before the production system actually exists.

In summary, CAPP is used to match, secure and optimize the connection between manufacturing processes and resources, demonstrated in Fig. 9.1.

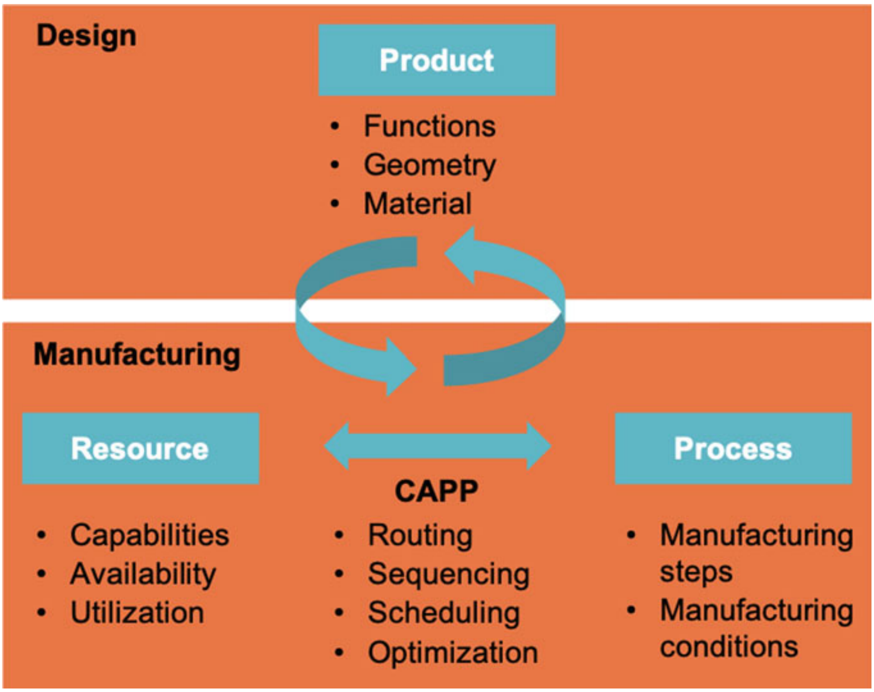


Fig. 9.1 Connection between product, process, resource and CAPP

9.1.1.3 What Are the Benefits of CAPP?

CAPP is used to reduce the time and effort required to create consistent process plans. Furthermore, CAPP is used as an automated interface between CAD and CAM to achieve full integration of structural and process data into the manufacturing system design.

The use of CAPP in virtual product creation leads to the following advantages:

- The process plans can be generated automatically from the product data by using feature recognition technology.
- The manual effort of scheduling is reduced because algorithms can be used to automatically create and compare different planning variants.
- The time required for process planning can be reduced because steps as the generation of process plans and scheduling can be automated.
- The planning quality can be increased, since the processes in production can be simulated virtually to identify and correct problems (such as material flow) before they are implemented.
- The utilization of manufacturing workplaces and machines can be increased, because in planning many different variants can be created and easily compared with acceptable manual effort. In addition, target fulfilment of planning variants can be checked simultaneously.

9.1.2 How Does CAPP Work?

CAPP systems pursue two different approaches—variant and generative—to translate design information into manufacturing steps. The variant approach uses the similarity of parts to segment them into different groups. There are master process plans for each part family which are used and edited to match the requirements of a certain component. Group technology (GT) code is widely used for the classification of parts into families of similar ones. In contrast, the generative approach creates a process plan for each part from scratch without manual effort. Manufacturing databases and appropriate part descriptions are used to generate a process plan for a certain part [2].

A lot of research in the area of CAPP took place in the last decades. The current research on CAPP systems focuses on the generic approach. The feature-based technology—originally a major research topic in the early nineties of the last century—is used to translate the implicit knowledge of the developer into a computer-interpretable way to automate and optimize the planning of manufacturing processes. A feature is described by a compilation of characteristics and/or properties of a product. The description of a feature consists of the relevant property itself (for example geometric shape and topology to identify machining features, compare Fig. 9.2), its value and its relation and constraints. Features can be used as integration elements over the entire life cycle of a product.

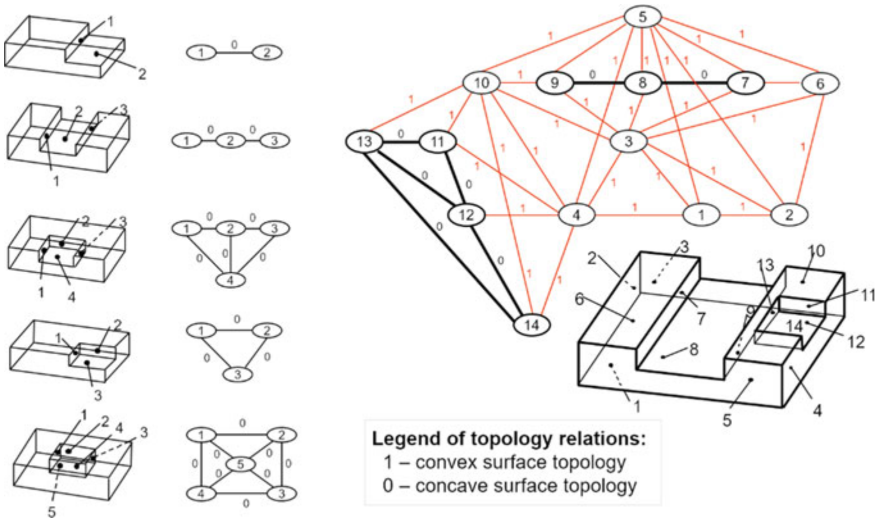


Fig. 9.2 Identification of milling machining features for process planning by recognizing topological regions of a digital design component

In addition to the feature-based technology, AI technologies such as knowledge-based systems, genetic algorithms and also artificial neural networks are used in CAPP systems to create and optimize manufacturing processes. The process plans for new products can be generated based on the geometry description, the material and other variables that influence the manufacturing decision [3].

However, in some areas like assembly planning of complex products such as vehicles, process planning still requires a lot of manual effort. Complex products and complex production systems lead to an enormous complexity in process planning that cannot be handled by a fully automated solution these days. The progress in CAPP is significantly slower compared to CAD and CAM, although much research has been done in recent years. The multidisciplinary nature of process planning makes it difficult to automate CAPP in the industrial praxis [4].

9.1.3 CAPP Methodology and Technology

In the following section, the steps by which a methodological and technological description of the process of manufacturing a part/product is built will be described. In addition, the main problems when using CAPP are to be considered.

As stated above, CAPP is the bridge between CAD and CAM. In this regard, CAPP has a large number of methods and steps in the planning of the production process.

The main approach of CAPP works as follows: according to a given model of a digital product (designed with CAD), a work plan is created for its production or assembly sequenced process steps in a way that it can be altered in terms of sequence of the process steps, type of working steps and duration of the working steps. In order to virtually simulate, test and modify an entire production process or, like in a specific case here, of an assembly sequence it is necessary to leverage a full digital model that consists of the following elements:

- the digital component which needs to be assembled to another part or sub-assembly (both to be represented with a 3D CAD or visualization model),
- the relevant digital representations of assembly resources (tools, fixtures, transport systems, safety devices etc.) and
- the digital representation and interaction model of a human worker (in case of a manual assembly task).

The description of one specific digital assembly sequence step, for example, includes information about the following core elements:

1. The 3D representation, the sequence and the trajectory of the components during the assembly operations.
2. The equipment which are used to perform the assembly tasks and the worker actions used in each operation.
3. The digital simulation tool which mathematically controls the processing and timing of all operations within the 3D environment.

Figure 9.3 displays the preparations for the production process using the Technomatix software (Siemens).

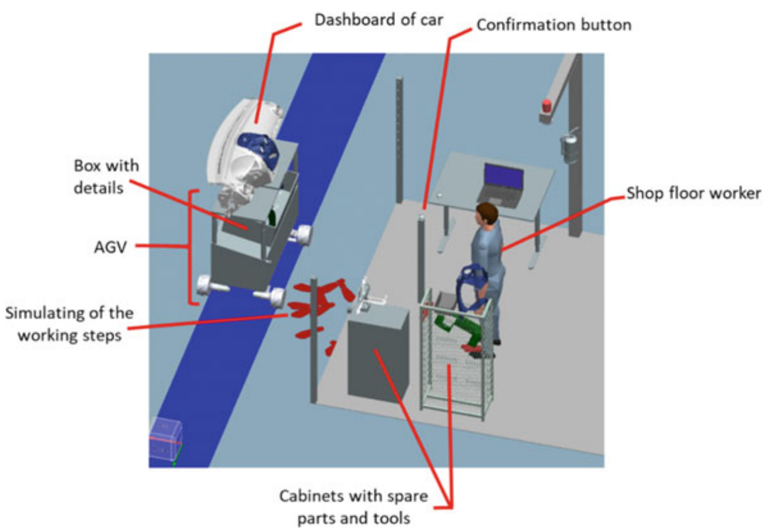


Fig. 9.3 CAPP: sequence of operations and operation elements in 3D

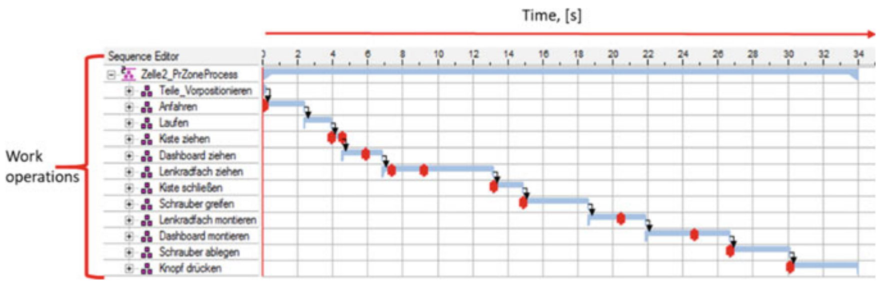


Fig. 9.4 Time sequence simulation of worker actions at the station

This example shows how the production of the car dashboard is planned. Each part of the assembly process is programmed with a specific action of the virtual model of the worker with the necessary cycle time.

In addition, a wide range of advanced programming functions for production planning, such as the visual components, typical interactions and assembly steps, is provided. A process engineer, therefore, can evaluate the movement of a manufacturing worker on the shop floor and his speed of work (compare the time chart of the assembly sequenced steps see Fig. 9.4).

In the automotive assembly example shown in Figs. 9.3 and 9.4, the simulation begins with a preset of parts. This operation ensures the preservation of the initial positions of all parts. An automated guided vehicle (AGV) is then launched. The AGV travels through the AGV line to the middle of the assembly station. The worker then walks to the AGV, opens the box under the AGV and takes the parts (a trim cover in this case) that need installation into the dashboard. Then the worker transfers the box to its original position and walks to the cabinets to get the relevant assembly tools (screwdriver, bolts etc.). The worker takes the tool and screws the part (cover) to the dashboard. Afterwards, the worker puts the tools back to the cabinet, presses the confirmation button, and allows the AGV to go to the next workstation. Accordingly, at this station, it is necessary to perform 12 different operations (see Fig. 9.4) in order to fasten the part (cover) with all necessary details. Such an assembly process sequence allows for optimization, both on behalf of the worker activities and movements as well as on behalf of the part installation sequence itself.

9.1.4 *Requirements for CAPP*

Production planning in general is a trustful, responsible, sometimes even complicated and time-consuming process, since reliable information connections to different stages of production, technology and software have to be implicitly and explicitly established. As a consequence, detailed requirements are imposed on CAPP to ensure the quality and integrity of the planning process in order to achieve high robustness for the subsequent production system operation:

- A process plan must ensure all quality requirements of the part defined in the part drawing or with the help of digital annotations at the 3D CAD model itself.
- A process plan should deliver on overall goals such as reasonably high production efficiency and high yield in order to fulfill production quota according to due dates.
- A process plan should ensure low production costs (both piece price and investments).
- A process plan should help to improve the working conditions and promote uninterrupted development of manufacturing technology [5].

In Fig. 9.5, a traditional paper-based process plan is shown as it has been used for more than 50 years. It includes many elements, such as: materials of parts, work equipment, number of operations, etc. Such documents are usually prepared for each operation of the production system. With the help of computer aided support

NJA COMPANY	ROUTING SHEET	Product No.		Page
		Part No.		of
		Part Name		

material		Blank		Number of part per unit		Quantity	

OP No.	Name of operation	Equipment	Jig or fixture	Tool	Gage	Standard Hours	Remarks

			Planner		Approved	
			Date		Date	
Alteration No.	Approved	Date	Issue No.		Issue Date	

Fig. 9.5 Example of routing sheet [5]

for production work planning those final documentations are just an output of the internal digital process data model which is generated, altered, simulated and tested within the CAPP environment as already shown in Figs. 9.3 and 9.4.

9.1.5 CAPP Challenges and Problems

Production planning and digital planning activities as part of CAPP pose mainly the following challenges:

- to ensure the principal technological, the business and the necessary geometrical accuracy to manufacture and assemble single part, (sub-) assemblies and/or full product in the given working conditions of the production cell, the entire production system or even within the complete factory. These challenges need constant attention and they are usually addressed within industry via different stages of feasibility studies and heuristic determinations which do include all manufacturing partners and suppliers.

  Unfortunately, up-to-date there still exist many interface challenges for the exchange of digital models of digital product and process models: besides general data exchange formats like STEP and IGES more specific data exchange models for manufacturing resources such as AutomationML have been developed and introduced over the last couple of years.
- to establish frameworks and platforms for flexible cost planning and competitive production price estimations across companies.
- to develop simulation methods for automatic efficiency analysis of resources and equipment in production and for adapting flexible production concepts for existing production line and machine regimes in factories.
- to develop production plans for low cost production based on frugal manufacturing principles.
- to maintain and adapt process plans to organize uninterrupted production of products with the possibility of further improvement under given conditions.
- using new *Industrie 4.0* design and planning systems for describing networked *Cyber Physical Production Systems* (CPPS) to enable future aspects such as (see more details in Chap. 20):

  – Modeling of digital twins and the associated digital analysis streams
  – Design and implementation of tools which enable automatic digital twin creation and process integration
  – Development and establishment of approaches for validating digital twins as part of digital production planning
  – Development of methods for validating real-world pro-ducts, plants etc. by using the digital twin at an early stage
  – Reverse design of the data analysis required for determining minimum sensor population and managed basic AI modules.

All these challenges and problems are typical and exist (or will exist in the future) at every enterprise. Achieving a balance among them will allow process and manufacturing engineers to adapt production for each specific purpose. Some problems are solved by purchasing new equipment, which oftentimes drive major adjustments of the manufacturing process themselves. However, one should always keep in mind that the main task of industrial CAPP is to develop such a manufacturing process for products, which will take the lowest effort or price in resources, working hours and equipment of the enterprise.

9.2 Computer-Aided Manufacturing—CAM

Modern digital manufacturing engineering is developing at a rapid pace in the direction of production automation with the widespread use of the latest robots, CNC (Computerized Numerical Control) technology and, of course, additional control and analysis software like PLC (Programming Logical Controller) or Operational Data Acquisition as part of Manufacturing Execution Systems (MES). Flexible technologies provided by software allow engineers to quickly and efficiently adjust the production process of parts for each individual request from the client. Automation of the product design process using CAD/CAPP/CAM technologies is a way to increase production efficiency and product quality. In this regard, this sub-chapter will consider CAM technology as well as the advantages it provides for engineers and its capabilities. A typical process of an engineer working with a CAM system will also be presented.

First of all, let us get acquainted with the definition of CAM.

According to Nageswara Rao [6], *CAM generally refers to the computer software used to develop the computer numerical control part programs for machining and other processing applications.*

Another definition, according to Alavala [7] states: *CAM is a computer system that helps to manage, plan, and design production operations in terms of resources and time.*

In summary, the author recommends the following definition of CAM: *CAM (Computer-Aided Manufacturing) provides methods, tools and information standards to help engineers carry out automated calculations of tool paths for processing on CNC (Computerized Numerical Control) and DNC (Distributed Computerized Control) machines digitally and provide the distribution and load of such digital control programs to production machines using computer and digital networks.*

9.2.1 CAD/CAM Integration

It is important to understand the relationship between CAM and CAD representations. CAD-systems are developed to create geometric and topologic models (2D and 3D) of parts, components and assemblies with the help of internal digital (and mathematical) representations and to create design documentation such as drawings (compare Chap. 7 CAD Modeling Techniques). Basically, modern CAD systems include all the necessary modules for modeling a three-dimensional part and the design of all the necessary supporting documents (specifications, sketches, etc.).

In turn, CAM-systems are designed to devise the processing of products on machines with computerized numerical control (CNC machines) and to transfer and load operating programs for these machines (milling, drilling, erosion, punching, turning, grinding, etc.). CAM systems are also called pre-production systems. Currently, they are almost the only way to manufacture complex parts and shorten their production cycle since the old days of manual settings with a tool machine are no longer state-of-the-art in industrial practice. CAM systems use a three-dimensional part model created in a CAD system.

How does the relationship between these two software solutions look like? The manufacturing engineer needs to take a series of actions in order to check the CAD design and to prepare the resulting control sequences for the execution of the individual machine operations at a given CNC machine before starting the operational production. For this, the engineer uses CAD-CAM systems in the following way (see Fig. 9.6):

- By engaging upfront in the development, design and analysis of the product with the help of a CAD system that provides active manufacturing feasibility support (e.g. applying rules of manufacturability for specific geometric shapes under given tool characteristics) to the CAD designer.
- By verifying the topology, shape and dimension of the CAD model and by simulating its manufacturing processing and its material behavior with the help of CAM knowledge and simulation according to the following aspects at a given CNC machine:
  - Recognizing specific machining features (see Fig. 9.2)
  - Minimizing tool clamping
  - Automating tool holdings
  - Simultaneous multi-axis kinematic operation
- Under appropriate physical conditions (i.e. by using verified CAD/CAM parameter settings of used materials, tool wear, cutting speed, tool forward speed, lubricant cooling, surface conditions, tool-workpiece angle etc.).
- By creating a final optimized control program for CNC machines via indicating the sequence of product processing processes for each surface area, such as, for instance: lathing, milling, grinding, slicing, drilling, etc., or, in other words, by using the CAM system.
- By issuing control commands to each individual CNC machine (using a CAM system) as part of the Distributed Numerical Control (DNC) network.
- If necessary, by carrying out verification at each stage of production of the part and adjusting the program for each individual CNC machine.

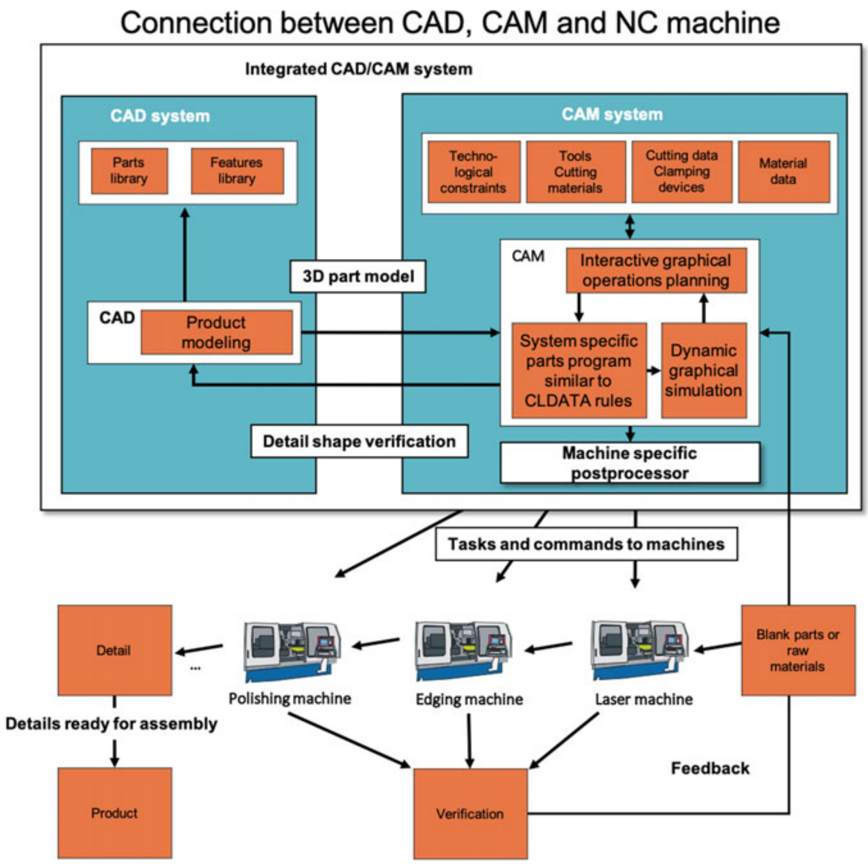


Fig. 9.6 Connection between CAD, CAM and NC machine

With the CAM graphical system, the engineer receives visual feedback for each step of the work piece processing if the appropriate settings of the individual process steps have been accomplished with the necessary manufacturing knowledge beforehand.

Another useful aspect of the CAM graphics system is its ability to simulate toolpaths. This is a computer animation that shows exactly how the program will work on a specific CNC machine with the given verified parameter settings of the physical behavior as described above. If the analysis shows that the machine operation does not work properly or according to anticipated work plan assumptions, the settings before the actual processing of the physical machine on the shop floor.

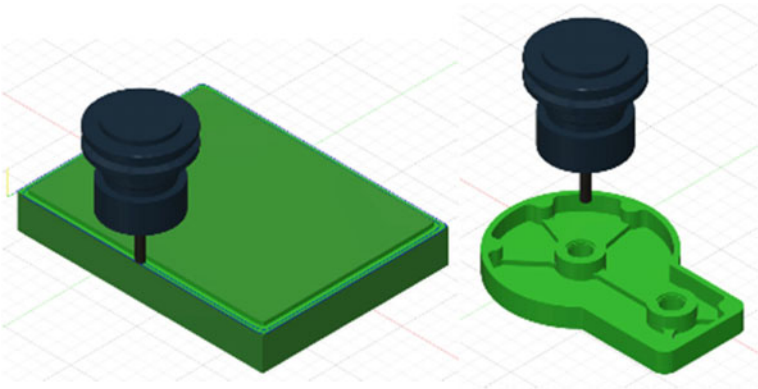


Fig. 9.7 Part manufacturing using CAM tools—milling operation with tool and tool holder (in black color), raw part on the left side and finished part on the right side, both in green color

9.2.2 Engineering Understanding of CAM

This section explains how and why engineers use CAM systems. By using CAM software, an engineer is able to develop and analyze the process of creating a part at each stage of the CNC operation. Each company produces products of varying complexity, so CAM tools are an indispensable technology to ensure proper and automatic production compliance.

Figure 9.7 shows a typical example of the result of an engineer working with CAM software. After receiving the 3D model, the CAM engineer must create the correct sequence of commands for its manufacture. To accomplish this, the engineer determines the necessary form of the raw work piece, selects the material and the appropriate tools for the job (Fig. 9.7, left side). Figure 9.7 on the right side, shows the final stage of the milling workpiece after the full machine operation simulation in the CAM software. Visual simulation during the processing shows how the manufacturing process evolves and which problem might occur (e.g. clash with tool clamping and fixtures which are not shown in Fig. 9.7).

9.2.3 Why Does an Engineer Use CAM?

Due to the general increase in production and the speed of delivery of the finished product to the buyer, it is necessary to respond more quickly to changes in production and produce the same products in a shorter time.

Therefore, best practices give better results. In order to be one of the best companies, process and manufacturing engineers must adhere to planned targets. Similarly, in order to increase the productivity of production processes, manufacturing and process engineers should use CAM software to simulate the manufacturing of a product on a tool machine and to finally transfer commands to the CNC machine (Fig. 9.8a).

CAM software allows process engineers to analyse and test the performance of 3D models even before the appearance of a physical prototype. By using these programs, they test the CAD model, speed and production capabilities on specific machines (Fig. 9.8b).

Designers will be able to perform simulations at any time during product design and development. However, engineers often model details at the concept stage and continue to refine them throughout the development cycle (Fig. 9.8c). This allows to evaluate the manufacturing characteristics of the product precisely and to optimize it in terms of cost and quality, leaving time for innovation and error correction.

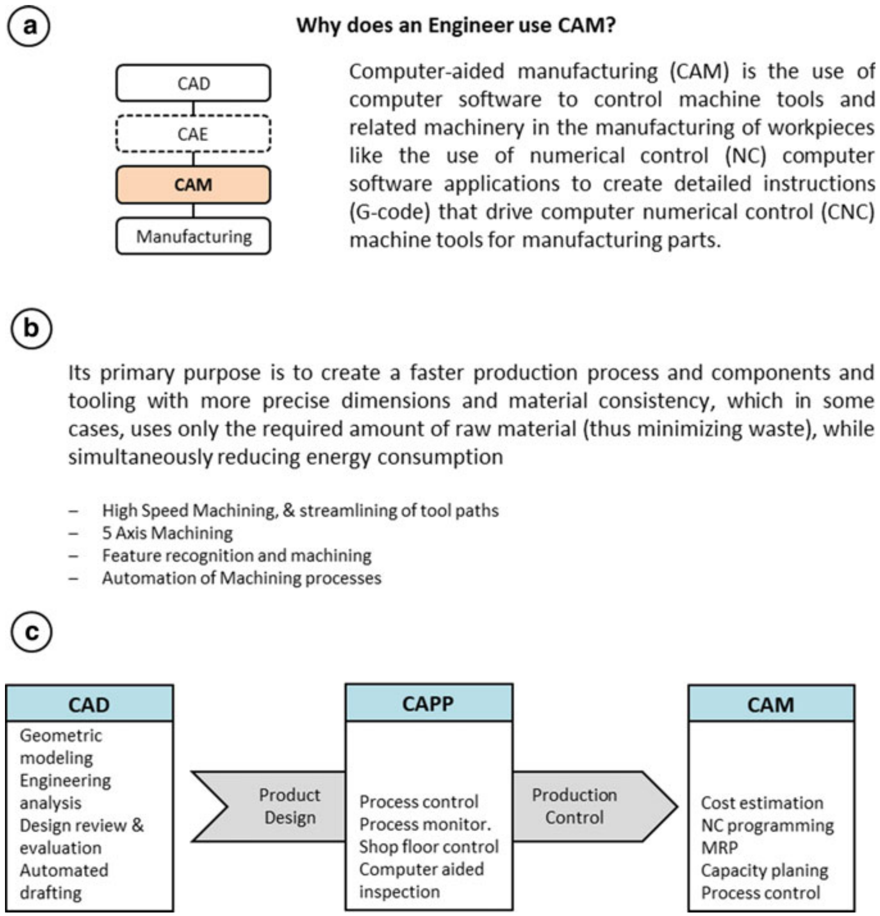


Fig. 9.8 CAM as final step in the overall process flow to accomplish a CAD design model within manufacturing (picture was provided)

Overall, it is worth noting that the full benefits of computer aided tools can only be applied if the interplay of leveraging the 3D CAD model description in CAD in the context of appropriate CAPP activities will lead into the final processing of the specific CAM working steps. Hence CAM can also be seen as the final process step to convert a CAD design model proposal into a manufactural work piece on a specific tool machine as part of a general manufacturing process.

9.2.4 What Are the Benefits of CAM?

CAM systems for planning, preparing and creating the process for manufacturing CNC parts are much faster than when doing this work in the traditional way.

The processes of preparing the control program by means of a computer application and by manufacturing a desired part on a CNC machine represents the first advantage of CAM. The second advantage of utilizing a CAM system and CNC machines is that a higher precision can be achieved in part manufacturing. Without such an approach, it would be impossible in today's competitive business environment to accomplish manufacturing operations of such a high amount of new and modified products in a fast, accurate and cost-efficient quality-controlled manner.

In addition, the ability to create and analyse a virtual three-dimensional model of a complex part before production starts allows, in many cases, avoiding design and technological errors even at the stage of production preparation. In this regard, it can be concluded that a modern engineering company can competitively and successfully occupy its niche in the market if it meets the following three conditions:

- Reducing the period of preparation for production and launch of products on the market to a minimum.
- Achieving lower cost of production compared to main competitors in due course of production optimization.
- Ensuring "best competitive" quality products.

Further to this, engineers have a number of significant advantages by using CAM systems, compared with machines under manual control, when it comes to creating high-precision and complex parts:

- High speed in component production.
- Lowering GD&T (Geometric Dimensioning and Tolerancing) deviations and higher consistency with each component or finished product in a predictable deviation range.
- Reaching greater operational efficiency due to computer-controlled machine operation, which do not need to take breaks as physical machine fitters.
- Achieving high complexity machining operations and high operating times of machines.

There exist some limitations, however. CAM-enabled machines are usually designed for a specific task and are not incredibly versatile in adapting to product design modifications as part of the on-going product refreshing cycles. Hence it is necessary to deploy solid and extended library concepts for already used, modified, derived and totally new CAM control programs in the context of associated CAPP working plans.

9.2.5 CAM Technology and Process

This section explains how a typical design process works by using CAM systems and it shows the associated steps and features of simulating the part (workpiece) processing process. The main features of CAM systems in engineering are also considered.

9.2.5.1 CAM Technology Features

CAM systems are designed to automatically create control programs based on geometric information prepared within the CAD system, CAM systems offer the capability and choice of working tools loadable at a specific tooling machine, a range of physical and kinematic parameters (which could be loaded from pre-prepared libraries as part of the tool and tool machine management database) and the tool working paths as created in the CAM system itself. The main advantages for an engineer when interacting with CAM are the visibility of the work, the convenience of choosing a geometry, the high speed of calculations and the ability to check and edit the created tool paths.

Different CAM systems may differ from each other in scope and capabilities. For example, there are systems for turning, milling, woodworking and engraving. Despite the fact that most modern CAM systems are able to create control programs for any type of production, such a separation by field of application remains relevant.

If an engineer needs to use milling, then they need to purchase a milling module for the corresponding CAM system. If only turning is needed, then it is enough to purchase a turning module of the same system. The modularity of building CAM systems is part of the marketing policy of software vendors of CAM systems and allows manufacturing enterprises to save significant funds by acquiring only the necessary design and technological capabilities.

9.2.5.2 Typical Design Process with CAM

Now we shall take a look at a simple example of how an engineer works in a CAM system. Typically, such a process involves four main steps:

Step 1: The CAD engineer develops a three-dimensional CAD-model of the detail with certain parameters, material and other features which should all have already

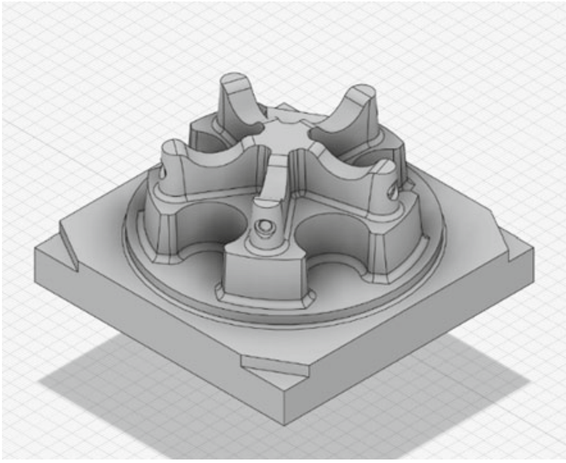


Fig. 9.9 CAD model of a component

considered Design for Manufacturing (DfM) rules. For instance, Fig. 9.9 shows a typical part considered to be manufactured on a CNC mill.

Step 2: The 3D model of the part is imported into the CAM system. The manufacturing engineer, who should have knowledge as production technologist and programmer, determines the surfaces and geometrical elements necessary for processing, makes the choice of the processing strategy as well as the cutting tool and finally sets the cutting mode. The system is then able to calculate the tool paths (Fig. 9.10, on the left side).

Step 3: In the CAM-system, a visual check of the arising trajectories is performed, the CAM programmer has the ability to quite easily correct errors that may appear, for example tool path correction or cutter change. In the Fig. 9.10 (on the right side), a detail within the production simulation is shown (potential clash). According to the

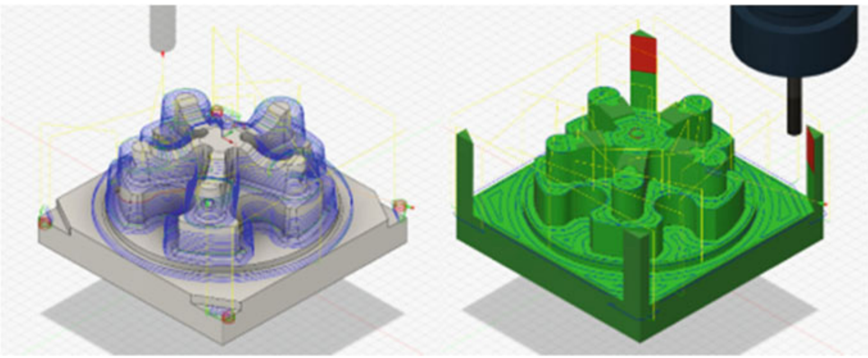


Fig. 9.10 CAM process features of a component

results of the simulation, the engineer can estimate the material removal and further optimize the process.

Step 4: The final delivery of the CAM system is the control program code. This code is created using the postprocessor, which in turn customizes the control program to the characteristics of a specific machine and the CNC system. Examples of such code are shown in Fig. 9.20. According to this code, the cutting head will pass from point to point throughout the entire workpiece, giving it the desired shape.

The post processor is a unique driver that converts the developed plan for the movement of the cutter (in the CAM program) and the technological commands into machine code. Such a code is developed in strict accordance with the capabilities of a particular CNC machine [8].

9.3 Numerical Control—NC

Numerical Control (NC) is an electronic method of controlling machine tools (CNC machines). CNC machines execute the individual processing steps for manufacturing automatically. The machining steps are defined in the NC program which is read by the CNC machine from a data carrier or data storage device (data base, server as part of a DNC network). Afterwards, the controller of the CNC machine evaluates and executes the work instructions.

9.3.1 Engineering Understanding of NC

This section explains why NC is used in production and what NC is doing for engineers. Moreover, it will be demonstrated how NC **programs** are used to manufacture individual workpieces and components.

9.3.1.1 Why Does an Engineer Use NC?

NC is a common control method in production because it leads to the following advantages:

- Automated, fast and high precise manufacturing
- Capability to automated recurring tasks
- Automatic generation of NC on the basis of CAD data
- Reduction of errors in the translation of CAD data into NC code due to automation
- Offering deeper understanding of the work process by graphical representation support
- Optimization of tool paths through upfront simulation
- Collision detecting using the NC program

- Conducting of NC programming comfortably in the office rather than at the tool machine on the shop floor
- Providing higher uptimes of CNC machines and higher overall productivity due to working on the NC program off-floor
- Offering free form surfaces manufactured through multi-axis control capabilities through NC.

Therefore, engineers can rely on NC technology for the physical production of a CAD model if all digital transformation steps and the right parameter settings in the NC code of a specific tool machine for a specific material can be ensured.

9.3.1.2 What is NC Doing for an Engineer?

Engineers use NC for automated, fast and high precise manufacturing of individual designed work pieces. Engineers do not have to control CNC machines during manufacturing. Numerical controlled machines execute machining steps automatically and can be adapted very quickly to another product by replacing the data carrier. The execution of NC programs can be repeated to manufacture additional work pieces without any further effort. The possibility of off-floor programming ensures that the machine tool is not blocked during the creation of NC programs, which enables a high utilization of machine tools. Moreover, engineers can create the NC programs automatically on the basis of CAD data. As a consequence, NC is nowadays used on almost all machine tools. Manual adjustment control of the machine itself is only used in machine experimentation and ad-hoc fabrication cases, complete shop-floor oriented tool machine programming is reduced more and more even in small enterprises.

9.3.2 How Does NC Work?

All work piece specific control information like path, feed and speed are written in the NC program. The NC program contains all necessary working steps block by block in the right order. There are different kinds of CNC machines and it is necessary to convert neutral code which is generated by CAM software to the exact code dialect used by a specific CNC machine. The NC postprocessor is computer software which converts general code of the geometry (CLDATA) to the code dialect for a specific CNC machine.

Cutter Location Data (CLDATA) is a programming language for NC processor output data which is standardized in DIN 66215 [9]. CLDATA describes the manufacturing operation in absolute terms. Every NC postprocessor can convert the standardized CLDATA files to CNC machine specific code. The structure of CLDATA is demonstrated in Fig. 9.11.

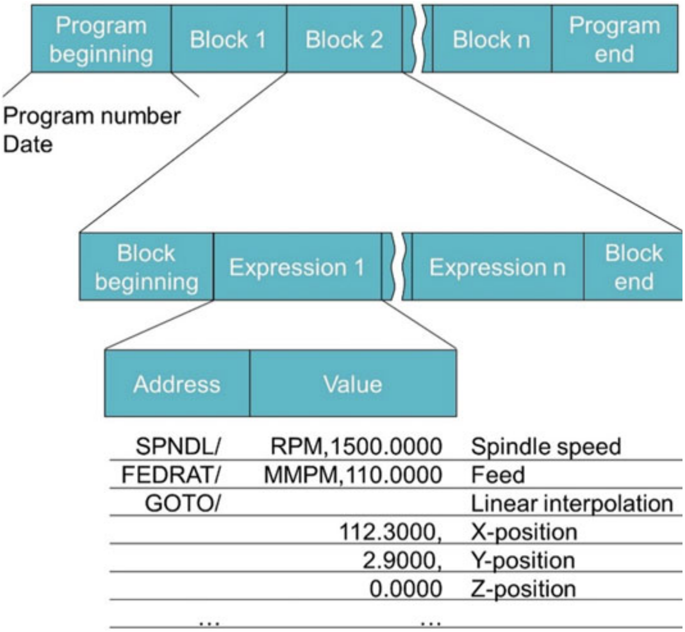


Fig. 9.11 Structure of CLDATA standardized in DIN 66215

The structure of machine specific NC programs is standardized in DIN 66025 sheets 1–3. Each block includes a number of expressions to parametrize different functions. The position information is stored as a numeric value for each axis. It is important to consider that it is the contour of the workpiece and not the tool path the one that is programmed. The tool path is calculated automatically at the machine. Figure 9.12 illustrates the structure of NC programs.

The NC program is stored on electronic data carriers or transmitted directly from the computer to the CNC machine. An industrial computer at the machine reads the NC program and executes the machining steps chronologically. An interpolation program in the CNC calculates intermediate positions because the path does not have to be parallel to the axes. The interpolation points set the position values for a simultaneous movement of all needed axes.

Closed position control loops are used to control the positions of the axes precisely. The actual positions of the axes are measured continuously. The differences between the position set values and the actual positions are amplified by the position controller and used to regulate the motors. Figure 9.13 demonstrates the functionality of the closed position control loop of a translational axis.

The relative movement between the work piece and the tool is used for automated machining of individual designed work pieces.

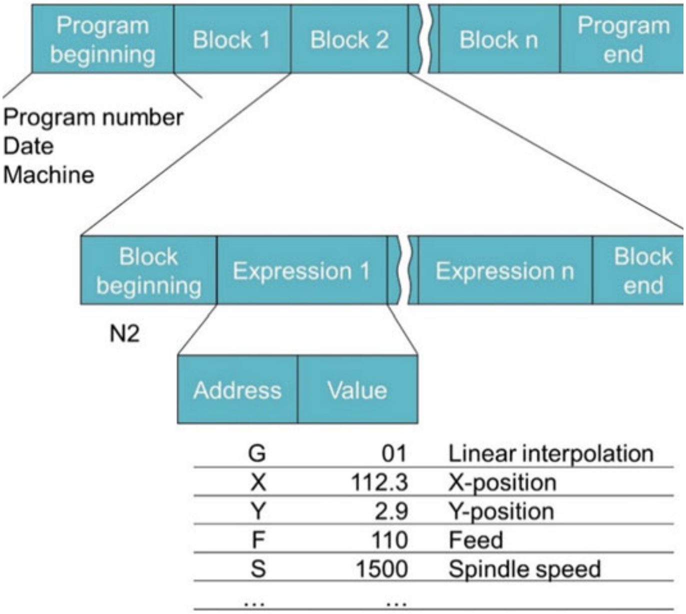


Fig. 9.12 Structure of machine specific NC programs standardized in DIN 66025 (representation based on [10], p. 525)

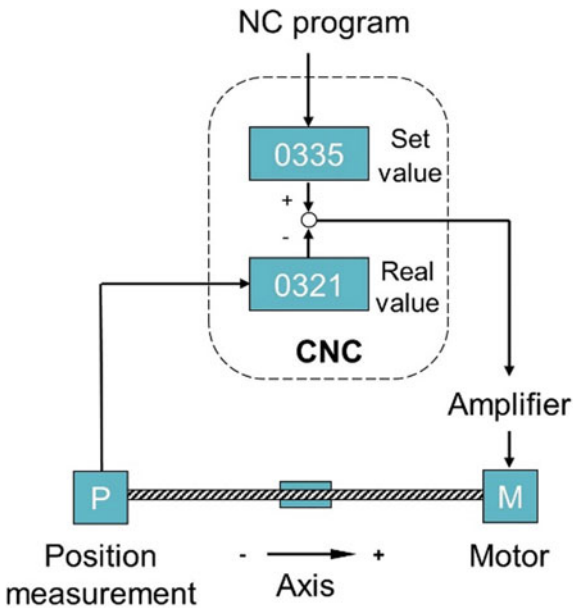


Fig. 9.13 Functionality of the closed position control loop (representation based on [10])

9.3.2.1 Where in the Product Development Process is NC Used?

CAx software is an integral part of today's product development process. Every product starts with an idea. CAD, CAE, CAPP, CAM and NC are used to turn the idea into a real product.

The first step in the process chain is design and development. In design and development CAD and CAE are used for design, digital mockup, simulations and optimizations. Afterwards, CAPP and CAM are utilized in production planning (Manufacturing Engineering) to assign resources, schedule operations, select tools and create NC programs. The N programs are transferred to the production and NC is used to execute the manufacturing steps automatically. The linkage and application areas of CAx systems in product development are shown in Fig. 9.14.

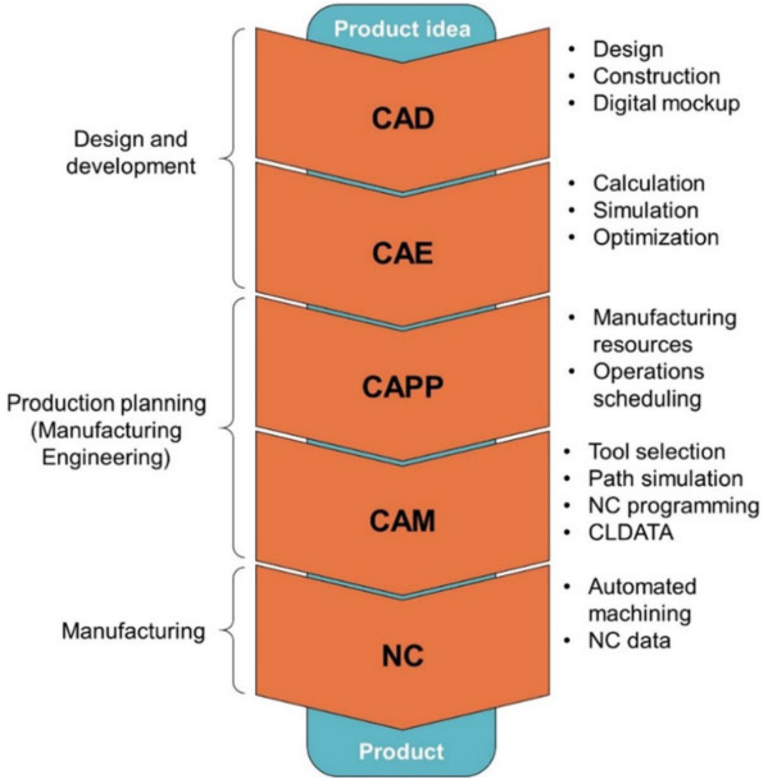


Fig. 9.14 CAx linkage in the product development process (representation based on [3])

9.3.2.2 What Is the Application Area of NC?

There is a wide area of application for NC. NC programs can be used to control and automate processing steps for manufacturing, assembly, equipping and inspection. Machine tools that use NC are for instance milling machines, lathes, drills, sawing machines, grinders, laser machines, 3D printer as well as combinations of these machine types.

9.3.2.3 NC Programming Technology

The following subsection will explain the features of NC and the NC programming process. NC program examples for a lathe process (see Fig. 9.19) and a milling process (see Fig. 9.20) are shown to demonstrate the standardized data input format of NC programs.

CNC machines are freely programmable machines, which usually consist of a combination of translational and rotational axes. Each axis is equipped with an electronic position measuring system and has a controllable drive. The measurements of the axes take place with a resolution of 0.0001 mm or 0.00001° and even finer to achieve precise work piece surfaces. The motion sequences and the technological information like feed (F), speed (S), tool (T) and miscellaneous functions (M) such as tool changes are specified in the exchangeable NC programs. Complex manufacturing steps such as high-speed milling would not be possible without NC [10].

There are three different control modes for NC as shown in Fig. 9.15. Point-to-Point control is only used for positioning when no tools are utilized. All programmed axes start simultaneously at rapid traverse until each axis has reached its target position. It is the fastest way possible to reach a certain position. With the line control, one individual axis can be traversed at a defined feed. So, the path is always parallel to the axes. The third and most relevant control mode is the continuous path control. Any two-dimensional and also three-dimensional path can be realized with the continuous path control. The movements of two or more axes are synchronized by the use of interpolation points in order to achieve the smallest possible deviation from the programmed path.

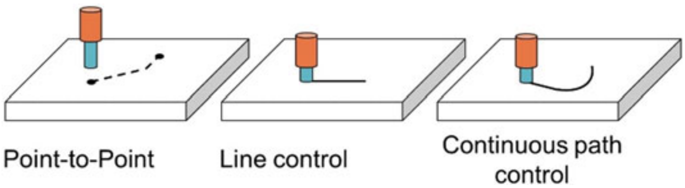


Fig. 9.15 Three different path control modes for NC

The NC technology enables:

- Easy program shifts
- Easy program modifications
- Short set-up times
- High flexibility
- High manufacturing accuracy
- Direct use of CAD data for programming [10].

9.3.2.4 Process Chain for a Milling Process

The geometries of the designed workpiece and the blank are created in a CAD system. CAD-NC modules or independent NC systems are used to generate the process steps by taking into account the tool geometry and technological information as cutting speed. Subsequently, the tool path is created and checked if necessary. A NC postprocessor is used to convert the machine-neutral tool path (CLDATA) into a machine-specific NC program to take into account the specific geometry, kinematic and switching functions of the CNC machine. In the last step of the process chain, the NC program is transferred to the milling machine to manufacture the workpiece. Figure 9.16 shows the NC process chain for a CNC milling process.

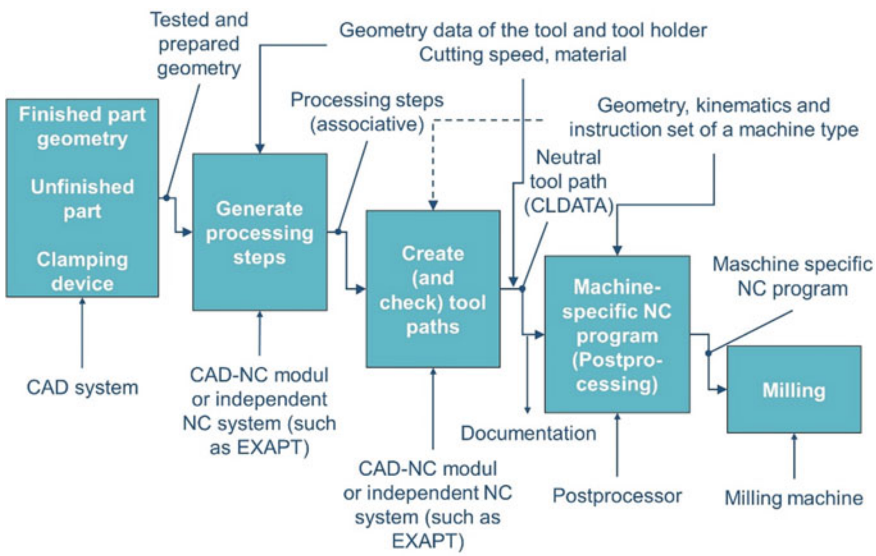


Fig. 9.16 Process chain for a CNC milling process

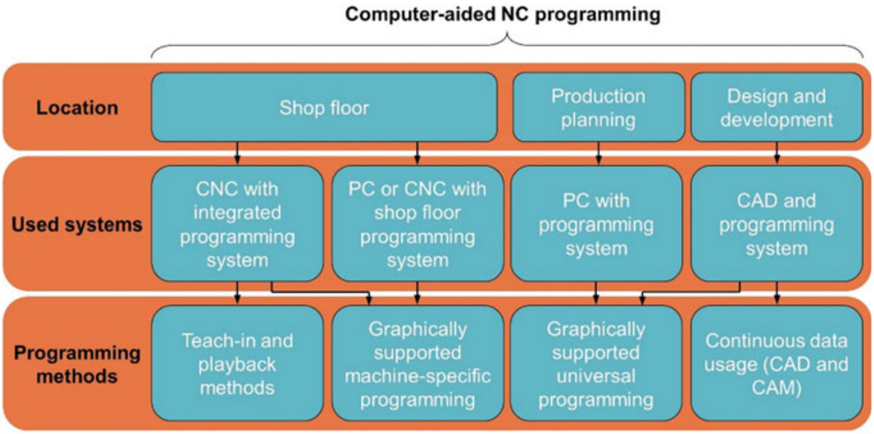


Fig. 9.17 Types of computer-aided NC programming (representation based on [10])

9.3.2.5 Typical Programming Process with NC

It is important to know that all common ways to create NC programs are computer-aided. There are different ways for computer-aided NC programming which can be distinguished by location, used systems and programming methods as shown in Fig. 9.17.

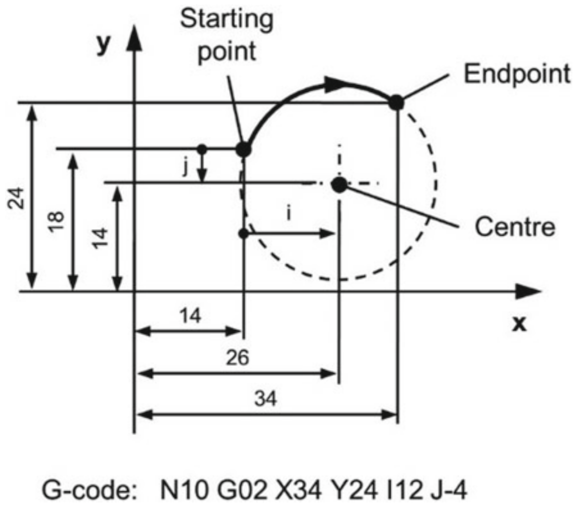
One option is to create the NC program directly on the shop floor. CNC machines often include an integrated programming system which can be used to create and edit NC programs. The advantage of programming on the shop floor is that the workers constantly monitor the progress in production, so, they can use their expertise to eliminate mistakes and optimize the process themselves. In order not to block the CNC machines during programming, in most cases, the NC programs are created externally and transferred to the CNC machine via a storage medium or a network connection.

In addition to shop floor programming, the NC programs can already be created in design and development or production planning. In these cases, the NC programs can be generated directly on the basis of CAD data. So, there is no need to create technical drawings and instructions for the operators as the NC program contains all the necessary geometric and technological information. It should be noted that these generated programs use a universal code that needs to be translated to the machine specific code dialect by means of a postprocessor.

9.3.2.6 Linear and Circular Interpolation

NC programs are not created manually and even changes are not inserted manually in the machine code these days. However, it may be advantageous to know and

Fig. 9.18 Programming circular interpolation



understand the standardized data input format of NC programs because it is used by almost all modern CNC machines.

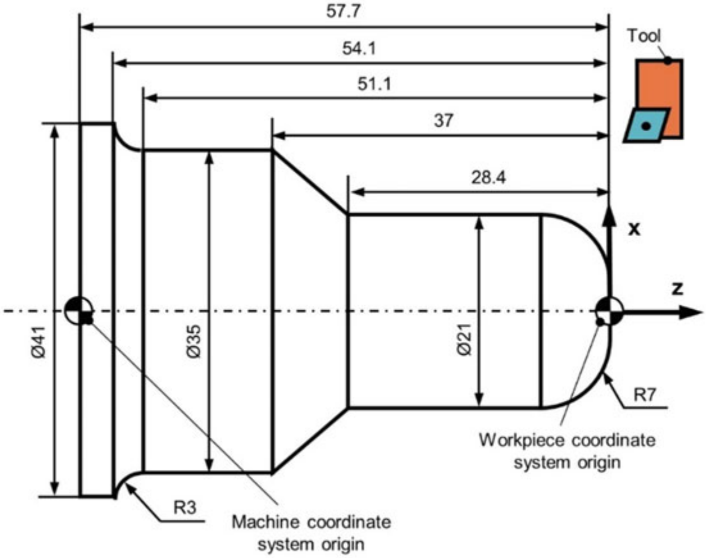
Important tasks are linear and circular interpolations. The command G01 is used for a linear interpolation between a start and end point. A high number of intermediate points are calculated automatically in order to get an accurately linear path. Circular interpolations are programmed with the commands G02 (clockwise) and G03 (counter clockwise). A programing example for a clockwise circular interpolation is illustrated in Fig. 9.18.

9.3.2.7 NC Code Examples

In the following two NC program examples are shown to demonstrate the standardized data input format G-code (standardized in ISO 6893) of NC programs. Figure 9.19 shows the G-code for a lathe process. When creating NC programs for lathes, it is important to consider that the X-values are always programmed using diameters. Figure 9.20 shows the G-code for a milling process.

9.3.2.8 Step-NC

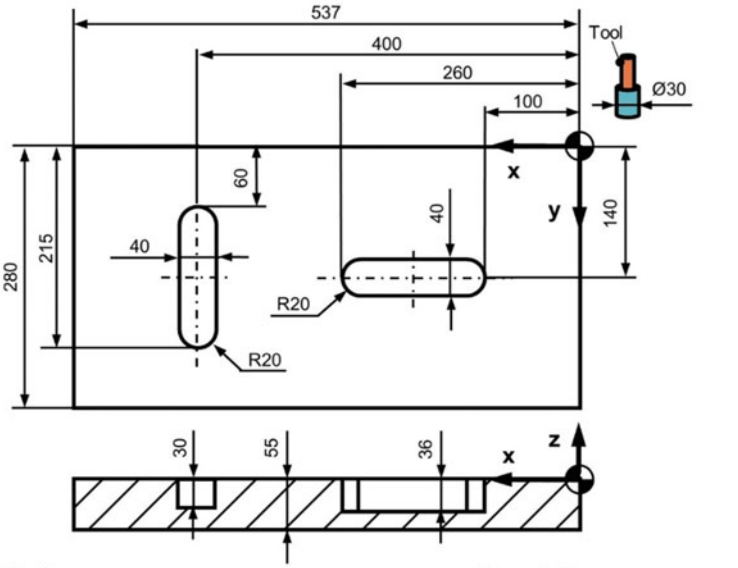
The most common programming language for CNC machines (G-code) has remained essentially unchanged since the early 1950s. Back then, paper tape was the most popular medium for data transfer between computers. Although the capabilities of computers and CNC machines have improved considerably since then, the same programming language is still used to control CNC machines [11].



Block						Description
N1	G54		Z57.7			Offset
N2	G90					Absolute positioning mode
N3	M04				S600	Spindle start counterclockwise
N4	G00	X-4	Z4			Rapid to starting point
N5	G01		Z1		F500	Prepositioning
N6	G02	X-2	Z0	I1	K0	Tangential approach
N7	G01	X7				Move along contour
N8	G03	X21	Z-7	I0	K-7	
N9	G01		Z-28.4			
N10		X35	Z-37			
N11			Z-51.1			
N12	G02	X41	Z-54.1	I3	K0	
N13	G01	X60				Tangential move off
N14	M05					Spindle stop
N15	M30					End of program

Fig. 9.19 G-code example for a lathe process

The control language STEP-NC (standardized in ISO 14649) was developed to replace G-code with a modern, associative communication protocol that connects the process data with the product description of the component. The control language STEP-NC is therefore not limited to axis movement commands of the machine tool. The machine tool can be provided with information about the desired result of the machining. The use of STEP-NC is intended to enable faster, more accurate and more autonomous machine tools that can access product and process models [11].



Block							Description
N1	M03					S1000	Spindle start clockwise
N2	G41						Start cutter radius compensation left
N3	G00	X181	Y159	Z2			Rapid above groove
N4	G01			Z-36		F1500	Move to cutting depth
N5	G03	X180	Y160		I1	J0	Tangential approach
N6	G01	X120					Move along contour
N7	G03		Y120		I0	J-20	
N8	G01	X240					
N9	G03		Y160		I0	J20	
N10	G01	X179					
N11				Z2			Move off
N12	G00	X419	Y139				Rapid above groove
N13	G01			Z-30			Move to cutting depth
N14	G03	X420	Y140		I0	J1	Tangential approach
N15	G01		Y195				Move along contour
N16	G03	X380			I-20	J0	
N17	G01		Y80				
N18	G03	X420			I20		
N19	G01		Y141				
N20				Z20			Move off
N21	M05						Spindle stop
N22	M30						End of program

Fig. 9.20 G-code example for a milling process

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