CHAPTER 14

Manufacturing Process Planning and Design

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1. INTRODUCTION

Manufacturing process planning is an important step in the product-realization process. It can be defined as "the function within a manufacturing facility that establishes which processes and parameters are to be used (as well as those machines capable of performing these processes) to convert a part from its initial form to a final form predetermined (usually by a design engineer) in an engineering drawing" (Chang et al. 1998, p. 515). Alternatively, it can be defined as the act of preparing detailed work instructions to produce a part. The result of process planning is a process plan. A process plan is a document used by the schedulers to schedule the production and by the machinist /NC part programmers to control/program the machine tools. Figure 1 shows a process plan for a part. The process plan is sometimes called an operation sheet or a route sheet. Depending on where they are used, some process plans are more detailed than others. As a rule, the more automated a manufacturing shop is, the more detailed the process plan has to be.

To differentiate the assembly planning for an assembled product, process planning focuses the planning on the production of a single part. In this chapter, when a product is mentioned, it refers to a discrete part as the final product. One important step in process planning is process selection, which is the selection of appropriate manufacturing processes for producing a part. When none of the existing processes can produce the part, a process may have to be designed for this purpose. Process design can also be interpreted as determining the parameters of a process for the manufacture of a part. In this case, process design is the detailing of the selected processes. Thus, process planning and process design are used for the same purpose—determining the methods of how to produce a part.

In this chapter, process planning and design are discussed. Techniques employed for process planning and process design are also introduced. Due to the vast number of manufacturing processes, it would be impossible to cover them all in this chapter. Only machining processes are focused upon here. However, early in the chapter, casting, forming, and welding examples are used to illustrate alternative production methods.

1.1. The Product-Realization Process

Manufacturing is an activity for producing a part from raw material. In discrete product manufacturing, the objective is to change the material geometry and properties. A sequence of manufacturing processes is used to create the desired shape. The product-realization process begins with product design. From the requirements, an engineering design specification is prepared. Through the design process (the details of which are omitted here), a design model is prepared. Traditionally, the design model is an engineering drawing (drafting) either prepared manually or on a CAD system. Since the

PROCESS PLAN — ACE Inc.

Part No. S0125-F — Material: steel 4340Si
Part Name: Housing
Original: S.D.Smart Date: 1/1/89 — Changes: ______ Date: ______
Checked: C.S.Good Date: 2/1/89 — Approved: T.C. Chang Date: 2/14/89

No.	Operation Description	Workstation	Setup	Tool	Time (Min)
10	Mill bottom surface 1	MILL01	see attach#1 for illustration	Face mill 6 teeth/4" dia	3 setup 5 machining
20	Mill top surface	MILL01	see attach#1	Face mill 6 teeth/4" dia	2 setup 6 machining
30	Drill 4 holes	DRL02	set on surface1	twist drill 1/2" dia 2" long	2 setup 3 machining

Figure 1 Process-Plan.

1990s, solid model for engineering design has gained popularity for representing design models. A design model must contain the complete geometry of the designed part, the dimensions and tolerances, the surface finish, the material, and the finished material properties. The design model is a document, or contract, between the designer and the manufacturing facility. The finished product is checked against the design model. Only when all the specifications on the design model are satisfied is the product accepted.

There are several steps in the product-realization process (Figure 2): design, process planning, manufacturing, and inspection. Process planning is a function linking the design and the manufacturing activities. The objective of manufacturing is to produce the product at an acceptable quality (instead of the best quality), in a desired time frame (not necessarily the shortest time), and at the lowest cost (lowest cost is always desirable). Because manufacturing follows the process plan, the quality of the process plan is critical to the success of manufacturing and thus product realization. In the following section, the more detailed steps of product realization are discussed.

1.2. From Design to Process Planning to Production

Before a product is materialized, it has to be designed and manufactured. Following are the major steps in this product realization process.

1.2.1. Selection of Materials

Materials are selected based on the functionalities of the part being made. Most parts are made from a single material. Material selection may not be the first step in design. However, it is an important decision to be made. Often, several materials all satisfy the functional requirements of the part. For example, one may choose steel, aluminum, of composite material for the part. Although the physical, mechanical, and electrical properties all satisfy the design requirements, the material and processing costs might be very different. The material cost is easily estimated (Table 1), but estimating the processing cost is more involved. For example, steel-part manufacturing is very different from composite-part manufacturing. Totally different machines and material-handling methods are needed. A good designer will take manufacturing issues into consideration. Design for manufacturing should begin with the proper selection of materials for manufacturing. In some cases, due to the material property, the geometry of the part will need to be changed.

1.2.2. Geometry Creation

The shape of a product can be determined by functional or aesthetic considerations. Individual parts in an assembly must fit together to form the assembly. They use the geometric shape to carry out a specific function. For example, an angle bracket is used for mounting a machine, a hole is used to

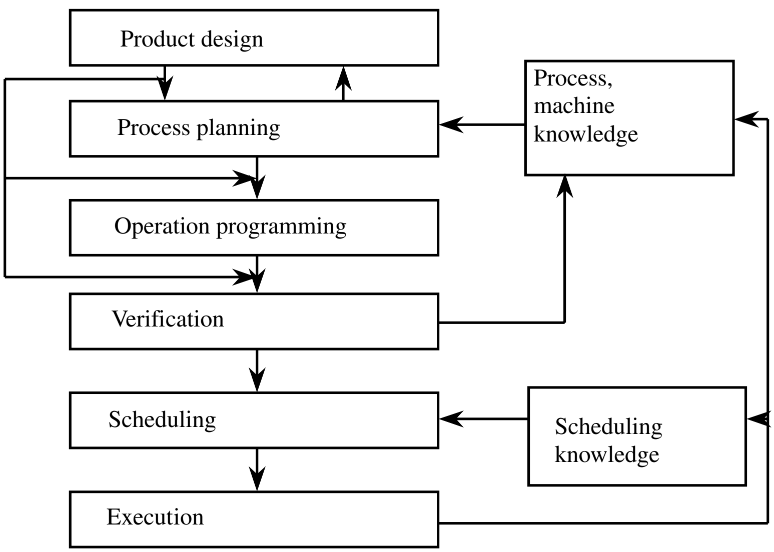

Figure 2 Product-Realization Process.

TABLE 1 Approximate Cost of Raw Materials as a Function of their Condition, Shape, and Size

Material	Cost ($)	Material	Cost ($)
Carbon-steel plate and sheet		Aluminum plate	
Hot rolled	60–70	2024 T351	530–590
Cold rolled	75–90	6061 T651	330–350
Carbon-steel bars		7075 T651	560–620
Hot rolled, round	55–80	Aluminum sheet	
Cold finished, round	60–200	2024 T3	610–650
Cold finished, square	90–170	3003 H14	275–300
Stainless steel sheet		6061 T6	360–400
304	230	Aluminum bars	
316	300–340	Round	275–510
410	375	Square	575–700
Stainless steel bars		Rectangular	550–1000
304 round	310–730	Aluminum extrusions	260–310
303 square	560–000		

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fit an axle, and a T-slot is used to hold a bolt. The designer must create the appropriate geometry for the part in order to satisfy the functional requirements. The ultimate objective of the designer is to create a functionally sound geometry. However, if this becomes a single-minded mission, the designed part may not be economically competitive in the marketplace. Cost must also be considered.

Manufacturing processes are employed to shape the material into the designed geometry. A large number of unrelated geometries will require many different processes and/or tools to create. The use of standard geometry can save money by limiting the number of machines and tools needed. For example, a standard-size hole means fewer drill bits are needed. Design for manufacturing also means imposing manufacturing constraints in designing the part geometry and dimension.

The designed geometry is modeled on a CAD system, either a drawing or a solid model (see Figure 3). More and more designs are modeled using 3D solid modelers, which not only provide excellent visualization of the part and assembly but also support the downstream applications, such as functional analysis, manufacturing planning, and part programming. The key is to capture the entire design geometry and design intents in the same model.

1.2.3. Function Analyses

Because the designed part must satisfy certain functional requirements, it is necessary to verify the suitability of the design before it is finalized. Engineering analyses such as kinematic analysis and heat transfer are carried out from the design. Finite element methods can be used, often directly from a design model. The more critical a product or part is, the more detailed an analysis needs to be conducted.

1.2.4. Design Evaluation

The task of design evaluation is to separate several design alternatives for the final selection of the design. Cost analysis, functionality comparison, and reliability analysis are all considerations. Based on the predefined criteria, an alternative is selected. At this point the design is ready for production.

1.2.5. Process Planning

Production begins with an assembly/part design, production quantity, and due date. However, before a production order can be executed, one must decide which machines, tools, and fixtures to use as well as how much time each production step will take. Production planning and scheduling are based on this information. As noted earlier, process planning is used to come up with this information. How to produce a part depends on many factors. Which process to use depends on the geometry and the material of the part. Production quality and urgency (due date) also play important roles. A very different production method will definitely be appropriate for producing a handful of parts than for a million of the same part. In the first case, machining may be used as much as possible. However, in the second case, some kind of casting or forming process will be preferable.

When the due date is very close, existing processes and machines must be used. The processes may not be optimal for the part, but the part can be produced in time to meet the due date. The cost

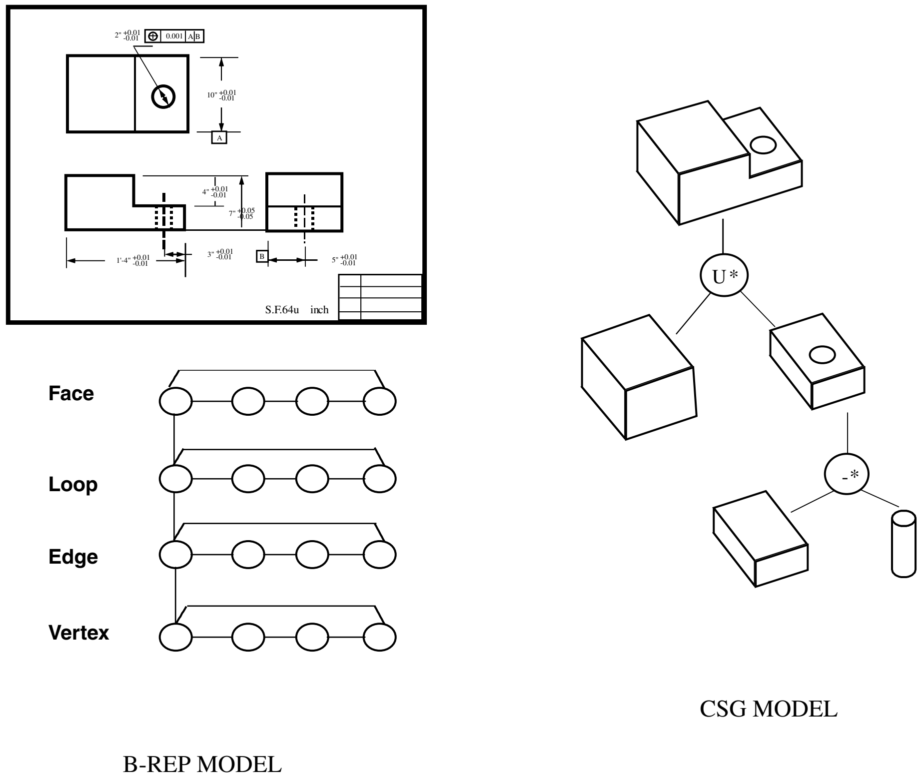


Figure 3 Design Representations.

will be high—one pays for urgent orders. On the other hand, when there is plenty of lead time, one should try to optimize the process. When the production quantity justifies the cost, it might be necessary to design new processes or machines for the part. One good example is the use of a transfer line for engine block production. Machines (stations) in a transfer line are specially designed (or configured) for a part (e.g., an engine block). Production is optimized. Lower cost and higher quality can be expected. Table 2 shows the recommended production systems for different production quantities and production lead times.

1.2.6. Production Planning and Scheduling

After process planning is complete, production is ready to begin. Production planning and scheduling are important functions in operating the manufacturing facility. Because multiple products or parts are being produced in the same manufacturing facility, the resource allocation must be done appropriately in order to maximize the production output. When a transfer line or production line (assembly line) is the choice, the line is balanced (equal numbers of tasks are allocated to each machine station)

TABLE 2 Recommended Production Methods

	Long Lead Time	Medium Lead Time	Short Lead Time
Mass production	Transfer-line	Product line	Job shop
Medium batch	Manufacturing cell Job shop	Job shop Manufacturing cell	Job shop
Small volume	Job shop	Job shop	Job shop

and designed. After a line is installed, the operation of the line is simple. Upon the workpiece being launched at one end of the line, the product is built sequentially through the line. However, in a shop environment, production scheduling is much more complex. For each planning horizon (day or week), what each machine should process and in which sequence must be decided. Predefined objectives such as short processing time, maximum throughput, and so on are achieved through proper scheduling. Scheduling uses information provided by the process plan. A poorly prepared process plan guarantees poor results in production.

1.2.7. Consideration of Production Quantity in Process Planning

As noted above, production quantity affects the manufacturing processes selected for a part. If the production quantity is not considered in process planning, the result may be an expensive part or a prolonged production delay. Large quantities make more specialized tools and machines feasible. Small-quantity production must use general-purpose machines. Although the total quantity may be high, in order not to build up inventory and incur high inventory cost, parts are usually manufactured in small batches of 50 parts or less. Therefore, production batch size is also a factor to be considered. There is decision making loop. The process plan is the input to production planning; production planning determines the most economical batch size; batch size, in turn, changes the process plan. A decision can be made iteratively.

2. PROCESS PLANNING

As noted above, process planning is a function that prepares the detailed work instructions for a part. The input to process planning is the design model and the outputs include processes, machines, tools, fixtures, and process sequence. In this section, the process planning steps are discussed. Please note that these steps are not strictly sequential. In general, they follow the order in which they are introduced. However, the planning process is an iterative process. For example, geometry analysis is the first step. Without knowing the geometry of the part, one cannot begin the planning process. However, when one selects processes or tools, geometric reasoning is needed to refine the understanding of the geometry. Another example is the iterative nature of setup planning and process selection. The result of one affects the other, and vice versa.

2.1. Geometry Analysis

The first step in process planning is geometry analysis. Because the selection of manufacturing processes is geometry related, the machining geometries on the part, called manufacturing features, need to be extracted. An experienced process planner can quickly and correctly identify all the pertinent manufacturing features on the part and relate them to the manufacturing processes. For example, the manufacturing features of holes, slots, steps, grooves, chamfers, and pockets are related to drilling, boring, reaming, and milling processes. The process planner also needs to note the access directions for each feature. Also called approach directions, these are the unobscured directions in which the feature can be approached by a tool. When features are related to other features, such as containment, intersection, and related in a pattern, these relationships must be captured. Feature relations are critical in deciding operation (process) sequence. Figure 4 shows a few features and their approach directions. The pocket at the center and steps around the center protrusion are approachable from the top. The hole may be approached from the top or from the bottom.

In computer-aided process planning, the geometry analysis (or geometric reasoning) is done by computer algorithms. The design model in the form of a solid model is analyzed. Based on the local geometry and topology, regions are extracted as features. To be significant to manufacturing, these features must be manufacturing features (Figure 5). Again, manufacturing features are geometric entities that can be created by a single manufacturing process or tool. Like manual geometry analysis, geometric reasoning must find feature access directions (approach directions) and feature relations. Due to the vague definitions of features, the large number of features, and the complexity in feature matching (matching a feature template with the geometric entities on the solid model), geometric reasoning is a very difficult problem to solve. This is one of the reasons why a practical, fully automatic process planner is still not available. However, a trained human planner can do geometry analysis relatively easily. More details on geometric reasoning can be found in Chang (1990).

2.2. Stock Selection

Manufacturing is a shape-transformation process. Beginning with a stock material, a sequence of manufacturing processes is applied to transform the stock into the final shape. When the transformation is done using machining, minimizing the volume of materials removed is desirable. Less material removal means less time spent in machining and less tool wear. The stock shape should be as close to the finished part geometry as possible. However, in addition to the minimum material removal rule, one also has to consider the difficulty of work holding. The stock material must be

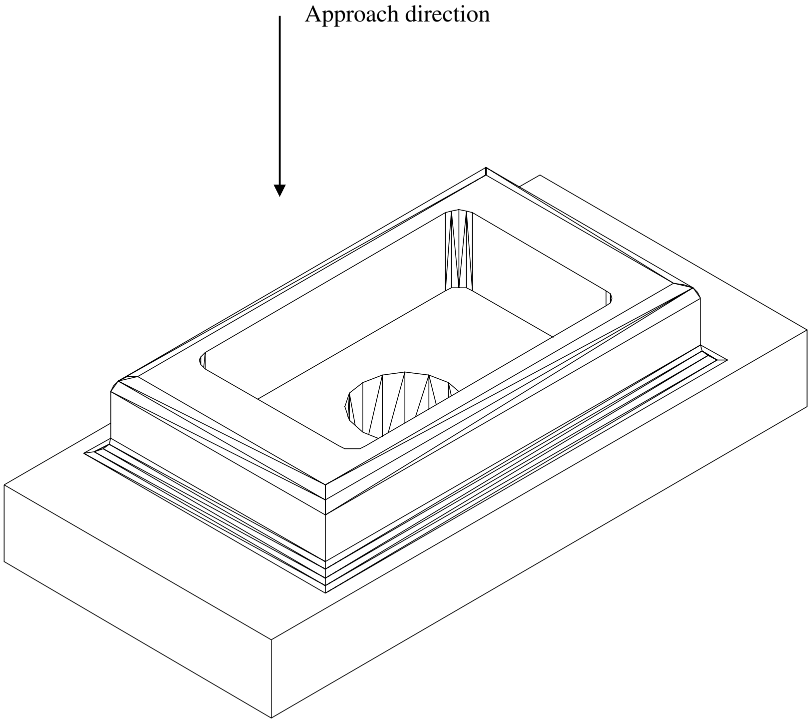


Figure 4 Protrusion, Pocket, and Hole.

clamped or chucked on the machine tool before cutting can be performed. This fixturing consideration has practical importance. However, raw materials can be purchased only in limited shapes and dimensions. For example, steel is supplied in sheets of different thickness, length, and width, strips, wires, bars, and so on. The general shape has to be determined, and then stock preparation (cutting) has to be done to produce the stock. This is also true for the forming processes.

After the stock material is selected, one can compare the stock with the finished part and decide the volume of material to be removed for each process. In automated process planning, often the difference between the stock and the part, called the delta volume, is calculated. Geometric reasoning is performed on the delta volume. Without first selecting the stock, one cannot be certain exactly how to proceed with the manufacturing processes.

In some cases, especially for mass production, minimizing metal removal means preparing a casting as the stock material. Machining is used to improve critical or hard-to-cast surfaces. In this case, the casting has to be designed based on the part. Using casting as the stock minimizes the machining yet requires a high initial investment (casting design, mold making, etc.).

2.3. Gross Process Determination

Process planning can be separated into two stages: gross planning and detailed planning. Often only detailed planning is discussed in the process planning literature. Actually, the gross planning is even more critical than the detailed planning. Gross planning is used to determine the general approach to produce a part. For example, the same part geometry may be created through casting, machining, 3D fabrication, or welding of sheet metal. Only when a general approach is determined may one proceed with the detailed planning.

2.3.1. Casting, Machining, and Joining

One of the first decisions a process planner needs to make is whether to cast the part or machine it. Rough casting, such as sand casting, requires a good amount of machining. However, precision casting, such as die casting and investment casting, can produce almost net shape part (finished part). The decision is based on both economics and material properties; this issue will be addressed below.

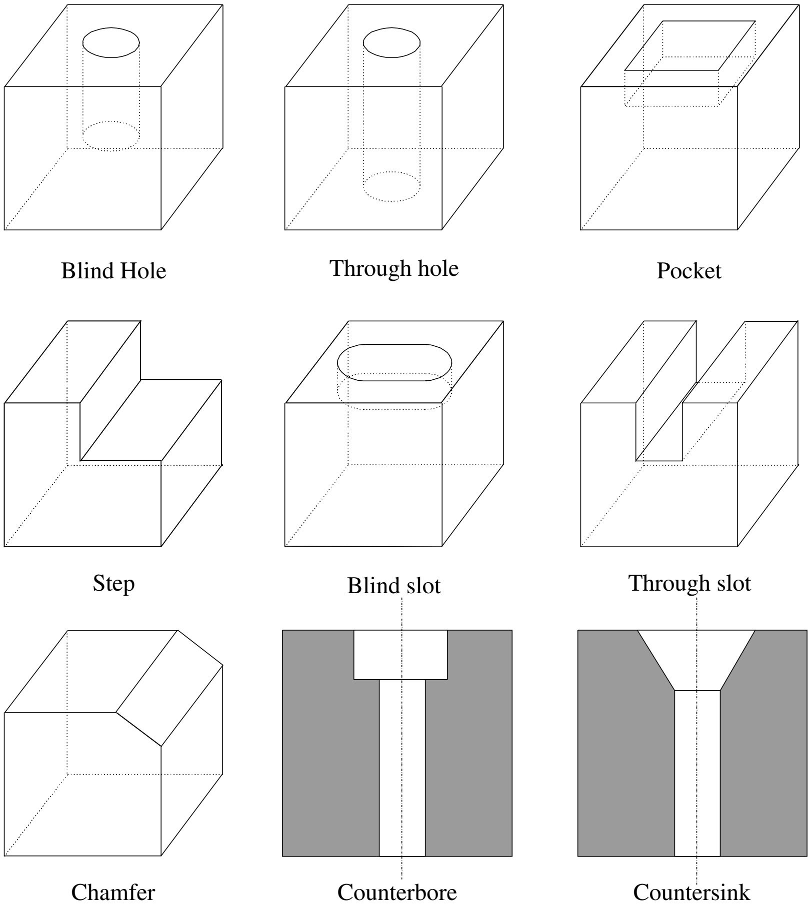


Figure 5 Some manufacturing Features.

In the initial evaluation, the technical feasibility and relative costs are taken into consideration. Process capabilities and relative cost for each casting and machining process are used in the evaluation. Based on the geometry to be created, material used, and production volume, one can propose several alternative processes. The process capability includes shape capabilities and accuracy. Casting processes, such as die casting and investment casting, can create intricate geometry with relative high precision (0.01 in.). However, sand casting is much worse. For tighter dimensional control, secondary machining is a must.

Certain parts can be built using the welding process as well. This is especially true for structural parts. Large structural parts such as ship hulls are always built using welding. Medium-sized structural parts such as airplane structure parts may be joined together from machined parts. Sectional structures for jet fighters are always machined from a solid piece of metal in order to obtain the maximum strength. For small structures, all manufacturing methods are possible. When there are several alternatives, an initial selection needs to be made.

2.3.2. Product Strength, Cost, etc.

Parts made using different stocks and processes exhibit different strength. As mentioned above, sectional structures for jet fighters are always machined from a solid piece of alloy steel. The raw material is homogeneous and rolled into the shape in the steel mill. It has high strength and consistent properties. When casting is used to form a part, a certain number of defects can be expected. The cooling and thus solidification of the material are not uniform. The surface area always solidifies first and at a much higher rate than the interior. A hard shell forms around the part. Depending on the complexity of the part, the type of mold used (sand, metal, etc.) and the mold design, voids, hot tear, cold shut, or other problems can happen. The part is not as strong as those produced using machining. In the case of welded parts, the welded join may not be as strong as the rest of the part.

As for the manufacturing cost, there is an even greater difference. For machining, the initial cost is low but the incremental cost is higher. The opposite is true for casting. Figure 6 shows the comparison. The initial cost for casting includes the cost of designing and building the mold and is relatively high. The slope of the incremental cost is the casting cost per piece. For machining, the initial cost is relatively much lower. On a manually controlled machine, only tools and fixtures need to be purchased. When a CNC machine is used, the programming cost has to be added to the fixed cost. However, the machining cost per piece will be lowered.

There are always alternative ways to make a part. Unless the way is specified by the designer, a good process planner always considers all possible alternatives and evaluate them. This evaluation need not always be carried out formally and precisely. Using past experience and with rough estimates, one can quickly eliminate most alternatives. The most promising alternatives have to be explored further before they are accepted or discarded.

2.4. Setup and Fixture Planning and Design

Let us assume that machining is the best alternative for the production of a part. Using the result of geometry analysis, we can group machining features based on their feasible approach directions. Most machining processes require the workpiece be positioned so that the tool orientation matches with the feature approach direction. For example, the part in Figure 7 consists of four holes. All holes have the same approach direction. Therefore, it is best to set up the workpiece with the holes aligned with the machine spindle. The position of the workpiece is called the setup position. When there are multiple approach directions, multiple setups may be needed to finish the machining operations.

A fixture is used to hold the workpiece at the desired setup position. For simple workpieces, a vise is sufficient to do the job. However, for more complex workpieces, locators and clamps are needed to position and clamp the workpiece on the machine table. After each setup the workpiece geometry is transformed (Figure 8). The finished part is obtained after the last setup is done. After a fixture is designed or configured (using modular figures), tool interference has to be checked. Obviously, fixture elements should not interfere with the tool motion. If the current fixture does interfere with the tool, either a new fixture needs to be designed or the machining feature that causes interference will not be cut during this setup. Again, this illustrates the iterative nature of process planning steps.

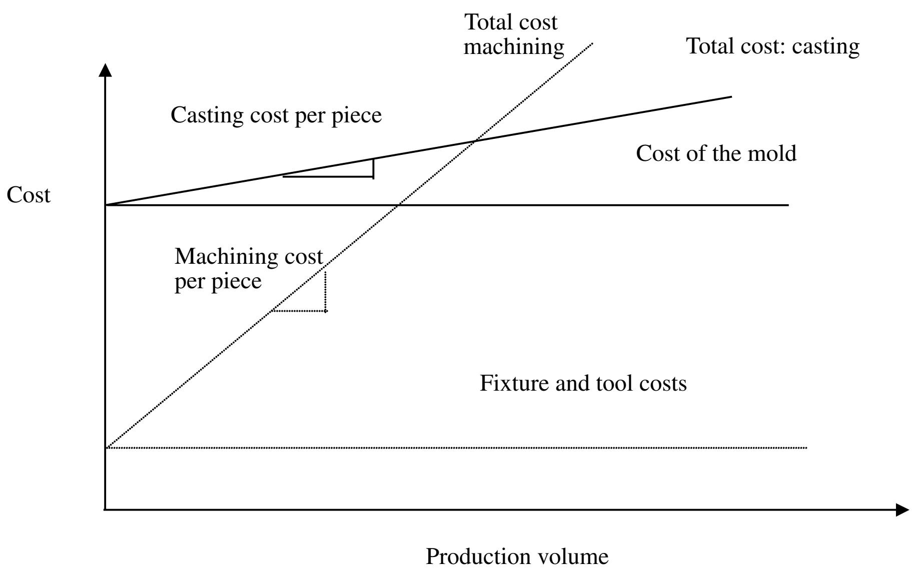


Figure 6 Costs vs. Production Volumes for Different Production Methods.

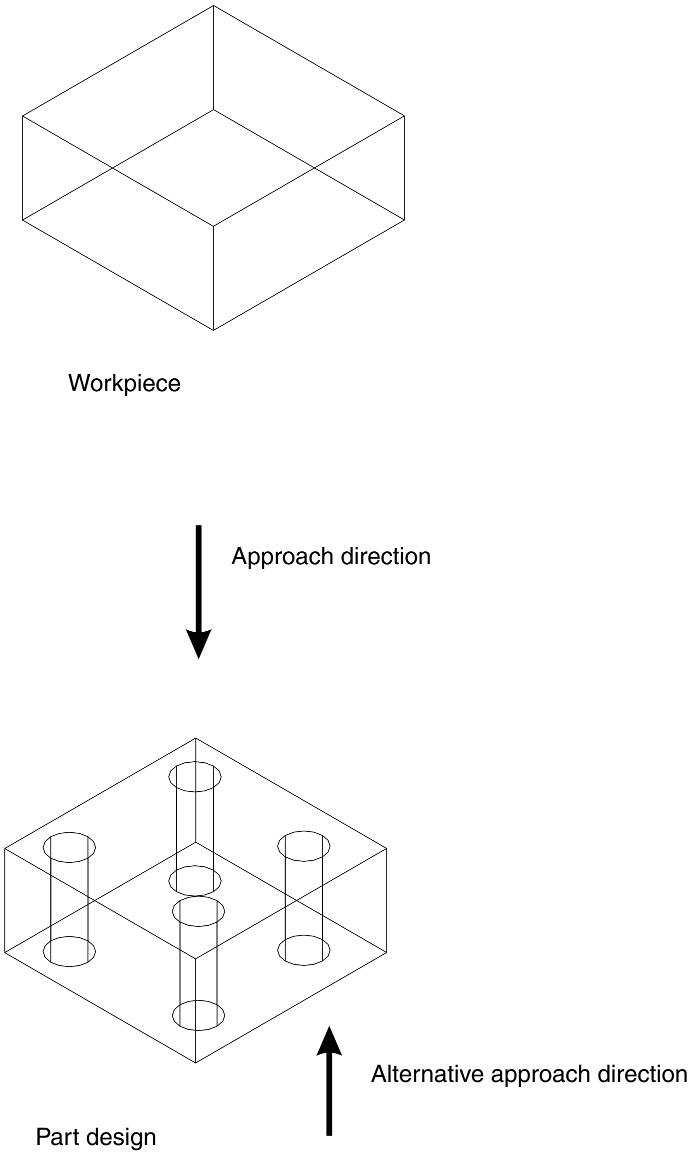


Figure 7 Workpiece and Features on a Part.

2.5. Process Selection

Process is defined as a specific type of manufacturing operation. Manufacturing processes can be classified as casting, forming, material-removal, and joining processes. Under casting are sand casting, investment casting, die casting, vacuum casting, centrifugal casting, inject molding, and so on. Forming includes rolling, forging, extrusion, drawing, powder metallurgy, thermoforming, spinning, and so on. Material removal includes milling, turning, drilling, broaching, sawing, filing, grinding, electrochemical machining (ECM), electrical-discharge machining (EDM), laser-beam machining, waterjet machining, ultrasonic machining, and so on. Joining processes include arc welding, electron-beam welding, ultrasonic welding, soldering, brazing, and so on. In this chapter only material-removal processes examples are used.

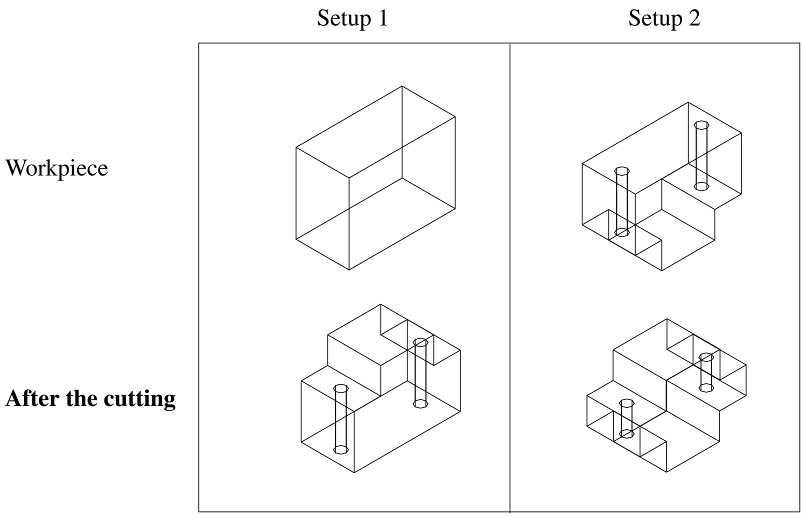


Figure 8 Setup of a Part.

Each process has its own geometric and technological capabilities. Geometric capability means the shapes a process can create and the geometric constraints it might have. For example, the drilling process usually creates round holes and due to the drill nose cone the hole bottom has the cone shape. Technological capability includes tolerances (both dimensional and geometrical), surface finish, and surface integrity. Processes are selected based on the machining features in a setup. In the previous example (Figure 7), a setup consists of four holes. The hole geometry matches the drilling process capability. Therefore, drilling is selected for the holes. In this example, the drilling sequence has no effect on the final product or the manufacturing cost. However, in many other cases the process sequence does matter. For example, in Figure 9 there are four holes and a step. It makes more sense to mill the steps before drilling the holes than the other way around. When the two left-hand holes are drilled first, much of the drilling is done in vain. The milling process will remove the top half of the holes drilled. The process sequence is determined based on the relationship between features and the technological constraints of the processes. A good process planner takes all these into consideration when selecting the processes.

2.6. Process Detailing

Process detailing involves filling the details for the process selected. It includes determining the tool for the process, tool parameters (total length, diameter, cutting length, etc.), and process parameters (speed, feed, depth of cut, etc.).

2.6.1. Tool Selection

In order to carry out the process selected for a feature, a cutting tool is needed. Many different cutting tools can be used for the same process. In drilling, for example, there are different types of drill bites, such as twist drill, spade drill, and gun drill. Each drill also comes with different diameters, cutting length, total length, nose angle, and tool material. For drilling the holes in the example (Figure 9), two different drill lengths with the same diameter are needed. Of course, the longer drill can be used to drill shorter holes, too. However, if the diameters are slightly different, separate drills need to be specified.

Figure 10 shows different kinds of drills and turn tools. The selection of a tool depends on the feature geometry and geometric constraints. In considering milling, there are even more tool parameters to consider. In addition to tool diameter, cutting depth, there are also such factors as number of cutting teeth, insert material, and rake angle. For end mills, there are also bottom-cutting and non-bottom-cutting types. Faced with this vast amount of choices, one must often rely on past experience and, for unfamiliar tools, handbooks.

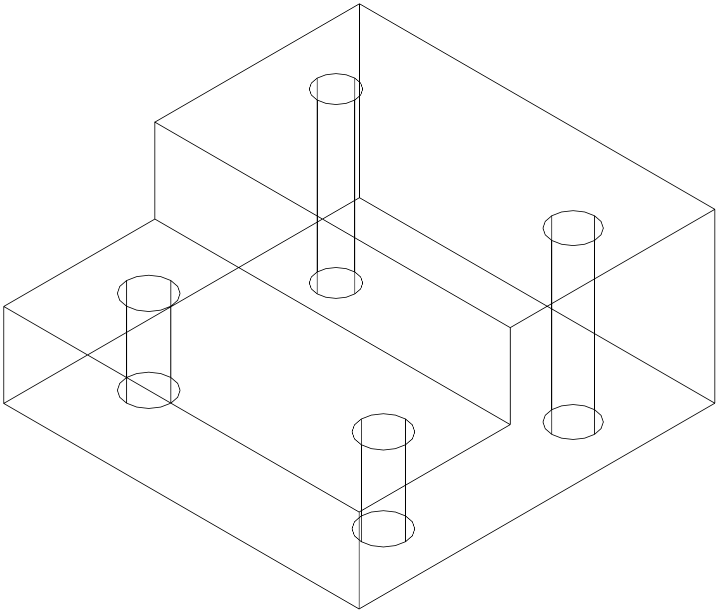


Figure 9 Sample Part with Holes and Step.

2.6.2. Process Parameters Determination

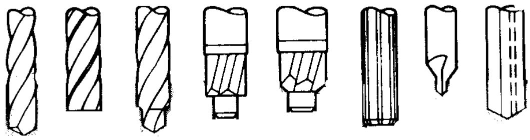
Process parameters include speed, feed, and depth of cut. They are critical to the cutting process. Higher parameter values generate higher material-removal rate, but they also reduce the tool life. High feed also means rougher surface finish. In drilling and turning, feed is measured as how much the tool advances for each rotation of the tool. In milling, it is the individual tooth advancement for each tool rotation. In turning, for example, smaller feed means closely spaced tool paths on the part surface. The finish will be better in this case. Higher feed separates the tool paths and in the worst case creates uncut spacing between two passes. Types of process, the tool and workpiece materials, and hardness of the workpiece material affect process parameters. The parameter values are determined through cutting experiments. They can be found in the tool vendor's data sheets and in the *Machining Data Handbook* (Metcut 1980). These data are usually based on the constant tool life value, often 60 minutes of cutting time. When the required surface finish is high, one must modify the recommended parameters from the handbook. For new materials not included in any of the cutting parameter handbooks, one must conduct one's own cutting experiments.

2.6.3. Process Optimization

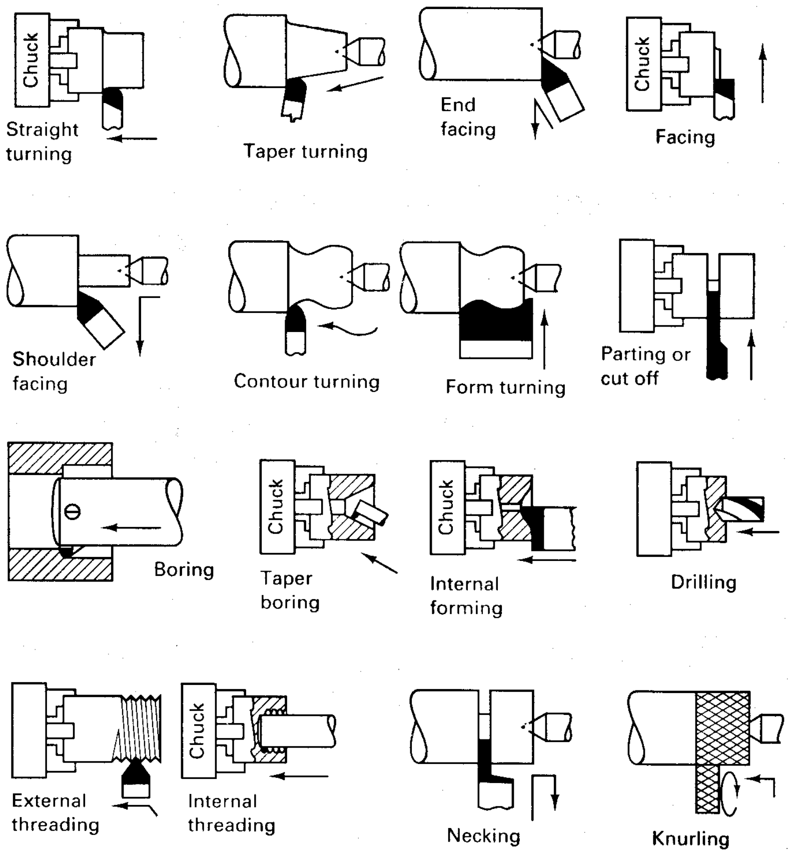
It is always desirable to optimize the production. While global optimization is almost impossible to achieve, optimization on the process level is worth trying. The total production time is the sum of the cutting time, the material handling time, and the tool-change time. Shorter cutting time means faster speed and feed and thus shorter tool life. With a shorter tool life, the tool needs to be changed more frequently and the total time is thus increased. Because there is a trade-off between cutting time and tool life, one may find the optimal cutting parameters for minimum production time or cost. The techniques of process optimization are based on an objective function (time, cost, or another criterion) and a set of constraints (power, cutting force, surface finish, etc). The process-optimization models will be discussed later in the chapter. Finding optimal cutting parameters is fairly complex and requires precise data on both tool life model and machining model. Except in mass production, process optimization is generally not considered.

2.7. Plan Analysis and Evaluation

In on an old study conducted in industry, when several process planners were given the same part design, they all came up with quite different process plans. When adopted for the product, each



Drills



Turn tools

Figure 10 Different Cutting Tools.

process plan resulted in different costs and part quality. If multiple process plans can be prepared for the same part, each plan must be analyzed and the best selected based on some preset criteria. If only one plan is prepared, it must be evaluated to ensure that the final result is acceptable. The final result here means the product quality.

2.7.1. *Machining Time and Cost Estimation*

Machining time can be calculated based on the cutting parameters and the feature geometry and dimension. It is used to estimate the production time and cost. It is also used in scheduling for determining the machine time. For turning and drilling, machining time can be calculated by the following formula:

$$T_m = \frac{L}{V_f}$$

$$V_f = fn$$

$$n = \frac{V}{\pi D}$$

where T_m = machining time, min
L = length of cut, in.
V_f = feed rate, ipm
f = feed, ipr (in. per revolution)
n = tool rpm
D = tool diameter, in.

For complex features, it is harder to estimate the length of the tool path. A rough estimation may be used. The material-removal rate (MRR) of the tool is calculated. The machining time is therefore the feature volume divided by the MRR. MRR for turning and drilling is:

$$\text{MRR} = V_f A$$

where A = the cross-sectional area of the cutting

For hole drilling,

$$A = \frac{\pi D^2}{4}$$

For turning,

$$A = 2\pi r^2 a_p$$

where r = cutting radius
a_p = the depth of cut

Machining cost can be calculated by the machining time times a machine and operator overhead rate.

2.7.2. Estimated Product Quality

The commonly considered technological capabilities of a process include tolerances and surface finish. Surface finish is determined by the process and process parameters. It is affected not by the order in which processes are applied but only by the last process operated upon the feature. However, tolerances are results of a sequence of processes. Operation sequences will affect the final tolerance. Using a simple 2D part, Figure 10 shows the result of different process sequences. The arrow lines are dimension and tolerance lines. The drawing shows that the designer had specified dimensions and tolerances between features *AB*, *BC*, and *CD*. Notice that in this case features are vertical surfaces. If one uses feature *A* as the setup reference for machine *B*, *B* for *C*, and *C* for *D*, the produce part tolerance will be the same as the process tolerance. However, it would be tedious to do it this way. One may use *A* as the reference for cutting *B*, *C*, and *D*. In this case, tolerance on *AB* is the result of the process that cut *B* (from *A* to *B*). However, the tolerance on *BC* is the result of processes that cut feature *B* (from *A* to *B*) and feature *C* (from *A* to *C*). The finished tolerance on *BC* is twice the process tolerance and twice that of *AB*. The same can be said for *CD*. If we choose *D* as the reference, of course, the tolerance on *CD* is smaller than that for *AB* and *BC*. So we may conclude that process sequence does affect the quality of the part produced. The question is whether the current process sequence satisfies the designed tolerance requirements. Often this question is answered with the tolerance charting method. Tolerance charting will be introduced in the next section.

3. TOOLS FOR PROCESS PLANNING

Process-planning steps were introduced in the previous section. This section discusses the tools used to carry out these steps. Manual process planning, which relies on human experience, will not be discussed. The tools discussed in this section are those used in computer-aided process-planning systems. They are used to assist the human planner in developing process plans. Most of these tools have been used in practical process-planning systems. Methodologies or algorithms used only in advanced research will not be introduced here.

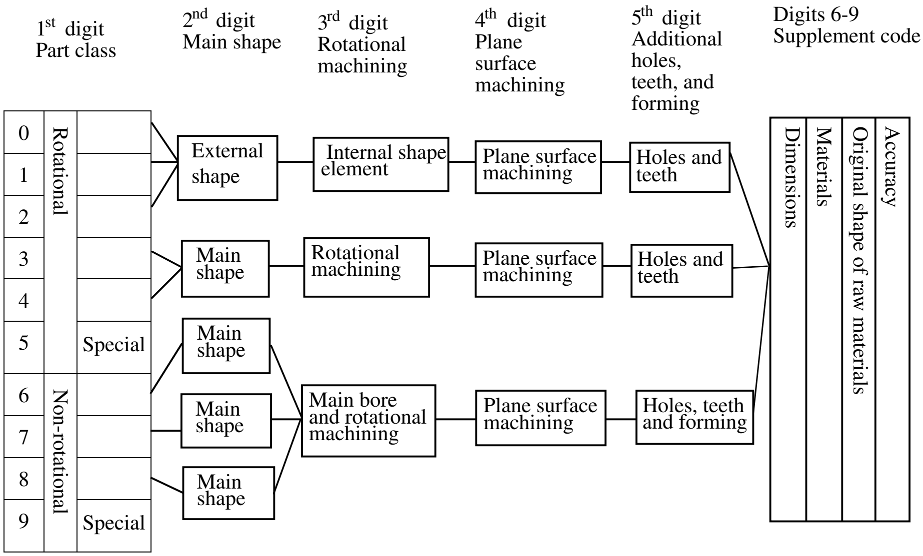


Figure 11 Opitz Code.

3.1. Group Technology

Group technology is a methodology of using the similarity among parts to simplify the production. The key is to identify the similarity. In a machine shop, the thousands of different parts produced may share a small number of geometric characteristics. Parts of similar shape may be produced on the same set of machine tools. The material-handling requirements may also be the same. Manufacturing cells can be designed to produce similar parts. This simplifies the material handling, reduces the complexity of scheduling, and increases the slope of the learning curve. A complex problem can be decomposed into smaller and simpler problems. This set of similar parts is called a part family. Identifying part families is an important step in applying group technology to different manufacturing problems. Group technology has been used in manufacturing system design, scheduling, product retrieval, fixture design, and process planning.

3.1.1. How GT Is Used in Process Planning

As mentioned in the introduction, similar parts can be produced on the same set of machine tools. Most likely they will follow the same process sequence. Therefore, if one collects all the existing process plans used in the shop and groups them based on the part family, one will find that the process plans for the family members are similar. Summarizing the process plans for the family allows a standard process plan to be defined. All parts in the family may share this standard process plan. When a new part is to be planned, one can find the part family of this part, based on the geometric characteristics. The standard process plan for the family is then modified for this new part. Using group technology for manufacturing is like using a library to find references for writing a paper. Without the library database, locating appropriate references will be much more difficult and thus so will the writing.

3.1.2. Coding and Classification

Group technology is based on the concept of similarity among parts. Classification or taxonomy is used for this purpose. The dictionary definition of taxonomy is "orderly classification of plants and animals according to their presumed natural relationships." Here, taxonomy is used to classify parts in manufacturing. There are many methods of part classification. To name just a few: visual observation, manual sorting of the parts, sorting photographs of the parts, and sorting engineering drawings. Because keeping the physical parts or drawing in the sorted order is tedious or sometimes impossible, it is necessary to create a convenient representation, called a coding system.

A coding system uses a few digits or alphanumeric codes to represent a group (family) of similar parts. The classification system is embedded into the coding system. For example, one can easily see that parts can be classified as rotational and nonrotational. A crude coding system can have "0" representing any rotational parts and "1" representing any nonrotational parts. Rotational parts can further be classified as rods, cylinders, and disks, based on the length-to-diameter ratio. The code can be refined to have "0" represent rod, "1" cylinder, "2" disk, and "3" nonrotational parts. Further, the external and internal shapes of the part can be classified as smooth, step, screw thread, and so on. Additional digits may be used to represent the external and internal shapes. Each digit refines the classification or adds additional characteristics.

There are many public domain and proprietary coding systems. Opitz (Opitz 1970), Dclass (Allen 1994), MICLASS (OIR 1983), KK3 (Chang et al. 1998) are but a few popular ones. Opitz code (Figure 12), developed by Professor Opitz of Aachen University in the 1960s, uses five digits to represent the geometry of the part and four supplemental digits to represent part dimension, material, raw material shape, and accuracy. If only the geometry is of concern, the supplemental digits need not be coded. Extensive code tables and illustrations are given to guide the user in coding parts. Given a five-digit code, one can have a rough idea of the shape of the part. The code can also be used for searching the part database to find similar parts. Other coding systems may be more detailed or cover a different part domain, but they all serve the same purpose.

3.1.3. Family Formation

To take advantage of the similarity among parts, one must group parts into families. If the geometry is used in defining the part family, the coding and classification system discussed in the previous subsection can be used. Such families are called design families because they are design geometry based. However, often one would like to form part families based on the production methods used. In this case, the part family is called a production family. Because the manufacturing methods are geometry related, members of a production family share many similar feature geometries as well.

Families may be formed using the visual observation method, as mentioned above, or using the sorting approach. In forming design families the coding system can be used as well. Parts with the same codes always belong to the same family. To enlarge the family, several codes may be included in the same family. The determination as which codes should be included is based purely on the applications considered.

To form a production family, one has to consider the manufacturing method. The first well-known production family formation method was called production flow analysis (Burbidge 1975). First, production flows, or process sequences, for all parts are collected. An incidence matrix with columns representing each part and rows representing each process, machine, or operation code (a certain process performed on a machine) is prepared based on the production flows. By sorting the rows and columns of the matrix, one may move the entries along the diagonal of the matrix (see Figure 13). In the matrix, one may conclude that parts 8, 5, 7, 2 belong to one family and 4, 1, 3, 6, 9, 10 belong to another family. Family one needs processes P1, P5, P6, and P3. Family two needs processes P3, P2, and P4. This approach can be tedious and requires human judgment on separating families. As can be seen, P3 is needed for both families. It is not uncommon to have overlapping entries.

Over the years, many mathematics-based sorting methods, called clustering analysis, have been developed. For more details see Kusiak (1990) and Chang et al. (1998).

3.1.4. Composite Component Concept

Given a family of parts, one can identify several features. When one takes all the features and merges them into an imaginary part, this imaginary part, called a *composite component,* is a superset containing the features of the family members. The composite component concept was developed before World War II in Russia, where it was used to design flexible fixtures for a part family. By adjustment of the fixture, it can accommodate all the parts belonging to a family. This concept can also be used in design. For example, parametric design uses a parameterized design model for a narrowly defined

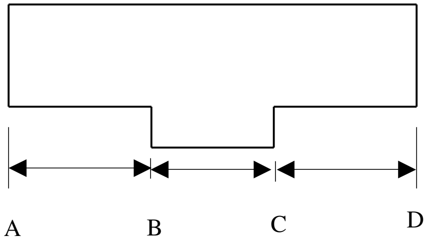


Figure 12 Tolerances.

Processes \ Parts	8	5	7	2	4	1	3	6	9	10
P1	1	1	1	1						
P5	1	1	1	1						
P6		1	1	1						
P3				1	1	1	1	1	1	
P2					1	1	1	1	1	1
P4					1	1	1	1	1	1

Figure 13 Production Flow Matrix.

family. One is the model for spur gears. Assigning parameters, such as pitch, number of teeth, outer diameter, pressure angle, teeth face width, hub diameter and length, hole diameter, and keyway and set screw, allows a drawing of the gear to be generated.

The same concept can be applied to process planning. When a process model (processes, tools, and cutting parameters) is developed for each of the features belonging to the composite component, a process plan can be generated using the parameters specified by the user. This concept has been used in developing several experimental and commercial process planners, such as CPPP (Dunn and Mann 1978). Because the same set of parameter data can be used to generate a process plan or a design drawing, CAD/CAM integration can be done. The limitation of this approach is that the family members must have very similar geometry. Not only do features have to be shared, but the relative position of features on family members have to be maintained. Otherwise, not only can the drawing not be done correctly, but the process plan generated will not be usable. The composite component concept is a tool for part families with minor differences among family members.

3.2. Process Mapping

Why a process can generate certain shapes depends on the geometry generation process of the tool. For example, a drill bit has two cutting edges (lips) (Figure 14). The drilling process requires the drill bit to rotate along its axis, then move the cutting edges downward. The rotating cutting edge creates a cone. Sweeping down the cone will remove a cylindrical volume of materials. Thus, the holes created always have a cone-shaped bottom. The turn tool has a single cutting edge. A layer of the material on a rotating workpiece is shaved off by the cutting edge. This layer is actually a tube-like volume. Therefore, the turn tool can reduce the diameter of a rotational workpiece.

A human process planner can use his or her experience and imagination to envision the shape a process/tool can create. However, in trying to automate process planning, it is essential to define the geometric capabilities of manufacturing processes explicitly. During process planning, for a given feature an inverse search is conducted to find the candidate process(es) for the feature. The relationship between features and processes is defined in a mapping between the two. In an automated process planning system, rules or algorithms are written based on this mapping.

3.2.1. Process for Features Mapping

The geometric capability of a process is summarized in Table 3. As can be seen, milling can create many different features (Volume Capabilities column). Drilling, reaming, and boring primarily create holes. Turning can create different axial symmetric parts. Other processes are also listed in the table.

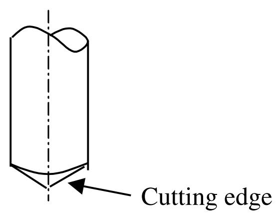


Figure 14 Drill Bit.

TABLE 3 Geometric Capabilities

Process	Subprocess	Cutters	Volume Capabilities
Milling	Face milling	Plain Inserted-tooth	flat bootom volume
	Peripheral milling	Plain Slitting Saw Form Inserted-tooth Staggered-tooth Angle T-slot cutter Woodruff keyseat cutter	flat bottom volume slot formed volume T-slot Internal groove
	End milling	Plain Shell end Hollow end Ball end	pocket, slot, flat sculptured surface, flat
Drilling		Twist drill Spade drill Deep-hole drill Gun drill Trepanning cutter Center drill Combination drill Countersink Counterbore	round hole round hole deep round hole deep round hole large round hole shallow round hole multiple diameter round hole countersink hole counterbore hole
Reaming		Shell reamer Expansion reamer Adjustable reamer Taper reamer	thin wall of round hole thin wall of round hole thin wall of round hole thin wall of round hole
Boring		Adjustable boring bar Simple boring bar	thin wall of round hole thin wall of round hole
Turning	Turning Facing Parting	Plain Inserted	? disk disk
	Knurling	Knurling tool	?
	Boring Drilling Reaming	Boring bars Drills Reamers	thin wall of round hole round hole thin wall of round hole
Broaching		 Form tool	flat bottom volume slot step polyhedral through hole formed through volume
Sawing		Hacksaw Bandsaw Circular saw	?
Shaping		Form tool	flat bottom volume, slot
Planing		Inserted tool	flat bottom volume
Grinding	Cylindrical grinding Centerless grinding Internal grinding External grinding Surface grinding	Grinding wheels Points	? Internal wall of round hole flat bottom volume
Honing		Honing stone	?
Lapping		Lap	most surfaces
Tapping		Tap	threaded wall of hole

One can easily find the entries for each process and determine the geometric capabilities of the process. Process planning is an inverse mapping. Given a feature, a process planner tries to find all processes that can create that feature.

The table alone is not sufficient. To select the correct process based on the geometry, one needs to look into the geometric constraints as well. Figure 15 provides a small sample of process constraints based on geometry. For example, on the upper-right corner is the "large hole through a small slot" constraint. One should not try to drill such a hole after the slot has been cut. The drill center will be in the air and not cutting any material. It will tend to slip and thus produce an inaccurate hole.

3.2.2. *Relative-Cost Table for Manufacturing Processes*

When conducting a feature-to-process mapping, one may find several candidate processes for the feature. Which process to choose also depends on the cost of the process. The process cost equation consists of a few terms: the tool and machine costs, the material removal rate, and the energy consumption. The relative cost of a process is the cost of removing a unit volume of material. Since the machining time is the inverse of the material removal rate (for a given machining volume), the cost is:

$$C = \frac{\text{tool and machine rates} + \text{energy cost}}{\text{MRR}}$$

where tool and machine rates are overhead cost of using the tool and the machine and energy cost is the energy cost per unit time.

Processes such as drilling, milling, and turning have higher material-removal rates and thus can finish a job faster at a lower cost. Finishing processes such as grinding, boring, and polishing have very low material-removal rates, and also consume more energy for the same amount of material removed. The relative cost is higher. Table 4 gives the price of machine costs, which are one of the factors in the relative cost equation. The energy consumption, for example, for cutting cast iron is 0.5–1.2 $\text{hp} \cdot \text{min/in}^3$. When grinding is used, the energy consumption is 4.5–22 $\text{hp} \cdot \text{min/in}^3$. Nontraditional processes such as a laser process consume much more energy.

3.3. Process Capability Analysis

Table 5 shows the technological capabilities of 13 processes. Because each shop may use machines and tools of different precision, the data are for reference only. Please note that all dimensions and tolerances are in inches and all surface finish values are in microinches. The process capability values can be used to decide whether a process can satisfy the design specifications of a feature. They can also be used to determine the need of a secondary process (finishing process). For example, a flat surface has a specified surface finish of 20 μin. Using Table 3, we chose flat end mill to cut the surface. From Table 5, we find that finish cut of end mill can create a surface finish of 50 μin. This is definitely not sufficient. Yet finish grinding can create a surface finish of 2 μin. Therefore, finish grinding will be used for finishing and milling for roughing. Milling is chosen for roughing because grinding has a very low material-removal rate. It is not economical to remove all the feature volume using grinding.

Process capability is shop specific. Each shop needs its own process capability database of its own before process planning can be done automatically. Collecting and analyzing capability data can be tedious. Some of these data can be collected through inspection, such as from the control charts. Others require experiments on the machines. Most of the processes that remove material quickly, such as milling, drilling, and turning, create poorer surface finish and accuracy.

3.4. Cost Model

Another extremely important factor is process economics. We are always interested in finding the most economical solution. Often it means the survival of the company. Process economics means the cost efficiency of the processes. For mass production, a very detailed economic analysis is necessary before a specific processing method can be selected. However, for the usual small to medium batch production, it is not practical to conduct a very detailed study. The savings cannot justify the amount of effort spent. Some rough estimation or just common sense should be used to select a better process. Whenever there are more than two candidate processes, both technologically suitable for the task, it is time to compare their relative costs. A process cost model can be stated as:

$$C = \text{labor cost} + \text{machine overhead} + \text{tool change cost} + \text{tool cost}$$

$$C = C_m(T_m + T_h) + (C_t + C_m\, t_t)\,\frac{T_m}{T_l}$$

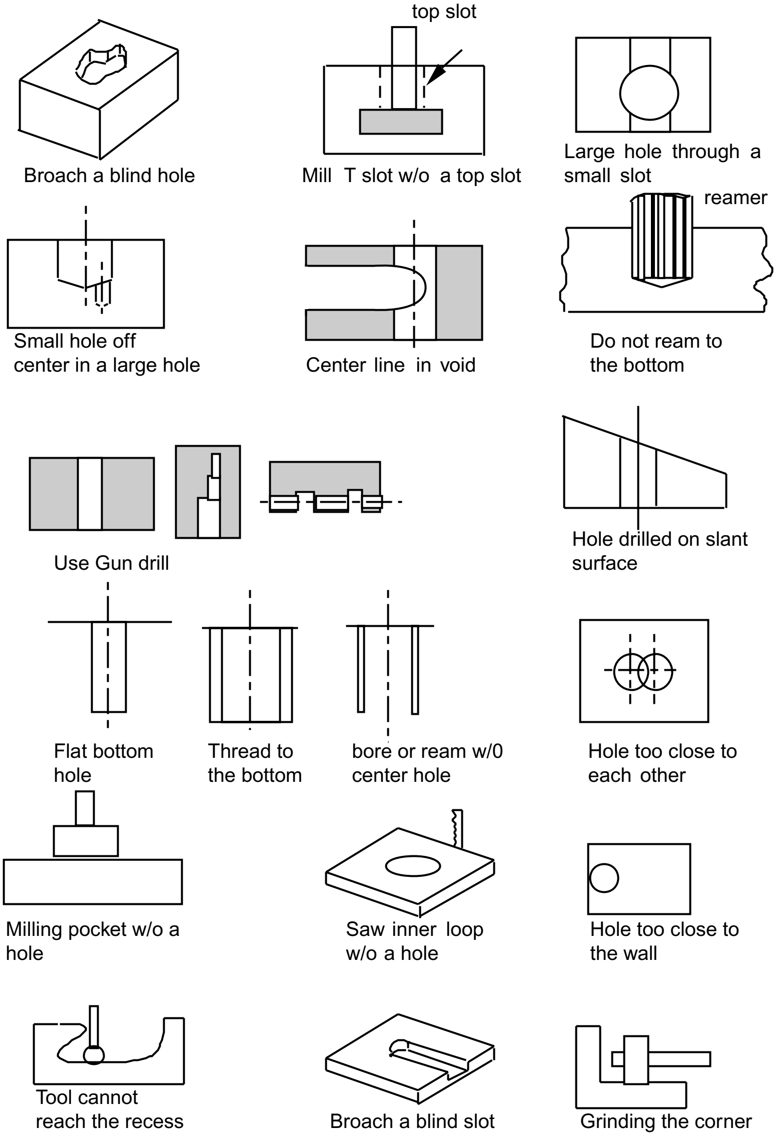


Figure 15 Process Constraints.

where C = total cost for the operation ($)
C_m = operator rate and machine overhead ($/hr)
C_t = cost of tool ($)
T_m = processing time (hr)
T_h = material-handling time, if any (hr)
T_t = tool change time (hr)
T_l = tool life (hr)

In the equation, T_m/T_l is the number of tool changes for the operation. It is determined by the tool life and the processing time. Processing time can be calculated by the necessary tool travel

TABLE 4 Cost of Machinery

Type of Machinery	Price range ($000)
Broaching	10–300
Drilling	10–100
Electrical discharge	30–150
Electromagnetic and electrohydraulic	50–150
Gear shaping	100–200
Grinding	
Cylindrical	40–150
Surface	20–100
Headers	100–150
Injection molding	30–150
Boring	
Jig	50–150
Horizontal boring mill	100–400
Flexible manufacturing system	>1000
Lathe	10–100
Single- and multi-spindle automatic	30–250
Vertical turret	100–400
Machining center	50–1000
Mechanical press	20–250
Milling	10–250
Robots	20–200
Roll forming	5–100
Rubber forming	50–500

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divided by the feed speed. For example, for drilling an x-in. deep hole using a feed speed of a ipm, $T_m = x/a/60$.

The tool life equation can be expressed as (for milling):

$$T_l = \frac{C}{V^{\alpha} f^{\beta} a_p^{\gamma}}$$

where C = a constant determined by the tool geometry, tool material, and workpiece material
V = the cutting speed, fpm
f = the feed, ipr
a_p = the depth of cut, in.
α, β, γ = coefficients

Unfortunately, several difficulties prohibit us from using this model to predict the operation cost. First, the cutter path is not known at the process-selection time. Generating a cutter path for each possible process to be machined would be very time consuming. The second problem is the availability of coefficients for each combination of tool-material type and workpiece-material type. There is little published data for tool life equations. Most of the tool life and machinability data are published in terms of recommended feed and speed. With these two major problems, this approach will probably not work for real-world problems. A quick and dirty way must be found to estimate the cost.

Since we are dealing with the machining of a single feature, it is reasonable to assume that the material-handling time is negligible. The chance of changing a tool during the operation is also minimal. Also, the feed and speed recommended by the *Machining Data Handbook* (Metcut 1980) usually make the tool life to be about 60 minutes. Since the recommended feed and speed are what are used in most machining operations, it is reasonable to assume that T_l = 1 hr. Therefore, the cost function can be simplified to:

TABLE 5 Process Technological Capabilities

Process	Subprocess	Cutters	Tolerances, Surface Finish, etc. Capabilities					
Milling	Face milling	Plain		roughing	finishing			
		Inserted-tooth	tol	0.002	0.001			
			flatness	0.001	0.001			
			angularity	0.001	0.001			
			parallelism	0.001	0.001			
			surface finish	50	30			
	Peripheral milling	Plain		roughing	finishing			
		Slitting saw	tol	0.002	0.001			
		Form	flatness	0.001	0.001			
		Inserted-tooth	surface finish	50	30			
		Staggered-tooth						
		Angle						
		T-slot cutter						
		Woodruff keyseat cutter						
		Form milling cutter						
	End milling	Plain		roughing	finishing			
		Shell end	tol	0.004	0.004			
		Hollow end	parallelism	0.0015	0.0015			
		Ball end	surface finish	60	50			
Drilling		Twist drill	length/diam = 3 usual = 8 maximum					
		Spade drill	mtl < Rc 30 usual < Rc 50 maximum					
		Trepanning cutter						
		Center drill		Dia	Tolerance		usual	best
		Combination drill		0–1/8	+0.003–0.001	true position	0.008	0.0004
		Countersink		1/8–1/4	+0.004–0.001	roundness	0.004	
		Counterbore		1/4–1/2	+0.006–0.001	surface finish	100	
				1/2–1	+0.008–0.002			
				1–2	+0.010–0.003			
				2–4	+0.012–0.004			
		Deep-hole drill		Dia	Tolerance			
		Gun drill		<5/8	0.0015	surface finish >100		
				>5/8	0.002	straightness 0.005 in 6 inch		

Units: Tolerances in inches; Surface finish in μ inches; Diameter and length in inches

Reaming		Shell reamer Expansion reamer Adjustable reamer Taper reamer	Dia	Tolerance			roughing	finishing
			0–1/2	0.0005 to 0.001		roundness	0.0005	0.0005
			1/2–1	0.001		true position	0.01	0.01
			1–2	0.002		surface finish	125	50
			2–4	0.003				
Boring		Adjustable boring bar Simple boring bar	length/dia	5 to 8				
			Dia	Tolerance		straightness		0.002
				roughing	finishing	roundness		0.003
						true position		0.0001
						surface finish		8
			0–3/4	0.001	0.0002			
			3/4–1	0.0015	0.0002			
			1–2	0.002	0.0004			
			2–4	0.003	0.0008			
			4–6	0.004	0.001			
			6–12	0.005	0.002			
Turning	Turning Facing Parting		diameter	tolerance		surface finish	250 to 16	
			to 1.0	0.001				
			1–2	0.002				
			2–4	0.003				
	Knurling	Plain Inserted Knurling tool						
	Boring Drilling Reaming	Boring bars Drills Reamers						
Broaching		Form tool	tolerance 0.001 surface finish 125 to 32					

TABLE 5 (*Continued*)

Process	Subprocess	Cutters	Tolerances, Surface Finish, etc. Capabilities				
			length to	squareness	surface finish	cutting rate	material
Sawing		Hacksaw	0.01	0.2	200–300	3–6 sq in./min	to Rc45
		Bandsaw	0.01	0.2	200–300	4–30 sq in./min	to Rc45
		Circular saw	0.008	0.2	125	7–36 sq in./min	to Rc45
Shaping		Form tool		roughing	finishing		
			location tol	0.005	0.001		
			flatness	0.001	0.0005		
Planing		Inserted tool	surface finish	60	32 (cast iron)		
			surface finish	125	32 (steel)		
Grinding	Internal grinding	Internal	Dia	Tolerance			
				roughing	finishing		
			0–1	0.00015	0.00005		
			1–2	0.0002	0.00005		
			2–4	0.0003	0.0001		
			4–8	0.0005	0.00013		
			8–10	0.0008	0.0002		
	Cylindrical grinding Centerless grinding	Center ground and centerless		roughing	finishing		
			tolerance	0.0005	0.0001		
			parallelism	0.0005	0.0002		
			roundness	0.0005	0.0001		
			surface fin	8	2		
	External grinding Surface grinding	flat		roughing	finishing		
			tolerance	0.001	0.0001		
			parallelism	0.001	0.0001		
			surface fin	32	2		

		Dia	Tolerance			
			roughing	finishing	surface finish	4
Honing	Honing stone				roundness	0.0005
		1	+0.0005–0.0	+0.0001–0.0		
		2	+0.0008–0.0	+0.0005–0.0		
		4	+0.0010–0.0	+0.0008–0.0		
			roughing	finishing		
Lapping	Lap	tolerance	0.000025	0.000015		
		flatness	0.000025	0.000012		
		surface fin	4–6	1–4		
Tapping	Tap	tolerance	0.003			
		roundness	0.003			
		surface fin	75			

$$C = \frac{(C_m + C_t)T_m}{60}$$

The machining time can be estimated by the material removal rate (MRR) and the volume (V) to be removed (current feature volume):

$$T_m = \frac{V}{\text{MRR} \cdot 60}$$

Therefore, the cost function can be rewritten as:

$$C = \frac{(C_m + C_t)V}{\text{MRR} \cdot 60}$$

The maximum material-removal rate data can be estimated using some simple equations (Chang 1990). First the tool size, feed, and speed need to be found. The volume to be removed can be estimated much more easily than the length of cutter path. Cost data can also be obtained from the accounting department. With these data the processing cost can be calculated. This cost information can be used to select the most economical process to use for machining a volumetric feature. Because in the processing cost function two variables, C_t and MRR, are related to the process, other capabilities of interest are tool cost and material–removal rate. These capabilities should be used for selecting economical machining processes.

Example. The hole to be drilled is 3 in. deep. The machine and operator rate is \$40/hr. The tool cost is \$10 each. What is the production cost of the hole?

$$V = \frac{\pi\, 1^2}{4}\, 3 = 2.356 \text{ in.}^3$$

$$C = (40 + 10)\,\frac{2.356}{6.93 \cdot 60} = \$0.283$$

The above model does not consider the fixed cost of tooling. The tool cost used in the model is the incremental tool cost. If special tools are needed, a fixed cost may be incurred. In that case, the fixed cost must be evenly distributed to the entire batch of parts made.

3.5. Tolerance Charting

Tolerance charting is a method for checking the proper in-process dimensions and tolerances from a process plan. It is used to verify whether the process sequence will yield the designed dimensions and tolerances. In most of the literature, *process* is replaced by *operation*. In this section we will use the term *process*. Tolerance charting begins with a part drawing and the process plan. On the process plan are processes and machines. Consequences of processes in terms of resultant dimensions and tolerances are marked on the chart. The processes that were used to produce the dimension and the tolerance are labeled for trace. This is done step by step following the sequence of processes. Finally, the specified dimensions and tolerances are compared to the resultant dimensions and tolerances. If any of the dimensions and tolerances are not satisfied, one can trace back to the sources. Then either a different process/machine is used to reduce the process tolerance or the process sequence is changed.

Figure 16 illustrates how a simplified tolerance chart works. The example part is a cylindrical part to be turned. The calculation section of the chart is omitted. On the top of the chart is the design. Note that the tolerance chart can handle one dimension at a time. The drawing is 2D and features are vertical lines (representing surfaces). The solid line shows the boundary of a cylinder with greater diameter at the center. The dashed line shows the stock boundary that encloses the part boundary. The designer has specified dimensions and tolerances between three feature sets. The dimension values are omitted in this example. The next section is the dimension and tolerance section. The thick horizontal lines show where the dimension and tolerance are specified. For example, the overall dimension is 3 and tolerance is 0.01. The following section is the process plan section. Four cuts are shown in the process plan. The first two cuts (10 and 12) use the left-hand side of the stock as the reference. They create two surfaces: surface C and surface D (at the same time the diameters are turned). The next two cuts (20 and 22) create the dimensions between BD and AD. Dimension AB is the result of cuts 20 and 22. Therefore, the tolerance for AB equals the sum of process tolerances for 20 and 22. In this case both are the same. To achieve the designed tolerance of 0.01, the process

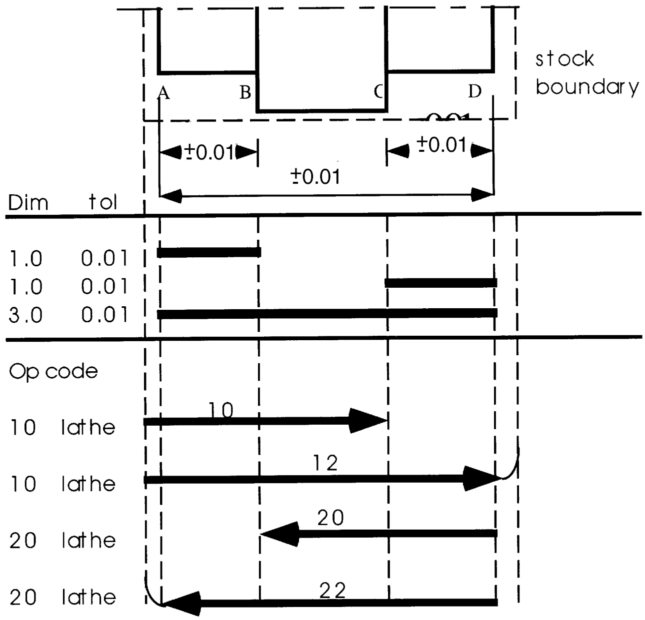

Figure 16 Tolerance Chart.

tolerance must be less than or equal to 0.01/2 = 0.005. The same can be found for *CD*, which is the result of processes 10 and 12. However, *AD* is the result of only one cut and thus the tolerance is better.

More details on this subject can be found in Curtis (1988).

4. COMPUTER-AIDED PROCESS PLANNING

Process planning has traditionally been experience based and performed manually. A problem facing modern industry is the lack of a skilled labor force to produce machined parts as in the past. Manual process planning also has other problems. Variability among the planners' judgment and experience can lead to differences in the perception of what constitutes the optimal or best method of production. This manifests itself in the fact that most industries have several different process plans for the same part, which leads to inconsistent plans and an additional amount of paperwork. To alleviate this problem, a computer-aided approach can be taken. Development in computer-aided process planning attempts to free the process planner from the planning process. Computer-aided process planning can eliminate many of the decisions required during planning. It has the following advantages:

- It reduces the demand on the skilled planner.
- It reduces the process-planning time.
- It reduces both process-planning and manufacturing cost.
- It creates consistent plans.
- It produces accurate plans.
- It increases productivity.

The benefits of computer-aided process planning systems have been documented in several industries. Such systems can reduce planning time from days to hours and result in large cost savings.

The idea of using computers in the process planning activity was discussed by Niebel (1965). Other early investigations on the feasibility of automated process planning can be found in Scheck (1966) and Berra and Barash (1968). Many industries also started research efforts in this direction in the late 1960s and early 1970s. Early attempts to automate process planning consisted primarily of building computer-assisted systems for report generation, storage, and retrieval of plans. A database system with a standard form editor is what many early systems encompassed. Formatting of plans was performed automatically by the system. Process planners simply filled in the details. The storage and retrieval of plans are based on part number, part name, or project ID. When used effectively, these systems can save up to 40% of a process planner's time. A typical example can be found in Lockheed's CAP system (1981). An example of a modern version is Pro/Process for Manufacturing (launched in 1996 and since discontinued). Such a system can by no means perform the process-planning tasks; rather, it helps reduce the clerical work required of the process planner.

The typical organization of using a process-planning system is shown in Figure 17. A human planner interprets an engineering drawing and translates it into the input data format for a process-planning system. Either interactively or automatically, a process plan is produced. The plan is then used by production planners for scheduling of production and used by industrial engineers to lay out the manufacturing cell and calculate production cost and time. A part programmer follows the instructions on the process plan and the engineering drawing to prepare NC (numerical control) part programs. The same organization applies to all kinds of process planning systems.

Perhaps the best-known automated process planning system is the CAM-I automated process planning system (CAPP) (Link 1976). (CAM-I stands for ComputerAided Manufacturing International, a nonprofit industrial research organization.) In CAPP, previously prepared process plans are stored in a database. When a new component is planned, a process plan for a similar component is retrieved and subsequently modified by a process planner to satisfy special requirements. The tech-

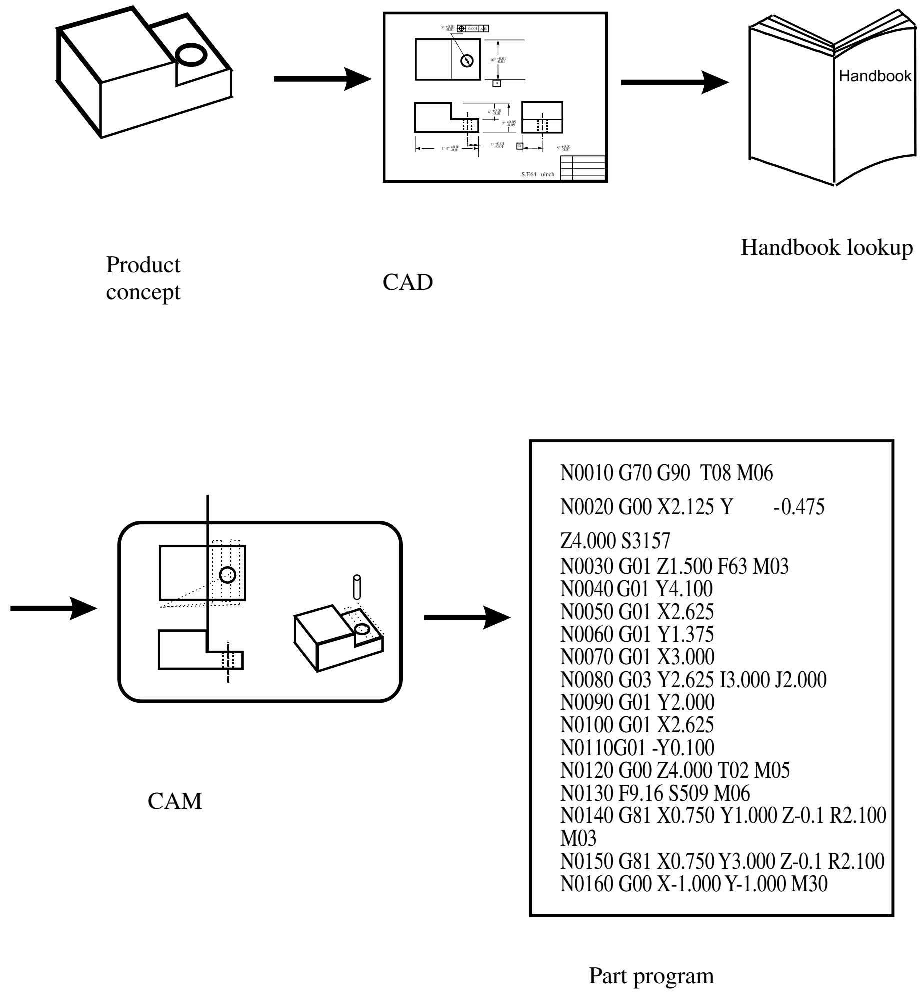

Figure 17 From Design to Part Program.

nique involved is called group technology (GT)-based variant planning (Burbidge 1975). Variant planning will be discussed in more detail in the next section.

Figure 18 represents the structure of a complete computer-aided process-planning system. Although no existing turnkey system integrates all of the functions shown in the figure (or even a goodly portion of them), it illustrates the functional dependencies of a complete process-planning system. It also helps to illustrate some of the constraints imposed on a process-planning system (e.g., available machines, tooling, and jigs).

In Figure 18, the modules are not necessarily arranged based on importance or decision sequence. The system monitor controls the execution sequence of the individual modules. Each module may require execution several times in order to obtain an optimum process plan. Iterations are required to reach feasibility as well as good economic balance.

The input to the system will most probably be a 3D model from a CAD database. The model contains not only the shape and dimensioning information, but also the tolerances and special features. The process plan can be routed directly to the production-planning system and production-control system. Time estimates and resource requirements can be sent to the production-planning system for scheduling. The part program, cutter location (CL) file, and material-handling control program can also be sent to the control system.

Process planning is the critical bridge between design and manufacturing. Design information can be translated into manufacturing language only through process planning. Today, both automated design (CAD) and manufacturing (CAM) have been implemented. Integrating, or bridging, these functions requires automated process planning as the key component.

There are two basic approaches to computer-aided process planning: variant and generative. The variant approach is used by the computer to retrieve plans for similar components using table look-up procedures. The process planner then edits the plan to create a variant to suit the specific requirements of the component being planned. Creation and modification of standard plans are the process planner's responsibility. The generative approach is based on generating a plan for each component without referring to existing plans. Generative systems are systems that perform many of the functions in a generative manner. The remaining functions are performed with the use of humans in the planning loop.

4.1. Variant Approach

The variant approach to process planning was the first approach used to computerize planning techniques. It is based on the idea that similar parts will have similar process plans. The computer can

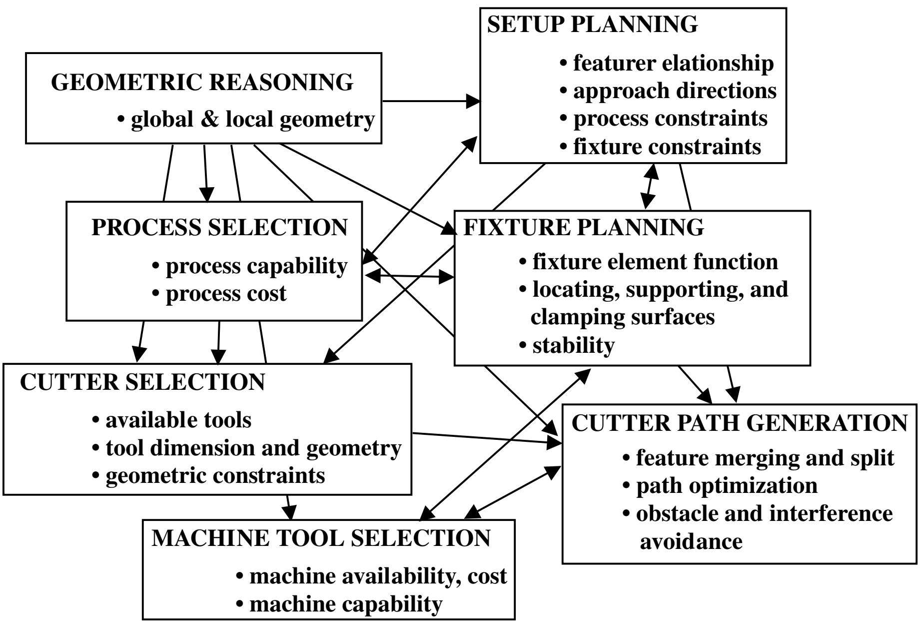

Figure 18 Process-Planning Functions.

be used as a tool to assist in the identification of similar plans, retrieving them and editing the plans to suit the requirements for specific parts.

A variant process planning system includes the following functions:

- Family formation
- Standard plan preparation
- Plan editing
- Databases

In order to implement such a concept, GT-based part coding and classification are used as a foundation. Individual parts are coded based upon several characteristics and attributes. Part families are created of "like" parts having sufficiently common attributes to group them into a family. This family formation is determined by analyzing the codes of the part spectrum. A "standard" plan consisting of a process plan to manufacture the entire family is created and stored for each part family. The development of a variant process-planning system has two stages: the preparatory stage and the production stage.

During the preparatory stage, existing components are coded, classified, and later grouped into families (Figure 19). The part family formation can be performed in several ways. Families can be formed based on geometric shapes or process similarities. Several methods can be used to form these groupings. A simple approach would be to compare the similarity of the part's code with other part codes. Since similar parts will have similar code characteristics, a logic that compares part of the code or the entire code can be used to determine similarity between parts.

Families can often be described by a set of family matrices. Each family has a binary matrix with a column for each digit in the code and a row for each value a code digit can have. A nonzero entry in the matrix indicates that the particular digit can have the value of that row. For example, entry (3,2) equals one implies that a code x3xxx can be a member of the family. Since the processes of all family members are similar, a standard plan can be assigned to the family.

The standard plan is structured and stored in a coded manner using operation codes (OP codes). An operation code represents a series of operations on one machine/workstation. For example, an OP code DRL10 may represent the sequence center drill, change drill, drill hole, change to reamer, and ream hole. A series of OP codes constitutes the representation of the standard process plan.

Before the system can be of any use, coding, classification, family formation, and standard plan preparation must be completed. The effectiveness and performance of the variant process-planning system depends to a very large extent on the effort put forth at this stage. The preparatory stage is a very time-consuming process.

The production stage occurs when the system is ready for production. New components can be planned in this stage. An incoming component is first coded. The code is then sent to a part family search routine to find the family to which it belongs. Because the standard plan is indexed by the family number, the standard plan can be easily retrieved from the database. Because the standard

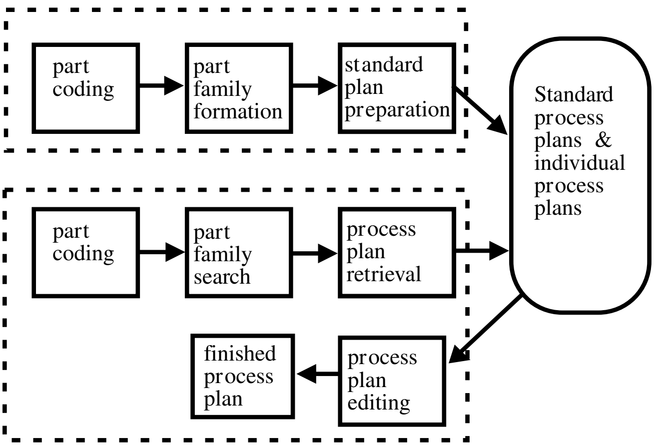

Figure 19 Variant Process Planning.

plan is designed for the entire family rather than for a specific component, editing the plan is unavoidable.

Variant process-planning systems are relatively easy to build. However, several problems are associated with them:

- The components to be planned are limited to similar components previously planned.
- Experienced process planners are still required to modify the standard plan for the specific component.
- Details of the plan cannot be generated.
- Variant planning cannot be used in an entirely automated manufacturing system, without additional process planning.

Despite these problems, the variant approach is still an effective method, especially when the primary objective is to improve the current practice of process planning. In most batch manufacturing industries, where similar components are produced repetitively, a variant system can improve the planning efficiency dramatically. Some other advantages of variant process planning are:

- Once a standard plan has been written, a variety of components can be planned.
- Comparatively simple programming and installation (compared with generative systems) is required to implement a planning system.
- The system is understandable and the planner has control of the final plan.
- It is easy to learn and easy to use.

The variant approach is the most popular approach in industry today. Most working systems are of this type, such as CAPP of CAM-I (Link 1976) and Multiplan of OIR (OIR 1983).

4.2. Generative Approach

Generative process planning is the second type of computer-aided process planning. It can be concisely defined as a system that automatically synthesizes a process plan for a new component. The generative approach envisions the creation of a process plan from information available in a manufacturing database without human intervention. Upon receiving the design model, the system is able to generate the required operations and operation sequence for the component.

A generative process-planning system consists of the following important functions:

- Design representation
- Feature recognition
- Knowledge representation
- System structures

Knowledge of manufacturing has to be captured and encoded into computer programs. A process planner's decision-making process can be imitated by applying decision logic. Other planning functions, such as machine selection, tool selection, and process optimization, can also be automated using generative planning techniques.

A generative process-planning system contains three main components:

- Part description
- Manufacturing databases
- Decision-making logic and algorithms

The definition of generative process planning used in industry today is somewhat relaxed. Thus, systems that contain some decision-making capability in process selection are called generative systems. Some of the so-called generative systems use a decision tree to retrieve a standard plan. Generative process planning is regarded as more advanced than variant process planning. Ideally, a generative process-planning system is a turnkey system with all the decision logic built in. Since this is still far from being realized, generative systems currently developed provide a wide range of capabilities and can at best be described as only semigenerative.

The generative process-planning approach has the following advantages:

- It generates consistent process plans rapidly.
- New components can be planned as easily as existing components.

- It has potential for integrating with an automated manufacturing facility to provide detailed control information.

Successful implementation of this approach requires the following key developments:

- The logic of process planning must be identified and captured.
- The part to be produced must be clearly and precisely defined in a computer-compatible format.
- The captured logic of process planning and the part-description data must be incorporated into a unified manufacturing database.

4.2.1. Part-Description Methods for Generative Process-Planning Systems

Part description forms a major part of the information needed for process planning. The way in which the part description is input into the process-planning system has a direct effect on the degree of automation that can be achieved. Since the aim is to automate the system, the part description should be in a computer-readable format. Traditionally, engineering drawings have been used to convey part descriptions and communicate between design and manufacturing. Understanding the engineering drawing was a task suited for well-trained human beings and initially not suitable for direct input for process planning. The requirements of the part-description methods include:

- Geometrical information
- Part shape
- Design features
- Technological information
- Tolerances
- Surface quality (surface finish, surface integrity)
- Special manufacturing notes
- Feature information
- Manufacturing features (e.g., slots, holes, pockets)

Before the representation method is decided, the following factors have to be determined:

- Data format required
- Ease of use for planning
- Interface with other functions, such as part programming and design
- Easy recognition of manufacturing features
- Easy extraction of planning information from the representation

Some of the representations used in a generative process-planning system include: GT code, line drawing, special language, symbolic representation, solid model, CSG, B-Rep, feature-based model. Extract and decompose features from a geometric model.

- Syntactic pattern recognition
- State transition diagram and automata
- Decomposition
- Logic
- Graph matching
- Face growing

5. COMPUTER-AIDED PROCESS PLANNING SYSTEMS SELECTION CRITERIA

Selecting a process-planning system for a company is not an easy task. Each machine shop has its own unique characteristics. Decision tables have been developed for selecting computer-aided process-planning systems. For example, Steudel and Tollers (1985) present a decision table for selecting CAPP solutions (the tables are also reprinted in Chang et al. [1991, chap. 13]). This approach assumes that certain decision rules can be written for each selection decision. However, often such rules are not available. Another approach is to compare the characteristics of the competing systems based on weights. Table 6 shows a comparison table for two process-planning systems. In the table are 12 major categories, most of which are divided into several subcategories. Weights can be assigned

TABLE 6 System Comparison Table

		Systems	
	Weight	System 1	System 2
1. Input data			
1.1. CAD file format		1	4
2. Workpiece understanding	**3**		
2.1. Shape analysis		0	5
2.2. Material analysis		1	1
2.3. Specification analysis		1	1
2.4. Tolerance analysis		2	3
Average		1	3
3. Process selection	**2**		
3.1. Feature hierarchy		3	5
3.2. Tolerance analysis		0	5
3.3. Process capability model		0	5
3.4. Specification analysis		0	2
3.5. Cost analysis		0	1
3.6. Capacity analysis		0	2
Average		**1**	**3**
4. Machine tool management	**2**		
4.1. Machine tool selection		0	5
4.2. Machine capability model		0	5
4.3. Maintenance planning		0	0
4.4. Environmental analysis		0	0
4.5. Flow analysis		0	0
4.6. Life-cycle analysis		0	0
4.7. Supplier development		0	0
4.8. Control specification		0	0
4.9. Facility planning		0	0
Average		**0**	**5**
5. Quality management	**2**		
5.1. Process-control planning		0	0
5.2. Gage planning		1	0
5.3. Scrap and rework management		0	0
5.4. Quality assurance		0	0
Average		**1**	**0**
6. Process design	**3**		
6.1. Tool selection		1	5
6.2. Fixture design		1	4
6.3. Gage design		1	0
6.4. Tool path generation		2	5
6.5. Operation sequencing		1	5
6.6. Process parameters		1	5
6.7. Feature accessibility		0	5
6.8. Tolerance analysis		0	4
Average	**1**	**4**	
7. Evaluation and validation	**3**		
7.1. Target cost		0	5
7.2. Tool path verification		5	4
7.3. Workpiece quality		0	0
7.4. Process reliability		0	0
7.5. Production times		1	5
Average		**2**	**3**
8. Document generation	**3**		
8.1. Tool/gage orders		2	4
8.2. Equipment orders		0	5
8.3. Operation sheets		2	4
8.4. Process routing		2	4
8.5. Part programs		5	5
8.6. Setup drawings		3	5
Average		**2**	**5**
9. Machine domain	**3**	**4**	**5**
10. Part domain	**3**	**4**	**4**
11. Platform	**1**	**5**	**3**
12. Technical support	**3**	**5**	**4**
Total		**65**	**101**

to either each major category or subcategory. The total weights may be used to determine the final selection. The comparison is not limited to the pair comparison as it is in the example; more systems can be added to the table.

The meanings of the categories in Table 6 are defined below:

- Input data: The process-planning system must interface with the existing CAD design system. The system can either read the native CAD data or can input through an data-exchange format such as IGES or STEP.
  - CAD file format: the design data file acceptable, e.g., Pro/E, CADDS, CATIA, IGES, STEP.
- Workpiece understanding:
  - Shape analysis: feature recognition; converting design data into manufacturing feature data.
  - Material analysis: identification of raw material shape, sizes, type (cast, bar, etc.), and weight.
  - Specification analysis: extracting other manufacturing specifications from the design (e.g., paint, hardness, surface treatment).
  - Tolerance analysis: extracting tolerance data from the design.
- Process selection:
  - Feature hierarchy: process selection based on hierarchically arranged manufacturing features.
  - Tolerance analysis: process selection based on the tolerance capabilities of processes vs. the design specifications.
  - Process capability model: a computer model that captures the capability of a process. Process models are used in process selection. They may be customized.
  - Specification analysis: understanding other manufacturing specifications and using them as the basis for selecting processes.
  - Cost analysis: estimating and analyzing manufacturing cost and using it as the basis for selecting processes.
  - Capacity analysis: machine selection with the consideration of the throughput of each machine.
- Machine tool management:
  - Machine tool selection: selecting appropriate machine tools for the job.
  - Machine capability model: a computer model that captures the process capability of a machine tool.
  - Maintenance planning: maintenance schedule for machine tools.
  - Environmental analysis: assessment of environmental requirements (temperature, pressure, humidity) necessary to achieve quality targets.
  - Flow analysis: production flow analysis (i.e., throughput).
  - Life-cycle analysis: the economic analysis, from cradle to grave, of asset costs to derive metrics like ROA.
  - Supplier development: identifying supplier for the machine tool.
  - Control specification: managing NC controller specifications for postprocessors.
  - Facility planning: integration with the facility planning functions.
- Quality management
  - Process control planning: generating control charts for process control.
  - Gage planning: CMM programming, gage calibration, certification planning.
  - Scrap and rework management: planning for management of the disposition of parts for scrap and rework
  - Quality assurance: generating quality assurance plan for certification. Process plans may be used for this purpose.
- Process design
  - Tool selection: selecting tools to be used for the machining of a part.
  - Fixture design: designing the fixture necessary for the workpiece holding under a given setup.
  - Gage design: designing the gage for inspecting the workpiece.
  - Tool path generation: generating the NC tool path for the part.
  - Operation sequencing: sequencing the NC tool path for the part
  - Process parameters: selecting process parameters, e.g., feed and speed, for each tool/cut.
  - Feature accessibility: analyzing the tool accessibility of each feature to be machined.

TABLE 7 Summary of System Functionalities

	System	
	System 1	System 2
1. Input data		
1.1. CAD file format	IGES	PDES, DXF
2. Workpiece understanding		
2.1. Shape analysis	N/A	Feature recognition
2.2. Material analysis	limited	limited
2.3. Specification analysis	Manual	Manual
2.4. Tolerance analysis	Manual	Manual input
3. Process selection		
3.1. Feature hierarchy	Pro/E	Yes
3.2. Tolerance analysis	Manual	Rules
3.3. Process capability model	N/A	Method hierarchy/DB
3.4. Specification analysis	Manual	limited
3.5. Cost analysis	N/A	implicit
3.6. Capacity analysis	N/A	implicit
4. Machine tool management		
4.1. Machine tool selection	Manual	Automatic
4.2. Machine capability model	N/A	Method hierarchy/DB
4.3. Maintenance planning	N/A	N/A
4.4. Environmental analysis	N/A	N/A
4.5. Flow analysis	N/A	N/A
4.6. Life-cycle analysis	N/A	N/A
4.7. Supplier development	N/A	N/A
4.8. Control specification	N/A	N/A
4.9. Facility planning	N/A	N/A
5. Quality management		
5.1. Process control planning	N/A	N/A
5.2. Gage planning	CMM/interactive	N/A
5.3. Scrap and Rework Management	N/A	N/A
5.4. Quality assurance	N/A	N/A
6. Process design		
6.1. Tool selection	Manual	Automatic
6.2. Fixture design	Manual	Automatic
6.3. Gage design	Manual	N/A
6.4. Tool path generation	Interactive	Automatic
6.5. Operation sequencing	Manual	Automatic
6.6. Process parameters	User-supplied DB	User-supplied RDB
6.7. Feature accessibility	N/A	Yes
6.8. Tolerance analysis	N/A	Yes
7. Evaluation and validation		
7.1. Target cost	N/A	Yes
7.2. Tool path verification	Pro/NC-Check	Yes
7.3. Workpiece quality	N/A	N/A
7.4. Process reliability	N/A	N/A
7.5. Production times	N/A	Yes
8. Document generation		
8.1. Tool/gage orders	User-defined template	Tool list
8.2. Equipment orders	N/A	Machine list
8.3. Operation sheets	User-defined template	Yes
8.4. Process routing	User-defined template	Yes
8.5. Part programs	Pro/E	APT
8.6. Setup drawings	Manual	Yes
9. Machine domain	Mill, lathe, etc.	Machining center
10. Part domain	Prismatic, turned	Prismatic 2 1/2D, turned
11. Platform	Workstations and PCs	SGI/HP, PC
12. Technical support	Local	Headquarters

  - Tolerance analysis: comparing the tolerance specification against the tolerance capabilities of the selected tools and machine tools; stacking up tolerance based on the setup and machine accuracy and setup error.
- Evaluation and validation:
  - Target cost: estimating the manufacturing cost of that part.
  - Tool path verification: graphically simulating the tool motion to ensure that the tool path has no collision with the fixture and the machine and produces correct part geometry.
  - Workpiece quality: confirming that quality indices are met.
  - Process reliability: reliability indexes for the processes selected for the part.
  - Production times: estimating the time it takes to produce the part.
- Document generation:
  - Tool/gage orders: job orders for tools and gages needed.
  - Equipment orders: job orders for equipment used.
  - Operation sheets: detailed description of each operation and operation parameters including gaging detail/instructions.
  - Process routing: process routing sheet. Lists operation sequence and processes.
  - Part programs: NC part program and part program format, e.g., RS 274, CL, BCL, APT source, COMPACT II source, postprocessed N-G code.
  - Setup drawings: drawings of the workpiece with fixture for each setup.
- Machine domain: machine tools that can be modeled and planned by the system.
- Part domain: types of part that can be planned by the system (e.g., turned, prismatic, casting).
- Platform: computer platform on which the software can be used.
- Technical support: technical support provided by the vendor.
- Total: total composite score based on the criteria above.

A composite score may not be sufficient for making the final decision. It is necessary to record the specifications in each subcategory. Table 7 illustrates such a table for the same comparison as in Figure 6. With these two tables, an appropriate computer-aided process planning system can be selected.

6. CONCLUSIONS

In this chapter, we have provided a general overview of manufacturing process planning and design. We have also discussed the tools used in process planning. As mentioned earlier in the chapter, automated process planning is especially important for small batch production. At a time when competition is keen and product changeover rapid, shortening the production lead time and production cost are critical to the survival of modern manufacturing industry. Process planning plays an important role in the product-realization process. In order to achieve the goals stated above, it is essential to put more focus on this planning function.

Process planning is a function that requires much human judgment. Over the past three decades, much effort has been put into automating process planning. Although progress has been made on geometric modeling and reasoning, knowledge-based systems, and computational geometry for tool-path generation, no robust integrated process-planning system has been developed. Developing an automated process-planning system is still a challenge to be fulfilled. In the meantime, many of these technologies have been integrated into CAD/CAM systems. They provide human planners with powerful tools to use in developing process plans. We can expect an increasing amount of planning automation be made available to manufacturing engineers. This chapter provides a general background to this important topic. Additional readings are included for those interested in a more in-depth investigation of the subject.

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