Manufacturing Engineering

An Introduction to the Basic Functions

Second Edition, Revised and Expanded

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Preface

The continuing growth and expansion of manufacturing technology worldwide, and the renaissance of American manufacturing in particular in the past several years, emphasize the importance of good manufacturing engineering as the driving force behind this phenomenon. The manufacturing engineers are the key players in this growth. It is they who must design the processes, the methods, and the tooling, then provide the planning, implementation, and follow-up that ensure success. The widespread acceptance of this book as an introduction to manufacturing engineering has led to the need to update, improve, and expand the original edition to keep pace with technology and continue as the primary introductory text and reference source on manufacturing engineering.

The purpose of the book remains the same, to provide the important, practical essentials of manufacturing engineering in a single, convenient reference source for use by all engineers and managers who need to know the basics of this important branch of engineering, as well as by the practicing manufacturing engineer who must review these essentials from time to time. Greater emphasis is now being given to the use of the book as a text for those studying manufacturing engineering in technical colleges and universities. To that end, questions have been added at the end of each chapter. An answer book will be provided for teachers.

A new chapter on manufacturability has been added because of recognition of the favorable impact that sound product design has on manufacturing cost and quality. This chapter covers the essential ingredients for a producible product design and highlights pitfalls to be avoided. Also new is an appendix of basic machining data including feeds and speeds, drill selection tables, sheet metal bend deductions, and similar data.

The chapter on cost estimating has been rewritten and expanded to fully treat all aspects of product cost estimating. New or updated material has been added to the chapters on preproduction planning, capital equipment and facilities, tooling, special processes, methods and detailed work planning, mechanization and automatic assembly and manufacturing engineering systems. The chapter on manufacturing research and development has been completely revised to emphasize the functions, facilities required, and goals and objective of this important aspect of manufacturing engineering. Finally, the appendix on manufacturing engineering terminology has been expanded with many new terms and definitions.

As before, the reader is assumed to have a working knowledge of engineering fundamentals, including some basic knowledge in manufacturing processes and engineering materials. The new material covering statistical process control requires a basic knowledge and understanding of statistics.

John P. Tanner

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Introduction

HISTORY AND DEVELOPMENT OF MANUFACTURING ENGINEERING

Manufacturing engineering is just now beginning to emerge as a separate and recognized engineering discipline. Much of what manufacturing engineering is today and hopes to be in the future stems from the past. The Industrial Revolution, which took place in the eighteenth and nineteenth centuries, also gave birth to an engineering discipline devoted exclusively to the engineering of manufacturing. With the Industrial Revolution came the beginning of the factory system as we know it today, the invention of the steam engine to replace water as the principal source of power, and advances in metal cutting and production of machine tools.

Early pioneers in manufacturing engineering include Matthew Boulton and James Watt, who fabricated and assembled Watt's steam engine and then, as partners, produced the steam engine commercially. Eli Whitney, with his invention of the cotton gin, made it possible to turn out 50 lb of cleaned cotton a day. This revolutionized the textile industry and made cotton the leading industry in the South. Of greater significance was his invention of interchangeable parts manufactured for muskets at his factory near New Haven, Conn. in 1798.

Joseph Whitworth, between 1840 and 1850, developed a measuring machine and a standard system of uniform measures and gauges, and, perhaps of greater importance, a uniform system of screw threads. Whitworth in 1857 perfected a hexagonal-barreled rifle of great range, accuracy, and penetrative power which was far superior to the Enfield, which was then largely in use. In 1865 Whitworth invented a rifled cannon that would fire a 250-lb shell some 6 miles. His invention of compressed cast steel for ordnance manufacture was another outstanding achievement.

Another pioneer in manufacturing engineering was Alfred Krupp, a German inventor and metallurgist, who discovered a method for casting steel into large ingots of up to 2 tons with no flaws. He also developed a new Bessemer steel for the production of weapons and railway wheels, and a method for hardening armor plate.

Frederic W. Taylor was an outstanding early pioneer in both industrial and manufacturing engineering. His achievements in scientific management are perhaps better known than his invention of the Taylor-White process of treating modern high-speed cutting tools, for which he received a gold medal at the Paris Exposition in 1900. He also wrote *The Art of Cutting Metals* in 1905. Taylor's studies on the use of fluids to aid the cutting of metals proved to machinists of his era that a heavy stream of water, flooding the tool-chip-workpiece contact area during cutting, would allow cutting speeds to be increased 30 to 40%.

The primary reason for Taylor's successes was that he had identified all of the variables involved in metal cutting by machine, and then applied the scientific rule of varying only one factor at a time. He identified some 12 variable factors in metal cutting, and from this devised a slide rule for the use of manufacturing engineers which substituted scientific control of the machine shop for the rule-of-thumb methods of the machinists of his day.

The most spectacular results of all were achieved when Taylor began to vary the composition of his steel tools and the degree of heat applied to them before letting them harden in air. From the experience of 14 years of experimental work he concluded that the best comparative basis of tool performance was the exact cutting speed in feet per minute which would cause the tool to be ruined after a 20-min run, all the other factors being held constant. These tool tests were the climax of Taylor's long years of experimentation. Taylor had succeeded in proving that in steel that contained 7% tungsten, 2% carbon, and 2.5% manganese, it was the manganese content which gave the steel its self-hardening characteristic.

Working in conjunction with Maunsel White in the Bethlehem Steel Works in 1892, Taylor made a discovery that astonished the engineering world of the time. He discovered that tungsten chrome tool steel performance would continue to improve with heating until the fusion point was reached. When such a tool was brought to cherry-red heat before cooling in air, a cutting speed of 30 ft/min was enough to cause failure in the prescribed period of 20 min. When a similar tool was heated to 2000°F, this being just below the fusion point, cutting speed could be increased to 80 or 90 ft/min before failure occurred. Up until this time all the recongized authorities on steels had insisted that the new alloy tool steels must not be heated above 1550°F.*

Other early pioneers in manufacturing engineering include Charles Norton, who worked with grinding wheels and grinding machines, Henry Ford, with the mass production of the automobile, and many more

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*Portions of the previous historical material adapted from L.T.C. Holt, *A Short History of Machine Tools*, MIT Press, Cambridge, 1967.

who have helped evolve the manufacturing engineering discipline to the stature and recognition that it has attained today.

In the early shops and factories of the eighteenth and ninteenth centuries, and in the early twentieth century prior to the World War II, the manufacturing engineering duties and responsibilities were part of the shop supervisor's job. There were no specialists in manufacturing engineering, production control, quality control, industrial engineering, and so on. Methods, processes, and tools were primitive for the most part, and labor was cheap.

As manufacturing organizations grew larger and manufacturing became more complex and specialized, the foreman could no longer perform as a supervisor of the production work force and have the time or knowledge to handle the planning, tooling, material control, or product inspection requirements necessary to keep the shop or factory operating. The need for the technical training and expertise of engineers to plan production, design processes and tools, and select and specify production equipment became more apparent as the industrialization of the Western world continued.

Manufacturing engineering evolved from the earlier traditional disciplines of civil, mechanical, and electrical engineering. Also, many of the technologies of traditional industrial engineering such as plant layout, methods, work measurement, cost analysis, and material handling are part of the manufacturing engineering discipline as we know it today.

Manufacturing engineering is the specialized knowledge and skill in engineering science and analysis applied to the design, operation, and control of manufacturing processes and systems. Included in this broad definition are the following primary activities:

1. Selection and design of manufacturing processes
2. Determination of sequences and methods for product fabrication, assembly, and test
3. Selection and design of production equipment
4. Selection and design of tools and test equipment
5. Layout of factory buildings, machines, equipment, materials, and storage facilities
6. Determination of standard times for manufacturing operations
7. Selection and design of manufacturing systems and computer-aided manufacturing techniques
8. Manufacturing cost estimating, cost analysis, and cost trade studies
9. Manufacturing research and development
10. Review of product designs and specifications to ensure manufacturing producibility
11. Management, coordination, and control of manufacturing operations

Manufacturing engineering is defined by the Society of Manufacturing Engineers (SME) as "that specialty of professional engineering which requires such education and experience as is necessary to understand, apply, and control engineering procedures in manufacturing processes and methods of production of industrial commodities and products, and requires the ability to plan the practices of manufacturing, to research and develop the tools, processes, machines and equipment, and to integrate the facilities and systems for producing quality with optimal expenditure."

The manufacturing engineer provides the link between engineering design and product build. He has the responsibility for the translation of highly technical engineering information into simple, easy-to-understand work instructions enabling production operators to easily understand the tasks they must perform to build the product. Not only must the manufacturing engineer determine the manufacturing process, but it must be the most efficient and most economical process. He must determine how the manufacturing process and materials must be configured to ensure maximum productivity. The manufacturing engineer must consider all manufacturing aspects: what is to be manufactured, in what quantity, what the schedule requirements are, how it will be built, and what it takes to build it.

It has only been in the past few years that there has been college-level, professional engineering training leading to a degree in manufacturing engineering. Now fully accredited programs in manufacturing engineering are offered at the associate, bachelor's, and master's levels. Associate and bachelor's degrees are also offered in manufacturing technology. Most manufacturing engineers received their college-level training in either industrial, mechanical, or electrical engineering. Many of the professional engineering societies such as the Society of Manufacturing Engineers offer specialized training and certification to practicing manufacturing engineers through seminars, short courses, and home study programs.

Certification indicates an engineer's ability to meet a given set of standards related to the many aspects of manufacturing engineering. In addition to academic requirements, certification pertains to the actual experience required of the manufacturing engineer. To meet the SME requirements for certification as a manufacturing engineer, an applicant must have a good record of 10 years or more in responsible charge of important manufacturing engineering projects, which have included:

—Planning and selecting methods for manufacture
—Designing equipment for manufacturing
—Research and development leading to the creation of new manufacturing methods or the improvement of existing processes
—Administration of manufacturing operations covering long-range planning, materials, production control, product configuration, manufacturing facilities, and production management systems

The Institute of Industrial Engineers has established separate divisions for industrial engineers working in manufacturing systems, production and inventory control, facilities planning and design, work measurement, and methods engineering. The American Society of Mechanical Engineers and the Institute of Electrical and Electronic Engineers have sections specializing in manufacturing engineering.

A manufacturing engineer is, by definition of the Society of Manufacturing Engineers, an engineer who has acquired certain standards of professional accomplishment. Many states now offer professional registration to manufacturing engineers. Manufacturing engineering is a branch of engineering which a candidate for registration can be examined and then licensed.

In our high-technology society, the professional manufacturing engineer is a key participant. His knowledge, expertise, and experience, along with those of professional engineers in other branches of engineering, make our standard of living what it is today. From the high-volume mass production of consumer goods to the manufacture of a highly complex military weapons system, the manufacturing engineer plays an important role. In the years to come the continued advance of the technology of manufacturing will depend upon the contribution of competent professional manufacturing engineers.

SCOPE OF MANUFACTURING ENGINEERING

All manufacturing is conversion: the conversion of raw materials into finished goods, the conversion of coal and iron ore into steel, and then the conversion of the steel into a modern automobile. The mining of bauxite and its conversion into aluminum bar stock, which is ultimately converted into screw machine parts, is among the almost limitless examples.

The manufacturing engineer must be there, planning and tooling the process of manufacture. Manufacturing engineers are found in almost every industry where manufacturing takes place. If the industry is highly specialized and has a technology all its own, then the manufacturing engineers in that industry must be knowledgeable and experienced in that technology. This results in a high degree of specialization in the manufacturing engineering field, yet there is a common, fundamental discipline of manufacturing engineering used by all practitioners, and that is what this book is about.

Manufacturing engineering grew and developed as a genuine engineering discipline in the metalworking industry, because in the early years of this century that was where the frontier of industrial technology existed. This frontier later moved to electronics, and now today into computers. Manufacturing engineers are found in mass production and assembly, such as in the automotive and consumer electronics industries.

The vast majority of industry today, in the modern industrial world, consists of job shop or job order manufacturing. Job order manufacturing offers a special challenge to the manufacturing engineer, in that production runs are short, and the costs of job planning and setup can easily eliminate job profitability if they are not controlled.

The majority of manufacturing engineers today work in private industry. Some few work for government agencies, educational institutions, or management and engineering consulting firms. They are found in the manufacturing of primary metal products, machinery, electrical and electronic equipment, transportation equipment, and miscellaneous manufactured products. Job responsibilities include developing methods of manufacture, designing tools and equipment for manufacturing, as well as administrative and supervisory responsibilities.

The manufacturing engineering function is subdivided into various areas of specialization. How the function is subdivided depends largely on the needs of the corporate structure. The subdivisions include process engineering, tool engineering, standards, plant engineering, administration and control, and research. The next section, on the organization of the manufacturing engineering department, will show how this should be done for best results.

ORGANIZING FOR MANUFACTURING ENGINEERING

As in organizing for any other company function, the same basic principles of organization must be followed. These principles include as a minimum:

1. Authority, responsibility, and acountability must be clearly defined.
2. The organization function must be integrated into the company plan of organization.
3. The new department must be able to perform its assigned tasks effectively.

The table of contents of this book shows a wide variety of activities that a manufacturing engineering department can perform. In many instances these activities may not all be included in the tasks assigned to a given company manufacturing engineering department.

Place in Company Organization

The scope of activities assigned in a given company is a prime factor in deciding where to fit the manufacturing engineering department in the plan of organization and how to organize it internally. In the majority of cases the manufacturing engineering department is part of the manufacturing or operations division, and reports to the chief operations or manufacturing executive. This is the recommended reporting level. Manufacturing engineering should be on the same organizational level as manufacturing shops, production control, material control, and plant engineering. This is the most effective organization placement for most companies. Figure 1 shows such an organization plan.

Often we find manufacturing engineering called production engineering, process engineering, or industrial and production engineering. The function is still the same: to provide manufacturing engineering services. Today, as never before, industry depends upon the manufacturing engineer to start the wheels of production turning. The proper placement of manufacturing engineering in the organization ensures that this will take place.

Internal Department Organization

The manufacturing engineering department may have an overall organization paralleling that of the shop or production operations department, or it may be organized into subdivisions by related functions. There are advantages and disadvantages associated with both forms of organization. First, the advantages of such an organization structure are as follows:

1. Engineers working on all aspects of an operating department's problems receive very broad training and a good understanding

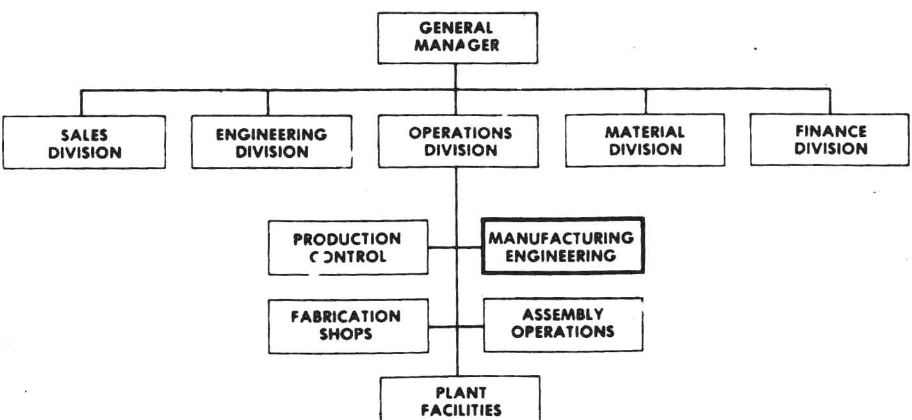

FIG. 1 Manufacturing engineering in the overall company organization.

of how manufacturing engineering services sustain and complement the operating department they serve.

2. This form of organization provides excellent specialized training for engineers for subsequent transfer as line supervisors of the department served.
3. This arrangement ensures that the highest priority problem in the shop department gets first attention.
4. Good rapport and a good working relationship usually develop between manufacturing engineers and shop supervision.
5. Since manufacturing engineering is highly technical and specialized, this arrangement allows assignment of the most qualified engineers to the appropriate shop operating department.

Figure 2 shows such an organization plan. The disadvantages of this kind of organization include the following:

1. Individual engineering proficiency in any one discipline is not likely to be obtained, since total support is required to cover the entire spectrum of services provided by manufacturing engineering.
2. Manufacturing engineering must be staffed with the degree and depth of experience needed to successfully support such an organizational arrangement.

In the department organization that groups related functions, the primary advantages are as follows:

1. Manufacturing engineers specialize within a narrow field, thus rapidly attaining a high degree of technical proficiency.
2. This organization form allows use of engineers with more limited experience because of the limited range of assigned duties.
3. Manufacturing engineers can easily be assigned to tasks that best suit their talents, interest, and experience.
4. This specialization makes it easier to recruit and staff the manufacturing engineering group because fewer engineers with heavy, diversified background experience are required.
5. A department organization that groups related functions is easier to manage and control.

Figure 3 shows a typical manufacturing engineering department organization that groups related functions. Disadvantages of this form of organization include:

1. The engineer specialist is less likely to be able to relate the effect of his work to the overall operation of the shop department he is supporting.

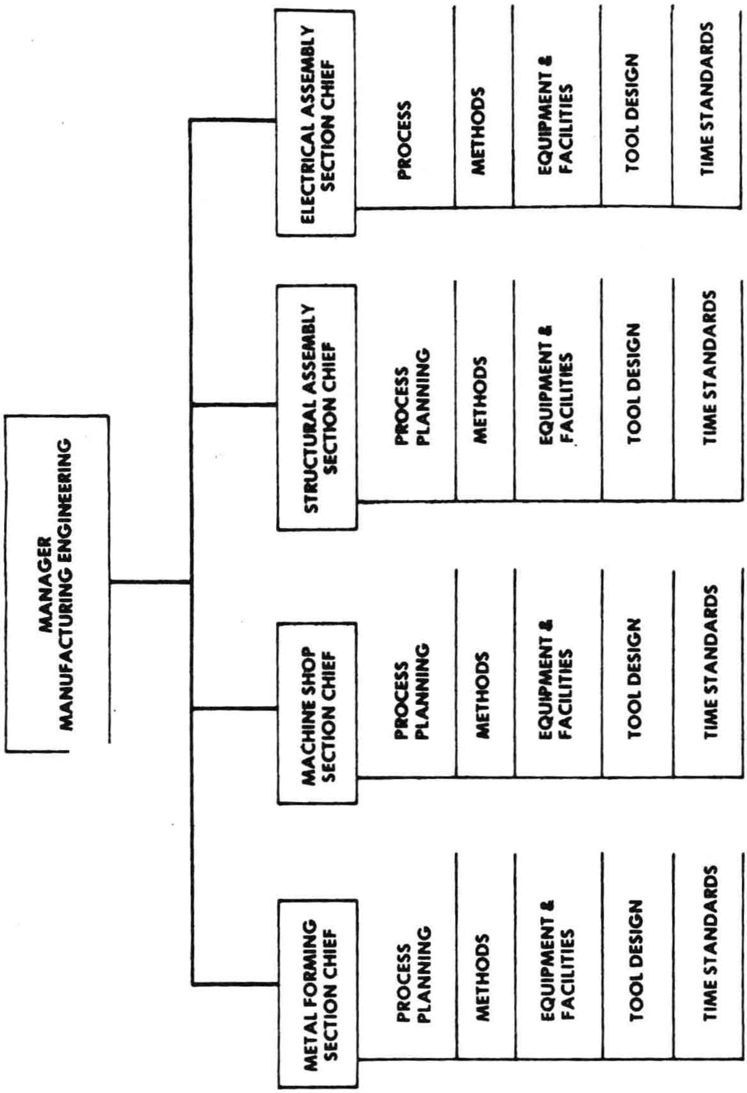

FIG. 2 Manufacturing engineering organization paralleling shop organization.

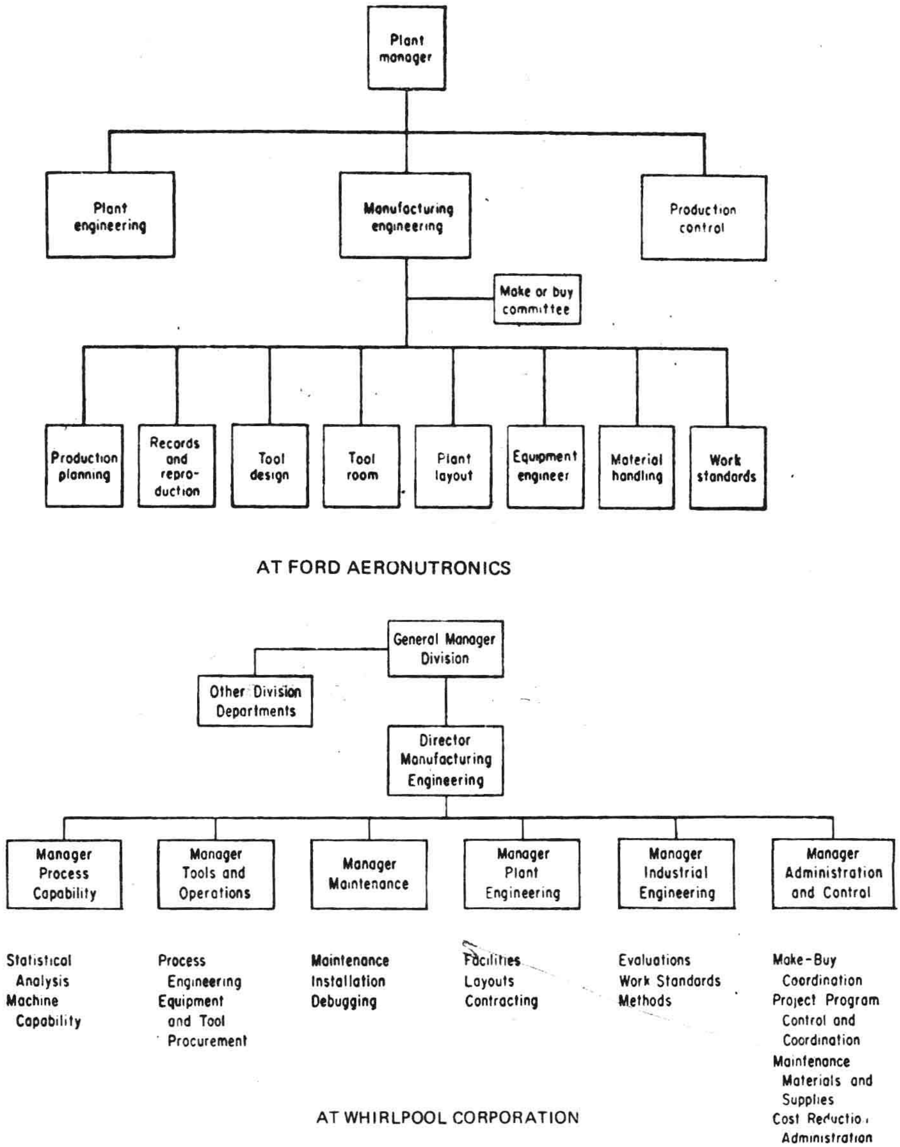

FIG. 3 Two related-function manufacturing engineering organizations. (Courtesy of the Ford Motor Company, Dearborn, Mich., and the Whirlpool Corporation, Benton Harbor, Mich.)

2. Because the manufacturing engineers are specialists and work in all shop departments, close working relationships are seldom developed with line management in any one department.
3. Cross-training of manufacturing engineers is more difficult, and the ability to shift personnel to areas of need from other specialized assignments is limited in the manufacturing engineering group.

Whichever organization form is selected, it should be pointed out that the degree of complexity of the manufacturing operations, not the organization form, is the determining factor in the amount of manufacturing engineering support required and, ultimately, the size of the manufacturing engineering department required.

There is no one best department organization. The department organization that parallels the shop organization is recommended for plants which primarily work to job order or short-run production, and the organization that groups related functions is best for plants where production runs are long and the number of jobs or product lines is small. The number and variety of internal organization forms of a manufacturing engineering department are almost infinite. Company size, however, plays a key role in determining department size and organization. The small company will typically have a senior manufacturing engineer reporting directly to the manufacturing manager or superintendent, with duties consisting of planning product manufacture and designing and ordering the tooling and production machines and equipment. Reporting to the senior manufacturing engineer may be a tool designer and a junior engineer. The senior manufacturing engineer in this situation must have heavy experience and be a qualified professional in every sense of the word.

In the medium-sized company, the organization of the manufacturing engineering department should take the form shown in Fig. 4. The various sections parallel the shop organization because of the need for a close working relationship with shop supervision. The manufacturing engineering department would be headed by a manager who reports to a director of manufacturing or operations. Sections within the department should be headed by section chiefs. Grade levels ranging from associate engineer, through engineer and senior engineer, up to lead engineer would be appropriate. Technician grades would include analyst, tool designer, and numerical control (N/C) programmer. Even though the organization is more formal, the emphasis is the same as for the small company. The need for the key positions to be filled by qualified professionals with heavy experience is extremely important.

The large-company organization should take the form shown in Fig. 5. A large company would have 900 or more employees, and the medium-sized company described above would have from 300 to 900 employees. The small company would have fewer than 300 employees. The large company with greater resources would employ more specialists