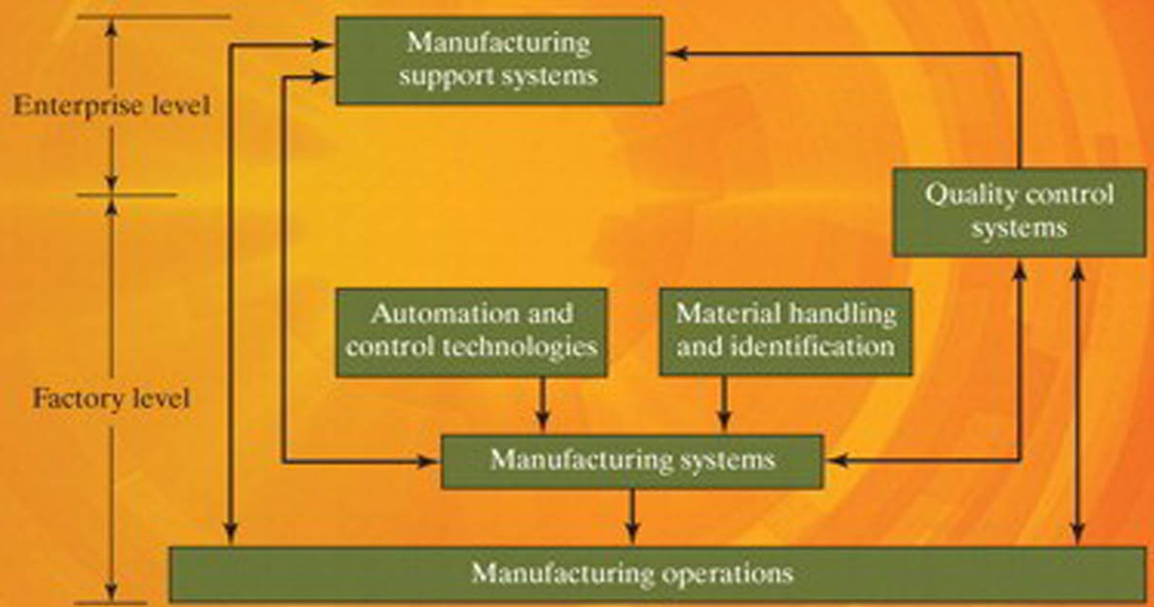
Automation, Production Systems, and Computer-Integrated Manufacturing

Fourth Edition



Mikell P. Groover

Abbreviations Used in This Book

Abbreviation	Unabbreviated Unit(s)
A	amps
C	Celsius, Centigrade
cm	centimeters
F	Fahrenheit
hp	horsepower
hr	hour, hours
Hz	hertz $(sec)^{-1}$
in	inch, inches
lbf	pounds force
m	meters
min	minute, minutes
mm	millimeters
MPa	megapascals (N/mm^2)
mV	millivolts
N	newtons
ops	operations
Pa	pascals (N/m^2)
pc	pieces, parts
rad	Radians
rev	revolutions
sec	second, seconds
V	volts
W	watts
wk	week, weeks
yr	year, years
μ-in	microinches
μm	microns, micrometers
μ-sec	microseconds
μV	microvolts
Ω	ohms

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Fourth Edition

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Contents

Preface

This book has a history. It was originally published in 1980 as *Automation, Production Systems, and Computer-Aided Manufacturing*. Topics included automated flow lines, assembly line balancing, numerical control, CAD/CAM, control theory, process control, production planning, group technology, and flexible manufacturing systems. A revised edition was published in 1986 with a change in title to *Automation, Production Systems, and Computer-Integrated Manufacturing*. Additional topics included industrial robotics, programmable logic controllers, automated assembly systems, material handling and storage, automatic identification techniques, shop floor control, and the future automated factory. The second edition of the new title was released in 2000 with a 2001 copyright. Many of the topics remained the same as in the 1986 edition, but much of the material on control theory was eliminated. The book was reorganized substantially, and most of the chapters were rewritten to bring the technical subject matter up to date. The third edition was released in 2007 with a 2008 copyright. It contained expanded coverage of new and emerging technologies (e.g., radio frequency identification, Six Sigma, lean production, enterprise resource planning).

The basic objective of this new edition remains the same as in the previous editions: to provide up-to-date coverage of production systems, how they are sometimes automated and computerized, and how they can be mathematically analyzed to obtain performance metrics. The textbook is designed primarily for engineering students at the advanced undergraduate or beginning graduate levels in industrial, mechanical, and manufacturing engineering. It has all the features of an engineering textbook: equations, example problems, diagrams, quantitative end-of-chapter exercises, and technical descriptions that seem designed to baffle college students. The book should also be useful for practicing engineers and managers who wish to learn about automation and production systems technologies in modern manufacturing.

NEW TO THIS EDITION

In this fourth edition of the current title (fifth edition of the original 1980 book), I have consolidated and reorganized many of the topics and eliminated material that I felt is no longer relevant. Among the new topics and other changes in the book are those listed below. Items marked with an asterisk (*) relate to recommendations made by the reviewers (see Acknowledgments).

- In Chapter 3 (Manufacturing Metrics and Economics), many of the equations have been revised to make them more robust. A new section on cost of a manufactured part has been added.

- In Chapter 6 (Hardware Components for Automation and Process Control), new content has been added on electric motors, including linear motors and the conversion of rotary motion to linear motion.* Several new figures have been added in support of the new content.*
- In Chapter 7 (Computer Numerical Control), the appendix on APT has been removed because this method of programming has been largely replaced in industry by CAD/CAM part programming, coverage of which has been expanded in this new edition. In addition, the mathematical models of positioning control have been improved.
- In Chapter 8 (Industrial Robotics), two new robot configurations have been added and two configurations have been eliminated because they are no longer relevant.
- In Chapter 9 (Discrete Control and Programmable Logic Controllers), corrections and improvements have been made in the ladder logic examples.* A section on programmable automation controllers has been added.
- In Chapter 10 (Material Transport Systems), the section on AGVS technologies has been updated.
- In Chapter 11 (Storage Systems), the section on automated storage/retrieval systems has been updated and shortened.*
- In Chapter 12 (Automatic Identification and Data Capture), the section on radio frequency identification (RFID) has been expanded and updated.*
- In Chapter 14 (Single-Station Manufacturing Cells), coverage of CNC machining centers and related machine tools has been expanded.
- In Chapter 15 (Manual Assembly Lines), coverage of mixed-model assembly lines has been moved to an appendix, on the assumption that some instructors may not want to include this topic in their courses. A new section on batch-model assembly lines has been included in the appendix.
- In Chapter 16 (Automated Production Lines), coverage of transfer lines with internal parts storage has been moved to an appendix, on the assumption that some instructors may not want to include this topic in their courses.
- In Chapter 18 (Group Technology and Cellular Manufacturing), the organization of the text has been substantially revised. A new section on performance metrics in cell operations has been added. Coverage of parts classification and coding has been reduced, and the Opitz system has been relocated to an appendix.
- In Chapter 19 (Flexible Manufacturing Cells and Systems), sections on mass customization, reconfigurable manufacturing systems, and agile manufacturing have been added.
- In Chapter 20 (Quality Programs for Manufacturing), the DMAIC procedure in Six Sigma has been relocated to an appendix, on the assumption that some instructors may not want to cover the detailed methodology of Six Sigma. If they do, those details are in the appendix.
- In Chapter 22 (Inspection Technologies), the mathematical details of coordinate metrology have been relocated to an appendix. The section on machine vision has been updated to include recent advances in camera technology.

- In Chapter 23 (Product Design and CAD/CAM in the Production System), the section on CAD has been updated to be consistent with modern industrial practice.*
- In Chapter 25 (Production Planning and Control Systems), the section on work-in-process inventory costs has been eliminated, and the sections on MRP II and ERP have been upgraded.
- More than 50% of the end-of-chapter problems are new or revised. The total number of problems is increased from 393 in the third edition to 416 in this edition.
- An appendix has been added listing answers to selected end-of-chapter problems (answers to a total of 88 problems, or 21% of the end-of-chapter problems).*
- A total of 36 new or revised figures are included in this new edition, for a total of 278 figures. By comparison, the third edition has 293 figures, so the net change is a reduction of 15 figures. This is due to the removal of outdated and extraneous figures throughout the book and the elimination of the appendix on APT in Chapter 7.
- A list of abbreviations used in the book, located in the inside front cover, has been added for readers' reference.

SUPPORT MATERIALS FOR INSTRUCTORS

For instructors who adopt the book for their courses, the following support materials are available at the Pearson website, www.pearsonhighered.com. Evidence that the book has been adopted as the main textbook for the course must be verified.

- A ***Solutions Manual*** covering all review questions and problems
- A complete set of ***PowerPoint*** slides for all chapters

Individual questions or comments may be directed to the author at Mikell.Groover@Lehigh.edu or mpg0@Lehigh.edu.

ACKNOWLEDGMENTS

A number of changes in the book were motivated by responses to a survey that was conducted by the publisher. Some very worthwhile suggestions were offered by the reviewers, and I have attempted to incorporate them into the text where appropriate and feasible. In any case, I appreciate the thoughtful efforts that they contributed to the project, and I am sure that the book is better as a result of their efforts than it otherwise would have been. Participants in the survey were T. S. Bukkapatnam, Oklahoma State University; Joseph Domblesky, Marquette University; Brent Donham, Texas A&M University; John Jackman, Iowa State University; Matthew Kuttolamadom, Texas A&M University; Frank Peters, Iowa State University; and Tony Schmitz, University of North Carolina-Charlotte.

I also acknowledge the following individuals at Pearson Education Inc. for their support during this project: Holly Stark, Executive Editor; Clare Romeo, Program

Manager; and Sandra Rodriguez, Editorial Assistant. In addition, I am grateful for the fine job done by George Jacob at Integra Software Services who served as Program Manager for the project. He and the copy editors working with him were thorough and meticulous in their review of the manuscript (I take back all of the bad things I have ever said about copy editors throughout the nearly 40 years I have been writing textbooks).

Also, I am in gratitude to all of the faculty who have adopted the previous editions of the book for their courses, thus making those projects commercially successful for Pearson Education Inc., so that I would be allowed to prepare this new edition.

Finally, I wish to thank Marcia Hamm Groover, my wife, my PowerPoint slide expert, my computer specialist (I write books about computer-related technologies, but she is the one who fixes my computer when it has problems), and my supporter on this and other textbook projects.

ABOUT THE AUTHOR

Mikell P. Groover is Professor Emeritus of Industrial and Systems Engineering at Lehigh University, where he taught and did research for 44 years. He received his B.A. in Arts and Science (1961), B.S. in Mechanical Engineering (1962), M.S. in Industrial Engineering (1966), and Ph.D. (1969), all from Lehigh. His industrial experience includes several years as a manufacturing engineer before embarking on graduate studies at Lehigh.

His teaching and research areas include manufacturing processes, production systems, automation, material handling, facilities planning, and work systems. He has received a number of teaching awards at Lehigh University, as well as the Albert G. Holzman Outstanding Educator Award from the Institute of Industrial Engineers (1995) and the SME Education Award from the Society of Manufacturing Engineers (2001). His publications include over 75 technical articles and 12 books (listed below). His books are used throughout the world and have been translated into French, German, Spanish, Portuguese, Russian, Japanese, Korean, and Chinese. The first edition of *Fundamentals of Modern Manufacturing* received the IIE Joint Publishers Award (1996) and the M. Eugene Merchant Manufacturing Textbook Award from the Society of Manufacturing Engineers (1996).

Dr. Groover is a member of the Institute of Industrial Engineers (IIE) and the Society of Manufacturing Engineers (SME). He is a Fellow of IIE and SME.

PREVIOUS BOOKS BY THE AUTHOR

Automation, Production Systems, and Computer-Aided Manufacturing, Prentice Hall, 1980.

CAD/CAM: Computer-Aided Design and Manufacturing, Prentice Hall, 1984 (co-authored with E. W. Zimmers, Jr.).

Industrial Robotics: Technology, Programming, and Applications, McGraw-Hill Book Company, 1986 (co-authored with M. Weiss, R. Nagel, and N. Odrey).

Automation, Production Systems, and Computer-Integrated Manufacturing, Prentice Hall, 1987.

Fundamentals of Modern Manufacturing: *Materials, Processes, and Systems*, originally published by Prentice Hall in 1996, and subsequently published by John Wiley & Sons, Inc., 1999.

Automation, Production Systems, and Computer-Integrated Manufacturing, Second Edition, Prentice Hall, 2001.

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Work Systems and the Methods, Measurement, and Management of Work, Pearson Prentice Hall, 2007.

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Chapter 1

Introduction

CHAPTER CONTENTS

The word *manufacturing* derives from two Latin words, *manus* (hand) and *factus* (make), so that the combination means *made by hand*. This was the way manufacturing was accomplished when the word first appeared in the English language around 1567. Commercial goods of those times were made by hand. The methods were handicraft, accomplished in small shops, and the goods were relatively simple, at least by today's standards. As many years passed, factories came into being, with many workers at a single site, and the work had to be organized using machines rather than handicraft techniques. The products became more complex, and so did the processes to make them. Workers had to specialize in their tasks. Rather than overseeing the fabrication of the entire product, they were responsible for only a small part of the total work. More up-front planning was required, and more coordination of the operations was needed to keep track of the work flow in the factories. Slowly but surely, the systems of production were being developed.

The systems of production are essential in modern manufacturing. This book is all about these production systems and how they are sometimes automated and computerized.

1.1 PRODUCTION SYSTEMS

A production system is a collection of people, equipment, and procedures organized to perform the manufacturing operations of a company. It consists of two major components as indicated in Figure 1.1:

1. *Facilities*. The physical facilities of the production system include the equipment, the way the equipment is laid out, and the factory in which the equipment is located.
2. *Manufacturing support systems*. These are the procedures used by the company to manage production and to solve the technical and logistics problems encountered in ordering materials, moving the work through the factory, and ensuring that products meet quality standards. Product design and certain business functions are included in the manufacturing support systems.

In modern manufacturing operations, portions of the production system are automated and/or computerized. In addition, production systems include people. People make these systems work. In general, direct labor people (blue-collar workers)

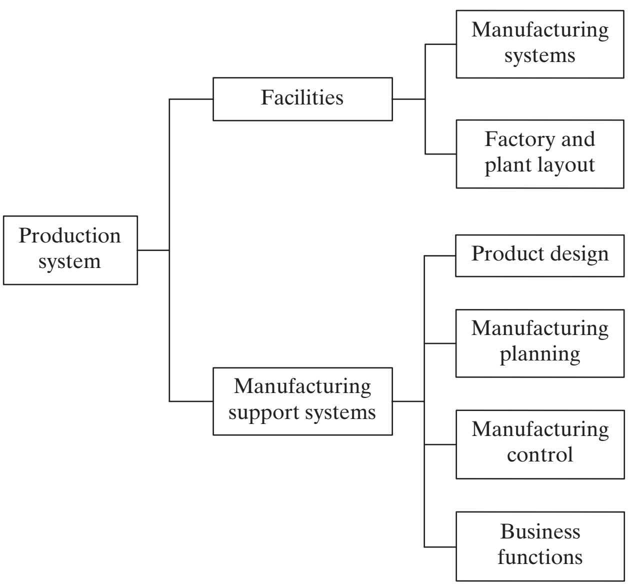

Figure 1.1 The production system consists of facilities and manufacturing support systems.

are responsible for operating the facilities, and professional staff people (white-collar workers) are responsible for the manufacturing support systems.

1.1.1 Facilities

The facilities in the production system consist of the factory, production machines and tooling, material handling equipment, inspection equipment, and computer systems that control the manufacturing operations. Facilities also include the ***plant layout***, which is the way the equipment is physically arranged in the factory. The equipment is usually organized into ***manufacturing systems***, which are the logical groupings of equipment and workers that accomplish the processing and assembly operations on parts and products made by the factory. Manufacturing systems can be individual work cells consisting of a single production machine and a worker assigned to that machine. More complex manufacturing systems consist of collections of machines and workers, for example, a production line. The manufacturing systems come in direct physical contact with the parts and/or assemblies being made. They "touch" the product.

In terms of human participation in the processes performed by the manufacturing systems, three basic categories can be distinguished, as portrayed in Figure 1.2: (a) manual work systems, (b) worker-machine systems, and (c) automated systems.

Manual Work Systems. A manual work system consists of one or more workers performing one or more tasks without the aid of powered tools. Manual material handling tasks are common activities in manual work systems. Production tasks commonly require the use of hand tools, such as screwdrivers and hammers. When using hand tools, a workholder is often employed to grasp the work part and position it securely for processing. Examples of production-related manual tasks involving the use of hand tools include

- A machinist using a file to round the edges of a rectangular part that has just been milled
- A quality control inspector using a micrometer to measure the diameter of a shaft
- A material handling worker using a dolly to move cartons in a warehouse
- A team of assembly workers putting together a piece of machinery using hand tools.

Worker-Machine Systems. In a worker-machine system, a human worker operates powered equipment, such as a machine tool or other production machine. This is one of the most widely used manufacturing systems. Worker-machine systems include

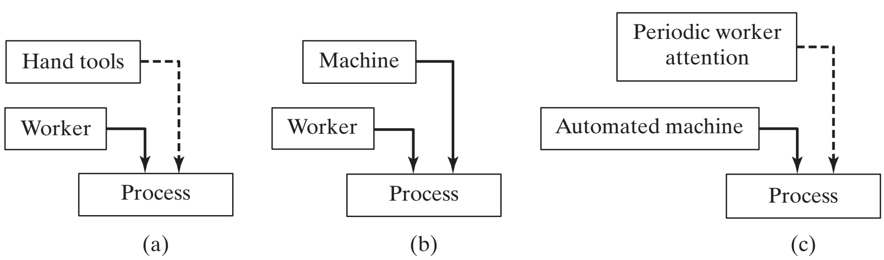

Figure 1.2 Three categories of manufacturing systems: (a) manual work system, (b) worker-machine system, and (c) fully automated system.

combinations of one or more workers and one or more pieces of equipment. The workers and machines are combined to take advantage of their relative strengths and attributes, which are listed in Table 1.1. Examples of worker-machine systems include the following:

- A machinist operating an engine lathe to fabricate a part for a product
- A fitter and an industrial robot working together in an arc–welding work cell
- A crew of workers operating a rolling mill that converts hot steel slabs into flat plates
- A production line in which the products are moved by mechanized conveyor and the workers at some of the stations use power tools to accomplish their processing or assembly tasks.

Automated Systems. An automated system is one in which a process is performed by a machine without the direct participation of a human worker. Automation is implemented using a program of instructions combined with a control system that executes the instructions. Power is required to drive the process and to operate the program and control system (these terms are defined more completely in Chapter 4).

There is not always a clear distinction between worker-machine systems and automated systems, because many worker-machine systems operate with some degree of automation. Two levels of automation can be identified: semiautomated and fully automated. A ***semiautomated machine*** performs a portion of the work cycle under some form of program control, and a human worker tends to the machine for the remainder of the cycle, by loading and unloading it, or by performing some other task each cycle. A ***fully automated machine*** is distinguished from its semiautomated counterpart by its capacity to operate for an extended period of time with no human attention. Extended period of time means longer than one work cycle; a worker is not required to be present during each cycle. Instead, the worker may need to tend the machine every tenth cycle, or every hundredth cycle. An example of this type of operation is found in many injection molding plants, where the molding machines run on automatic cycles, but periodically the molded parts at the machine must be collected by a worker. Figure 1.2(c) depicts a fully automated system. The semiautomated system is best portrayed by Figure 1.2(b).

In certain fully automated processes, one or more workers are required to be present to continuously monitor the operation, and make sure that it performs according to the intended specifications. Examples of these kinds of automated processes include complex

TABLE 1.1 Relative Strengths and Attributes of Humans and Machines

Humans	Machines
Sense unexpected stimuli	Perform repetitive tasks consistently
Develop new solutions to problems	Store large amounts of data
Cope with abstract problems	Retrieve data from memory reliably
Adapt to change	Perform multiple tasks simultaneously
Generalize from observations	Apply high forces and power
Learn from experience	Perform simple computations quickly
Make decisions based on incomplete data	Make routine decisions quickly

chemical processes, oil refineries, and nuclear power plants. The workers do not actively participate in the process except to make occasional adjustments in the equipment settings, perform periodic maintenance, and spring into action if something goes wrong.

1.1.2 Manufacturing Support Systems

To operate the production facilities efficiently, a company must organize itself to design the processes and equipment, plan and control the production orders, and satisfy product quality requirements. These functions are accomplished by manufacturing support systems—people and procedures by which a company manages its production operations. Most of these support systems do not directly contact the product, but they plan and control its progress through the factory.

Manufacturing support involves a sequence of activities, as depicted in Figure 1.3. The activities consist of four functions that include much information flow and data processing: (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control.

Business Functions. The business functions are the principal means by which the company communicates with the customer. They are, therefore, the beginning and the end of the information-processing sequence. Included in this category are sales and marketing, sales forecasting, order entry, and customer billing.

The order to produce a product typically originates from the customer and proceeds into the company through the sales department of the firm. The production order will be in one of the following forms: (1) an order to manufacture an item to the customer's specifications, (2) a customer order to buy one or more of the manufacturer's proprietary products, or (3) an internal company order based on a forecast of future demand for a proprietary product.

Product Design. If the product is manufactured to customer design, the design has been provided by the customer, and the manufacturer's product design department is not involved. If the product is to be produced to customer specifications, the manufacturer's product design department may be contracted to do the design work for the product as well as to manufacture it.

If the product is proprietary, the manufacturing firm is responsible for its development and design. The sequence of events that initiates a new product design often originates in the sales department; the direction of information flow is indicated in Figure 1.3. The departments of the firm that are organized to accomplish product design might include research and development, design engineering, and perhaps a prototype shop.

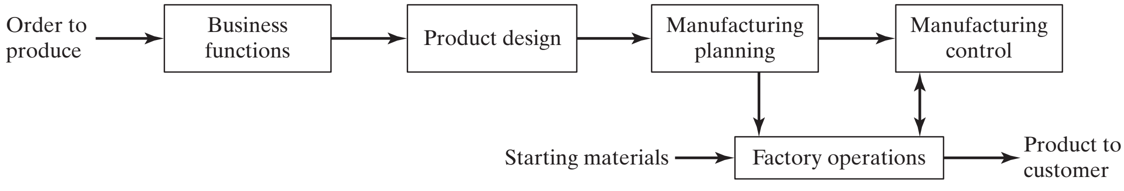

Figure 1.3 Sequence of information-processing activities in a typical manufacturing firm.

Manufacturing Planning. The information and documentation that constitute the product design flows into the manufacturing planning function. The information-processing activities in manufacturing planning include process planning, master scheduling, material requirements planning, and capacity planning.

Process planning consists of determining the sequence of individual processing and assembly operations needed to produce the part. The manufacturing engineering department is responsible for planning the processes and related technical details such as tooling. Manufacturing planning includes logistics issues, commonly known as production planning. The authorization to produce the product must be translated into the ***master production schedule***, which is a listing of the products to be made, the dates on which they are to be delivered, and the quantities of each. Based on this master schedule, the individual components and subassemblies that make up each product must be scheduled. Raw materials must be purchased or requisitioned from storage, parts must be ordered from suppliers, and all of these items must be planned so they are available when needed. The computations for this planning are made by ***material requirements planning***. In addition, the master schedule must not list more quantities of products than the factory is capable of producing each month with its given number of machines and manpower. ***Capacity planning*** is concerned with determining the human and equipment resources of the firm and checking to make sure that the production plan is feasible.

Manufacturing Control. Manufacturing control is concerned with managing and controlling the physical operations in the factory to implement the manufacturing plans. The flow of information is from planning to control as indicated in Figure 1.3. Information also flows back and forth between manufacturing control and the factory operations. Included in this function are shop floor control, inventory control, and quality control.

Shop floor control deals with the problem of monitoring the progress of the product as it is being processed, assembled, moved, and inspected in the factory. Shop floor control is concerned with inventory in the sense that the materials being processed in the factory are work-in-process inventory. Thus, shop floor control and inventory control overlap to some extent. ***Inventory control*** attempts to strike a proper balance between the risk of too little inventory (with possible stock-outs of materials) and the carrying cost of too much inventory. It deals with such issues as deciding the right quantities of materials to order and when to reorder a given item when stock is low. The function of ***quality control*** is to ensure that the quality of the product and its components meet the standards specified by the product designer. To accomplish its mission, quality control depends on inspection activities performed in the factory at various times during the manufacture of the product. Also, raw materials and component parts from outside sources are sometimes inspected when they are received, and final inspection and testing of the finished product is performed to ensure functional quality and appearance. Quality control also includes data collection and problem-solving approaches to address process problems related to quality, such as statistical process control (SPC) and Six Sigma.

1.2 AUTOMATION IN PRODUCTION SYSTEMS

Some components of the firm's production system are likely to be automated, whereas others will be operated manually or clerically. The automated elements of the production system can be separated into two categories: (1) automation of the manufacturing

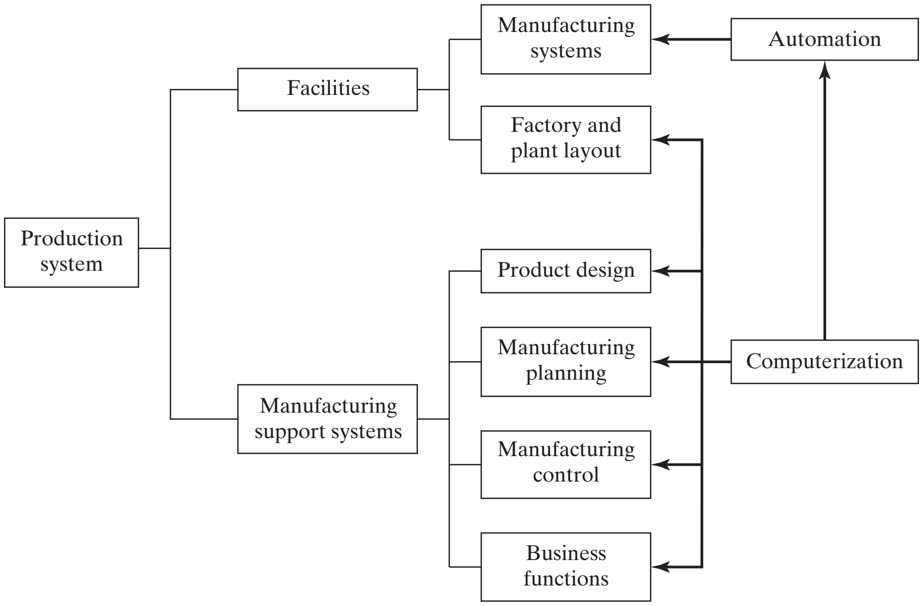

Figure 1.4 Opportunities for automation and computerization in a production system.

systems in the factory, and (2) computerization of the manufacturing support systems. In modern production systems, the two categories are closely related, because the automated manufacturing systems on the factory floor are themselves usually implemented by computer systems that are integrated with the manufacturing support systems and management information system operating at the plant and enterprise levels. The two categories of automation are shown in Figure 1.4 as an overlay on Figure 1.1.

1.2.1 Automated Manufacturing Systems

Automated manufacturing systems operate in the factory on the physical product. They perform operations such as processing, assembly, inspection, and material handling, in many cases accomplishing more than one of these operations in the same system. They are called automated because they perform their operations with a reduced level of human participation compared with the corresponding manual process. In some highly automated systems, there is virtually no human participation. Examples of automated manufacturing systems include:

- Automated machine tools that process parts
- Transfer lines that perform a series of machining operations
- Automated assembly systems
- Manufacturing systems that use industrial robots to perform processing or assembly operations
- Automatic material handling and storage systems to integrate manufacturing operations
- Automatic inspection systems for quality control.

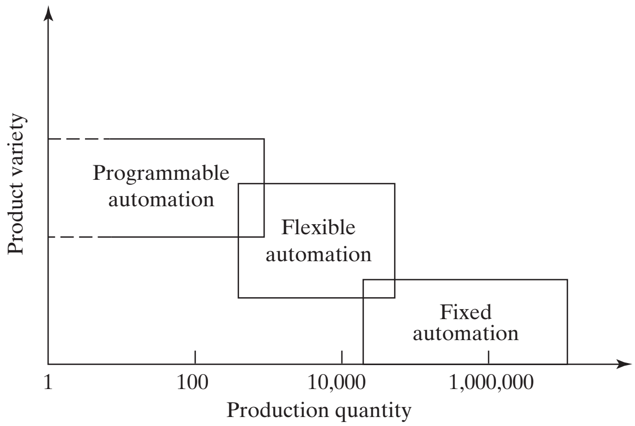

Figure 1.5 Three types of automation relative to production quantity and product variety.

Automated manufacturing systems can be classified into three basic types: (1) fixed automation, (2) programmable automation, and (3) flexible automation. They generally operate as fully automated systems although semiautomated systems are common in programmable automation. The relative positions of the three types of automation for different production volumes and product varieties are depicted in Figure 1.5.

Fixed Automation. Fixed automation is a system in which the sequence of processing (or assembly) operations is fixed by the equipment configuration. Each operation in the sequence is usually simple, involving perhaps a plain linear or rotational motion or an uncomplicated combination of the two, such as feeding a rotating spindle. It is the integration and coordination of many such operations in one piece of equipment that makes the system complex. Typical features of fixed automation are (1) high initial investment for custom-engineered equipment, (2) high production rates, and (3) inflexibility of the equipment to accommodate product variety.

The economic justification for fixed automation is found in products that are made in very large quantities and at high production rates. The high initial cost of the equipment can be spread over a very large number of units, thus minimizing the unit cost relative to alternative methods of production. Examples of fixed automation include machining transfer lines and automated assembly machines.

Programmable Automation. In programmable automation, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. The operation sequence is controlled by a ***program***, which is a set of instructions coded so that they can be read and interpreted by the system. New programs can be prepared and entered into the equipment to produce new products. Some of the features that characterize programmable automation include (1) high investment in general-purpose equipment, (2) lower production rates than fixed automation, (3) flexibility to deal with variations and changes in product configuration, and (4) high suitability for batch production.

Programmable automated systems are used in low- and medium-volume production. The parts or products are typically made in batches. To produce each new batch of a different item, the system must be reprogrammed with the set of machine instructions that correspond to the new item. The physical setup of the machine must also be changed: Tools must be loaded, fixtures must be attached to the machine table, and any required machine settings must be entered. This changeover takes time. Consequently, the typical cycle for a given batch includes a period during which the setup and reprogramming take place, followed by a period in which the parts are produced. Examples of programmable automation include numerically controlled (NC) machine tools, industrial robots, and programmable logic controllers.

Flexible Automation. Flexible automation is an extension of programmable automation. A flexible automated system is capable of producing a variety of parts or products with virtually no time lost for changeovers from one design to the next. There is no lost production time while reprogramming the system and altering the physical setup (tooling, fixtures, machine settings). Accordingly, the system can produce various mixes and schedules of parts or products instead of requiring that they be made in batches. What makes flexible automation possible is that the differences between parts processed by the system are not significant, so the amount of changeover between designs is minimal. Features of flexible automation include (1) high investment for a custom-engineered system, (2) continuous production of variable mixtures of parts or products, (3) medium production rates, and (4) flexibility to deal with product design variations. Examples of flexible automation are flexible manufacturing systems that perform machining processes.

1.2.2 Computerized Manufacturing Support Systems

Automation of the manufacturing support systems is aimed at reducing the amount of manual and clerical effort in product design, manufacturing planning and control, and the business functions of the firm. Nearly all modern manufacturing support systems are implemented using computers. Indeed, computer technology is used to implement automation of the manufacturing systems in the factory as well. ***Computer-integrated manufacturing*** (CIM) denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform the various information-processing functions needed in a manufacturing firm. True CIM involves integrating all of these functions in one system that operates throughout the enterprise. Other terms are used to identify specific elements of the CIM system; for example, *computer-aided design* (CAD) supports the product design function. *Computer-aided manufacturing* (CAM) is used for functions related to manufacturing engineering, such as process planning and numerical control part programming. Some computer systems perform both CAD and CAM, and so the term *CAD/CAM* is used to indicate the integration of the two into one system.

Computer-integrated manufacturing involves the information-processing activities that provide the data and knowledge required to successfully produce the product. These activities are accomplished to implement the four basic manufacturing support functions identified earlier: (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control.

1.2.3 Reasons for Automating

Companies undertake projects in automation and computer-integrated manufacturing for good reasons, some of which are the following:

1. *Increase labor productivity*. Automating a manufacturing operation invariably increases production rate and labor productivity. This means greater output per hour of labor input.
2. *Reduce labor cost*. Increasing labor cost has been, and continues to be, the trend in the world's industrialized societies. Consequently, higher investment in automation has become economically justifiable to replace manual operations. Machines are increasingly being substituted for human labor to reduce unit product cost.
3. *Mitigate the effects of labor shortages*. There is a general shortage of labor in many advanced nations, and this has stimulated the development of automated operations as a substitute for labor.
4. *Reduce or eliminate routine manual and clerical tasks*. An argument can be put forth that there is social value in automating operations that are routine, boring, fatiguing, and possibly irksome. Automating such tasks improves the general level of working conditions.
5. *Improve worker safety*. Automating a given operation and transferring the worker from active participation in the process to a monitoring role, or removing the worker from the operation altogether, makes the work safer. The safety and physical well-being of the worker has become a national objective with the enactment of the Occupational Safety and Health Act (OSHA) in 1970. This has provided an impetus for automation.
6. *Improve product quality*. Automation not only results in higher production rates than manual operation, it also performs the manufacturing process with greater consistency and conformity to quality specifications.
7. *Reduce manufacturing lead time*. Automation helps reduce the elapsed time between customer order and product delivery, providing a competitive advantage to the manufacturer for future orders. By reducing manufacturing lead time, the manufacturer also reduces work-in-process inventory.
8. *Accomplish processes that cannot be done manually*. Certain operations cannot be accomplished without the aid of a machine. These processes require precision, miniaturization, or complexity of geometry that cannot be achieved manually. Examples include certain integrated circuit fabrication operations, rapid prototyping processes based on computer graphics (CAD) models, and the machining of complex, mathematically defined surfaces using computer numerical control. These processes can only be realized by computer-controlled systems.
9. *Avoid the high cost of not automating*. There is a significant competitive advantage gained in automating a manufacturing plant. The advantage cannot always be demonstrated on a company's project authorization form. The benefits of automation often show up in unexpected and intangible ways, such as in improved quality, higher sales, better labor relations, and better company image. Companies that do not automate are likely to find themselves at a competitive disadvantage with their customers, their employees, and the general public.

1.3 MANUAL LABOR IN PRODUCTION SYSTEMS

Is there a place for manual labor in the modern production system? The answer is yes. Even in a highly automated production system, humans are still a necessary component of the manufacturing enterprise. For the foreseeable future, people will be required to manage and maintain the plant, even in those cases where they do not participate directly in its manufacturing operations. The discussion of the labor issue is separated into two parts, corresponding to the previous distinction between facilities and manufacturing support: (1) manual labor in factory operations and (2) labor in manufacturing support systems.

1.3.1 Manual Labor in Factory Operations

There is no denying that the long-term trend in manufacturing is toward greater use of automated machines to substitute for manual labor. This has been true throughout human history, and there is every reason to believe the trend will continue. It has been made possible by applying advances in technology to factory operations. In parallel and sometimes in conflict with this technologically driven trend are issues of economics that continue to find reasons for employing manual labor in manufacturing.

Certainly one of the current economic realities in the world is that there are countries whose average hourly wage rates are so low that most automation projects are difficult to justify strictly on the basis of cost reduction. These countries include China, India, Mexico, and many countries in Eastern Europe, Southeast Asia, and Latin America. With the passage of the North American Free Trade Agreement (NAFTA), the North American continent has become one large labor pool. Within this pool, Mexico's labor rate is an order of magnitude less than that in the United States. U.S. corporate executives who make decisions on factory locations and the outsourcing of work must reckon with this reality.

In addition to the labor cost issue, there are other reasons, ultimately based on economics, that make the use of manual labor a feasible alternative to automation. Humans possess certain attributes that give them an advantage over machines in certain situations and certain kinds of tasks (Table 1.1). A number of situations can be listed in which manual labor is preferred over automation:

- *Task is technologically too difficult to automate*. Certain tasks are very difficult (either technologically or economically) to automate. Reasons for the difficulty include (1) problems with physical access to the work location, (2) adjustments required in the task, (3) manual dexterity requirements, and (4) demands on hand–eye coordination. Manual labor is used to perform the tasks in these cases. Examples include automobile final assembly lines where many final trim operations are accomplished by human workers, inspection tasks that require judgment to assess quality, and material handling tasks that involve flexible or fragile materials.
- *Short product life cycle*. If a product must be designed and introduced in a short period of time to meet a near-term window of opportunity in the marketplace, or if the product is anticipated to be on the market for a relatively short period, then a manufacturing method designed around manual labor allows for a much sooner product launch than does an automated method. Tooling for manual production can be fabricated in much less time and at much lower cost than comparable automation tooling.

- *Customized product*. If the customer requires a one-of-a-kind item with unique features, manual labor has the advantage as the appropriate production resource because of its versatility and adaptability. Humans are more flexible than any automated machine.
- *Ups and downs in demand*. Changes in demand for a product necessitate changes in production output levels. Such changes are more easily made when manual labor is used as the means of production. An automated manufacturing system has a fixed cost associated with its investment. If output is reduced, that fixed cost must be spread over fewer units, driving up the unit cost of the product. On the other hand, an automated system has an ultimate upper limit on its output capacity. It cannot produce more than its rated capacity. By contrast, manual labor can be added or reduced as needed to meet demand, and the associated cost of the resource is in direct proportion to its employment. Manual labor can be used to augment the output of an existing automated system during those periods when demand exceeds the capacity of the automated system.
- *Need to reduce risk of product failure*. A company introducing a new product to the market never knows for sure what the ultimate success of that product will be. Some products will have long life cycles, while others will be on the market for relatively short periods. The use of manual labor as the productive resource at the beginning of the product's life reduces the company's risk of losing a significant investment in automation if the product fails to achieve a long market life. Section 1.4.3 discusses an automation migration strategy that is suitable for introducing a new product.
- *Lack of capital*. Companies are sometimes forced to use manual labor in their production operations when they lack the capital to invest in automated equipment.

1.3.2 Labor in Manufacturing Support Systems

In manufacturing support functions, many of the routine manual and clerical tasks can be automated using computer systems. Certain production planning activities are better accomplished by computers than by clerks. Material requirements planning (MRP, Section 25.2) is an example. In material requirements planning, order releases are generated for component parts and raw materials based on the master production schedule for final products. This requires a massive amount of data processing that is best suited to computer automation. Many commercial software packages are available to perform MRP. With few exceptions, companies that use MRP rely on computers to perform the computations. Humans are still required to interpret and implement the MRP output and to manage the production planning function.

In modern production systems, the computer is used as an aid in performing virtually all manufacturing support activities. Computer-aided design systems are used in product design. The human designer is still required to do the creative work. The CAD system is a tool that augments the designer's creative talents. Computer-aided process planning systems are used by manufacturing engineers to plan the production methods and routings. In these examples, humans are integral components in the operation of the manufacturing support functions, and the computer-aided systems are tools to increase productivity and improve quality. CAD and CAM systems rarely operate completely in automatic mode.

Humans will continue to be needed in manufacturing support systems, even as the level of automation in these systems increases. People will be needed to do the decision making, learning, engineering, evaluating, managing, and other functions for which