

Automation, Production Systems, and Computer-Integrated Manufacturing

Second Edition

Mikell P. Groover

*Professor of Industrial
and Manufacturing Systems Engineering
Lehigh University*

Prentice
Hall

Prentice Hall
Upper Saddle River, NJ 07458

008878

Library of Congress Cataloging-in-Publication Data

Groover, Mikell P.

Automation, production systems, and computer-integrated manufacturing / Mikell P. Groover.

p. cm.

Includes bibliographical references and index.

ISBN 0-13-088978-4

1. Manufacturing processes--Automation. 2. Production Control. 3. CAD/CAM systems. 4. Robots, Industrial. 5. Computer integrated manufacturing systems. I. Title.

TS183 .G76 2000

670.42'7--dc21

00-029821

Vice-president and Editorial Director: *Marcia Horton*

Acquisitions editor: *Laura Curless*

Editorial assistant: *Laurie S. Friedman*

Executive managing editor: *Vince O'Brien*

Managing editor: *David A. George*

Vice-President of production and manufacturing: *David W. Riccardi*

Editorial supervision: *Scott Disanno*

Cover director: *Jayne Conte*

Cover: *Bruce Kenselaar*

Marketing manager: *Danny Hoyt*

Manufacturing buyer: *Pat Brown*

Prentice
Hall

©2001 by Prentice-Hall, Inc.

Upper Saddle River, New Jersey 07458

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and equations to determine their effectiveness. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Reprinted with corrections January, 2000.

Printed in the United States of America

10 9 8 7 6 5 4 3 2

ISBN 0-13-088978-4

Prentice-Hall International (UK) Limited, *London*

Prentice-Hall of Australia Pty. Limited, *Sydney*

Prentice-Hall Canada Inc., *Toronto*

Prentice-Hall Hispanoamericana, S.A., *Mexico*

Prentice-Hall of India Private Limited, *New Delhi*

Prentice-Hall of Japan, Inc., *Tokyo*

Pearson Education Pte. Ltd., *Singapore*

Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Automation, Production Systems, and Computer-Integrated Manufacturing

Second Edition

Mikell P. Grogan

*Professor of Industrial
and Manufacturing Systems
Lehigh University*

Prentice
Hall

Preface

The first edition of this book was published in 1980 under the title *Automation, Production Systems, and Computer-Aided Manufacturing*. A revision was published in 1987 with about 200 more pages and a slightly different title: *Automation, Production Systems, and Computer Integrated Manufacturing*. The additional pages expanded the coverage of topics like industrial robotics, programmable logic controllers, material handling and storage, and quality control. But much of the book was very similar to the 1980 text. By the time I started work on the current volume (technically the second edition of the 1987 title, but in fact the third generation of the 1980 publication), it was clear that the book was in need of a thorough rewriting. New technologies had been developed and existing technologies had advanced, new theories and methodologies had emerged in the research literature, and my own understanding of automation and production systems had grown and matured (at least I think so). Readers of the two previous books will find this new volume to be quite different from its predecessors. Its organization is significantly changed, new topics have been added, and some topics from the previous editions have been discarded or reduced in coverage. It is not an exaggeration to say that the entire text has been rewritten (readers will find very few instances where I have used the same wording as in the previous editions). Nearly all of the figures are new. It is essentially a new book.

There is a risk in changing the book so much. Both of the previous editions have been very successful for Prentice Hall and me. Many instructors have adopted the book and have become accustomed to its organization and coverage. Many courses have been developed based on the book. What will these instructors think of the new edition, with all of its new and different features? My hope is that they will try out the new book and find it to be a significant improvement over the 1987 edition, as well as any other textbook on the subject.

Specifically, what are the changes in this new edition? To begin with, the organization has been substantially revised. Following two introductory chapters, the book is organized into five main parts:

- I. **Automation and control technologies:** Six chapters on automation, industrial computer control, control system components, numerical control, industrial robotics, and programmable logic controllers.
- II. **Material handling technologies:** Four chapters covering conventional and automated material handling systems (e.g., conveyor systems and automated guided vehicle systems), conventional and automated storage systems, and automatic identification and data capture.
- III. **Manufacturing systems:** Seven chapters on a manufacturing systems taxonomy, single station cells, group technology, flexible manufacturing systems, manual assembly lines, transfer lines, and automated assembly.

- IV. **Quality control systems:** Four chapters covering quality assurance, statistical process control, inspection principles, and inspection technologies (e.g., coordinate measuring machines and machine vision).
- V. **Manufacturing support systems:** Four chapters on product design and CAD/CAM, process planning, production planning and control, and lean production and agile manufacturing.

Other changes in organization and coverage in the current edition, compared with the 1987 book, include:

- Expanded coverage of automation fundamentals, numerical control programming, group technology, flexible manufacturing systems, material handling and storage, quality control and inspection, inspection technologies, programmable logic controllers.
- New chapters or sections on manufacturing systems, single station manufacturing systems, mixed-model assembly line analysis, quality assurance and statistical process control, Taguchi methods, inspection principles and technologies, concurrent engineering, automatic identification and data collection, lean and agile manufacturing.
- Consolidation of numerical control into one chapter (the old edition had three chapters).
- Consolidation of industrial robotics into one chapter (the old edition had three chapters).
- The chapters on control systems have been completely revised to reflect current industry practice and technology.
- More quantitative problems on more topics: nearly 400 problems in the new edition, which is almost a 50% increase over the 1987 edition.
- Historical notes describing the development and historical background of many of the automation technologies.

With all of these changes and new features, the principle objective of the book remains the same. It is a textbook designed primarily for engineering students at the advanced undergraduate or beginning graduate levels. It has the characteristics of an engineering textbook: equations, example problems, diagrams, and end-of-chapter exercises. A **Solutions Manual** is available from Prentice Hall for instructors who adopt the book.

The book should also be useful for practicing engineers and managers who wish to learn about automation and production systems technologies in modern manufacturing. In several chapters, application guidelines are presented to help readers decide whether the particular technology may be appropriate for their operations.

Acknowledgments

Several people should be mentioned for their contributions to the current edition. I am grateful to the following: Prof. G. Srinivasan of the Indian Institute of Technology, Madras, India, for his thoughtful reviews of Chapters 15 and 16*; Prof. Kalyan Ghosh, Department of Mathematics and Industrial Engineering at Ecole Polytechnique in Montreal, Quebec, Canada, for his suggestions on topics for this new edition; Prof. Steve Goldman, Department of Philosophy here at Lehigh who reviewed Chapter 27 on lean and agile production, and Marcia Hamm Groover, who was very helpful in solving my computer problems for me (she is my “computer tutor” and my wife). I must also thank several graduate students here at Lehigh (past and present) who did some of the research for the book for me: David Aber, Jose Basto, Pongsak Dulyapraphant, Murat Erkoc, Peter Heugler, Charalambos Marangos, Brant Matthews, Jianbiao Pan, Hulya Sener, Steve Wang, and Tongquiang Wu. I am also grateful for the help and encouragement provided by several editors at Prentice Hall, namely Marcia Horton, Bill Stenquist, Laura Curless, and Scott Disanno. Finally, I am thankful to all of the instructors who adopted the two previous editions, thus making those books commercially successful so that Prentice Hall would allow me to prepare this new edition.

* Chapters 15 and 16 are concerned with group technology and flexible manufacturing systems, respectively. Prof. Srinivasan first read about these topics in my 1980 *Automation, Production Systems, and Computer-Aided Manufacturing*, while he was a student. He became interested in these topics and went on to make these his principal research areas. Now he is a GT and FMS expert, and so I asked him to review these chapters for me, which he graciously agreed to do.

About The Author

Mikell P. Groover is Professor of Industrial and Manufacturing Systems Engineering at Lehigh University, where he also serves as Director of the Manufacturing Technology Laboratory. He holds the following degrees, all from Lehigh: B.A. (1961) in Arts and Science, B.S. (1962) in Mechanical Engineering, M.S. (1966) and Ph.D. (1969) in Industrial Engineering. He is a Registered Professional Engineer in Pennsylvania (since 1972). His industrial experience includes full-time employment at Eastman Kodak Company as a Manufacturing Engineer. Since joining Lehigh, he has done consulting, research, and project work for a number of industrial companies including Ingersoll-Rand, Air Products & Chemicals, Bethlehem Steel, and Hershey Foods.

His teaching and research areas include manufacturing processes, metal cutting theory, automation and robotics, production systems, material handling, facilities planning, and work systems. He has received a number of teaching awards, including the *Albert Holzman Outstanding Educator Award* from the Institute of Industrial Engineers (IIE). His publications include over 75 technical articles and papers which have appeared in *Industrial Engineering*, *IIE Transactions*, *NAMRC Proceedings*, *ASME Transactions*, *IEEE Spectrum*, *International Journal of Production Systems*, *Encyclopaedia Britannica*, *SME Technical Papers*, and others. Professor Groover's avocation is writing textbooks on topics in manufacturing and automation. His previous books are used throughout the world and have been translated into French, German, Korean, Spanish, Portuguese, Russian, Japanese, and Chinese. His book *Fundamentals of Modern Manufacturing* received the 1996 *IIE Joint Publishers Award* and the 1996 *M. Eugene Merchant Manufacturing Textbook Award* from the Society of Manufacturing Engineers.

Dr. Groover is a member of the Institute of Industrial Engineers, American Society of Mechanical Engineers (ASME), Society of Manufacturing Engineers (SME), and North American Manufacturing Research Institute (NAMRI). 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, 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, Prentice Hall, 1996.

Contents

Chapter 1	INTRODUCTION	1
1.1	Production System Facilities	2
1.2	Manufacturing Support Systems	7
1.3	Automation in Production Systems	9
1.4	Manual Labor in Production Systems	14
1.5	Automation Principles and Strategies	17
1.6	Organization of the Book	21
Chapter 2	MANUFACTURING OPERATIONS	24
2.1	Manufacturing Industries and Products	28
2.2	Manufacturing Operations	31
2.3	Product/Production Relationships	35
2.4	Production Concepts and Mathematical Models	40
2.5	Costs of Manufacturing Operations	48
PART I:	AUTOMATION AND CONTROL TECHNOLOGIES	61
Chapter 3	INTRODUCTION TO AUTOMATION	61
3.1	Basic Elements of an Automated System	63
3.2	Advanced Automation Functions	71
3.3	Levels of Automation	76
Chapter 4	INDUSTRIAL CONTROL SYSTEMS	79
4.1	Process Industries versus Discrete Manufacturing Industries	80
4.2	Continuous versus Discrete Control	82
4.3	Computer Process Control	88
4.4	Forms of Computer Process Control	96
Chapter 5	SENSORS, ACTUATORS, AND OTHER CONTROL SYSTEM COMPONENTS	107
5.1	Sensors	108
5.2	Actuators	111
5.3	Analog-to-Digital Conversion	112
5.4	Digital-to-Analog Conversion	115
5.5	Input/Output Devices for Discrete Data	117

Chapter 6	NUMERICAL CONTROL	120
6.1	Fundamentals of NC Technology	122
6.2	Computer Numerical Control	128
6.3	DNC	134
6.4	Applications of Numerical Control	137
6.5	NC Part Programming	145
6.6	Engineering Analysis of NC Positioning Systems	179
Chapter 6	APPENDIX: APT WORD DEFINITIONS	196
Chapter 7	INDUSTRIAL ROBOTICS	210
7.1	Robot Anatomy and Related Attributes	212
7.2	Robot Control Systems	218
7.3	End Effectors	220
7.4	Sensors in Robotics	222
7.5	Industrial Robot Applications	222
7.6	Robot Programming	230
7.7	Engineering Analysis of Industrial Robots	240
Chapter 8	DISCRETE CONTROL USING PROGRAMMABLE LOGIC CONTROLLERS AND PERSONAL COMPUTERS	257
8.1	Discrete Process Control	257
8.2	Ladder Logic Diagrams	264
8.3	Programmable Logic Controllers	268
8.4	Personal Computers Using Soft Logic	275
Part II:	MATERIAL HANDLING AND IDENTIFICATION TECHNOLOGIES	
Chapter 9	INTRODUCTION TO MATERIAL HANDLING	281
9.1	Overview of Material Handling Equipment	282
9.2	Considerations in Material Handling System Design	285
9.3	The 10 Principles of Material Handling	288
Chapter 10	MATERIAL TRANSPORT SYSTEMS	292
10.1	Industrial Trucks	293
10.2	Automated Guided Vehicle Systems	295
10.3	Monorails and Other Rail Guided Vehicles	302
10.4	Conveyor Systems	303
10.5	Cranes and Hoists	309
10.6	Analysis of Material Transport Systems	311
Chapter 11	STORAGE SYSTEMS	328
11.1	Storage System Performance	329
11.2	Storage Location Strategies	331
11.3	Conventional Storage Methods and Equipment	332

11.4	Automated Storage Systems	335	
11.5	Engineering Analysis of Storage Systems	344	
Chapter 12	AUTOMATIC DATA CAPTURE		357
12.1	Overview of Automatic Identification Methods	358	
12.2	Bar Code Technology	361	
12.3	Other ADC Technologies	370	
PART III: MANUFACTURING SYSTEMS			
Chapter 13	INTRODUCTION TO MANUFACTURING SYSTEMS		375
13.1	Components of a Manufacturing System	376	
13.2	Classification of Manufacturing Systems	381	
13.3	Overview of the Classification Scheme	388	
13.4	Manufacturing Progress Functions (Learning Curves)	392	
Chapter 14	SINGLE STATION MANUFACTURING CELLS		397
14.1	Single Station Manned Workstations	398	
14.2	Single Station Automated Cells	399	
14.3	Applications	404	
14.4	Analysis of Single Station Cells	409	
Chapter 15	GROUP TECHNOLOGY AND CELLULAR MANUFACTURING		420
15.1	Part Families	422	
15.2	Parts Classification and Coding	425	
15.3	Production Flow Analysis	431	
15.4	Cellular Manufacturing	434	
15.5	Application Considerations in Group Technology	439	
15.6	Quantitative Analysis in Cellular Manufacturing	442	
Chapter 16	FLEXIBLE MANUFACTURING SYSTEMS		460
16.1	What is an FMS?	462	
16.2	FMS Components	469	
16.3	FMS Applications and Benefits	480	
16.4	FMS Planning and Implementation Issues	485	
16.5	Quantitative Analysis of Flexible Manufacturing Systems	487	
Chapter 17	MANUAL ASSEMBLY LINES		514
17.1	Fundamentals of Manual Assembly Lines	516	
17.2	Alternative Assembly Systems	523	
17.3	Design for Assembly	524	
17.4	Analysis of Single Model Assembly Lines	525	
17.5	Line Balancing Algorithms	534	
17.6	Mixed Model Assembly Lines	540	
17.7	Other Considerations in Assembly Line Design	552	

Chapter 18	TRANSFER LINES AND SIMILAR AUTOMATED MANUFACTURING SYSTEMS	566
	18.1 Fundamentals of Automated Production Lines	565
	18.2 Applications of Automated Production Lines	575
	18.3 Analysis of Transfer Lines with No Internal Storage	579
	18.4 Analysis of Transfer Lines with Storage Buffers	587
Chapter 19	AUTOMATED ASSEMBLY SYSTEMS	601
	19.1 Fundamentals of Automated Assembly Systems	602
	19.2 Design for Automated Assembly	606
	19.3 Quantitative Analysis of Assembly Systems	610
 PART IV: QUALITY CONTROL SYSTEMS		
Chapter 20	INTRODUCTION TO QUALITY ASSURANCE	631
	20.1 Quality Defined	633
	20.2 Traditional and Modern Quality Control	635
	20.3 Taguchi Methods in Quality Engineering	638
	20.4 ISO 9000	648
Chapter 21	STATISTICAL PROCESS CONTROL	654
	21.1 Process Variability and Process Capability	655
	21.2 Control Charts	658
	21.3 Other SPC Tools	667
	21.4 Implementing Statistical Process Control	672
Chapter 22	INSPECTION PRINCIPLES AND PRACTICES	681
	22.1 Inspection Fundamentals	682
	22.2 Sampling versus 100% Inspection	687
	22.3 Automated Inspection	692
	22.4 When and Where to Inspect	694
	22.5 Quantitative Analysis of Inspection	698
Chapter 23	INSPECTION TECHNOLOGIES	711
	23.1 Inspection Metrology	712
	23.2 Contact versus Noncontact Inspection Techniques	717
	23.3 Conventional Measuring and Gaging Techniques	718
	23.4 Coordinate Measuring Machines	720
	23.5 Surface Measurement	736
	23.6 Machine Vision	738
	23.7 Other Optical Inspection Techniques	745
	23.8 Noncontact Nonoptical Inspection Technologies	747

PART V: MANUFACTURING SUPPORT SYSTEMS

Chapter 24	PRODUCT DESIGN AND CAD/CAM IN THE PRODUCTION SYSTEM	753
	24.1 Product Design and CAD 755	
	24.2 CAD System Hardware 761	
	24.3 CAM, CAD/CAM, and CIM 764	
	24.4 Quality Function Deployment 767	
Chapter 25	PROCESS PLANNING AND CONCURRENT ENGINEERING	775
	25.1 Process Planning 776	
	25.2 Computer-Aided Process Planning (CAPP) 782	
	25.3 Concurrent Engineering and Design for Manufacturing 785	
	25.4 Advanced Manufacturing Planning 791	
Chapter 26	PRODUCTION PLANNING AND CONTROL SYSTEMS	796
	26.1 Aggregate Production Planning and the Master Production Schedule 798	
	26.2 Material Requirements Planning (MRP) 800	
	26.3 Capacity Planning 806	
	26.4 Shop Floor Control 808	
	26.5 Inventory Control 814	
	26.6 Manufacturing Resource Planning (MRP II) 822	
	26.7 Just-In-Time Production Systems 823	
Chapter 27	LEAN PRODUCTION AND AGILE MANUFACTURING	832
	27.1 Lean Production 833	
	27.2 Agile Manufacturing 835	
	27.3 Comparison of Lean and Agile 843	

Introduction

CHAPTER CONTENTS

- 1.1 Production System Facilities
 - 1.1.1 Low Quantity Production
 - 1.1.2 Medium Quantity Production
 - 1.1.3 High Production
- 1.2 Manufacturing Support Systems
- 1.3 Automation in Production Systems
 - 1.3.1 Automated Manufacturing Systems
 - 1.3.2 Computerized Manufacturing Support Systems
 - 1.3.3 Reasons for Automating
- 1.4 Manual Labor in Production Systems
 - 1.4.1 Manual Labor in Factory Operations
 - 1.4.2 Labor in Manufacturing Support Systems
- 1.5 Automation Principles and Strategies
 - 1.5.1 USA Principle
 - 1.5.2 Ten Strategies of Automation and Production Systems
 - 1.5.3 Automation Migration Strategy
- 1.6 Organization of the Book

This book is about production systems that are used to manufacture products and the parts assembled into those products. The *production system* is the collection of people, equipment, and procedures organized to accomplish the manufacturing operations of a company (or other organization). Production systems can be divided into two categories or levels as indicated in Figure 1.1:

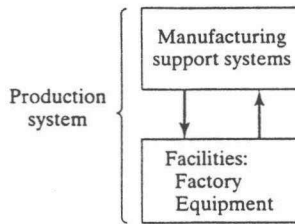


Figure 1.1 The production system consists of facilities and manufacturing support systems.

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

In modern manufacturing operations, portions of the production system are automated and/or computerized. However, production systems include people. People make these systems work. In general, direct labor people (*blue collar workers*) are responsible for operating the facilities, and professional staff people (*white collar workers*) are responsible for the manufacturing support systems.

In this introductory chapter, we consider these two aspects of production systems and how they are sometimes automated and/or computerized in modern industrial practice. In Chapter 2, we examine the manufacturing operations that the production systems are intended to accomplish.

PRODUCTION SYSTEM FACILITIES¹

The *facilities* in the production system are the factory, production machines and tooling, material handling equipment, inspection equipment, and the 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 logical groupings, and we refer to these equipment arrangements and the workers who operate them as the *manufacturing systems* in the factory. Manufacturing systems can be individual work cells, consisting of a single production machine and worker assigned to that machine. We more commonly think of manufacturing systems as groups 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.

A manufacturing company attempts to *organize* its facilities in the most efficient way to serve the particular mission of that plant. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given type of manufacturing. Of course, one of the most important factors that determine the type of manufacturing is the type of products that are made. Our book is concerned primarily with

¹Portions of this section are based on M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems* [2].

the production of discrete parts and products, compared with products that are in liquid or bulk form, such as chemicals (we examine the distinction in Section 2.1).

If we limit our discussion to discrete products, the quantity produced by a factory has a very significant influence on its facilities and the way manufacturing is organized. *Production quantity* refers to the number of units of a given part or product produced annually by the plant. The annual part or product quantities produced in a given factory can be classified into three ranges:

1. *Low production*: Quantities in the range of 1 to 100 units per year.
2. *Medium production*: Quantities in the range of 100 to 10,000 units annually.
3. *High production*: Production quantities are 10,000 to millions of units.

The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the types of products we are dealing with, these boundaries may shift by an order of magnitude or so.

Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. *Product variety* refers to the different product designs or types that are produced in a plant. Different products have different shapes and sizes and styles; they perform different functions; they are sometimes intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. When the number of product types made in a factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. When product variety is high, production quantity tends to be low; and vice versa. This relationship is depicted in Figure 1.2. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.2. In general, a given factory tends to be limited to the product variety value that is correlated with that production quantity.

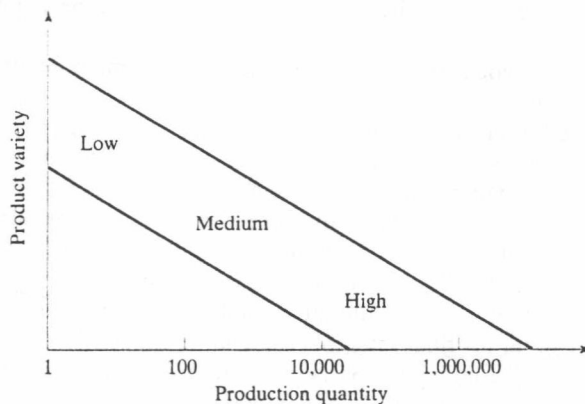


Figure 1.2 Relationship between product variety and production quantity in discrete product manufacturing.

Although we have identified product variety as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity is, because details on how much the designs differ are not captured simply by the number of different designs. The differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Products can be different, but the extent of the differences may be small or great. The automotive industry provides some examples to illustrate this point. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are nearly the same. In different plants, the same auto company builds heavy trucks. Let us use the terms “hard” and “soft” to describe these differences in product variety. *Hard product variety* is when the products differ substantially. In an assembled product, hard variety is characterized by a low proportion of common parts among the products; in many cases, there are no common parts. The difference between a car and a truck is hard. *Soft product variety* is when there are only small differences between products, such as the differences between car models made on the same production line. There is a high proportion of common parts among assembled products whose variety is soft. The variety between different product categories tends to be hard; the variety between different models within the same product category tends to be soft.

We can use the three production quantity ranges to identify three basic categories of production plants. Although there are variations in the work organization within each category, usually depending on the amount of product variety, this is nevertheless a reasonable way to classify factories for the purpose of our discussion.

1.1.1 Low Quantity Production

The type of production facility usually associated with the quantity range of 1 to 100 units/year is the *job shop*, which makes low quantities of specialized and customized products. The products are typically complex, such as space capsules, aircraft, and special machinery. Job shop production can also include fabricating the component parts for the products. Customer orders for these kinds of items are often special, and repeat orders may never occur. Equipment in a job shop is general purpose and the labor force is highly skilled.

A job shop must be designed for maximum flexibility to deal with the wide part and product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move in the factory, it typically remains in a single location, at least during its final assembly. Workers and processing equipment are brought to the product, rather than moving the product to the equipment. This type of layout is referred to as a *fixed-position layout*, shown in Figure 1.3(a). In the pure situation, the product remains in a single location during its entire fabrication. Examples of such products include ships, aircraft, railway locomotives, and heavy machinery. In actual practice, these items are usually built in large modules at single locations, and then the completed modules are brought together for final assembly using large-capacity cranes.

The individual parts that comprise these large products are often made in factories that have a *process layout*, in which the equipment is arranged according to function or type. The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.3(b). Different parts, each requiring a different operation sequence.