CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Over thousands of years, the methods of production, operations, and manufacturing systems have been continually developed and improved. Such systems have been the concern of people from ancient Egyptians along the Nile River to Henry Ford in Detroit; from businessmen in the British Isles during the industrial revolution to current integrated circuits (IC) manufacturers. Manufacturing systems are concerned with the conversion of physical inputs into physical outputs by using workers, machines, and equipment. Production systems are concerned with the modeling and engineering management of converting inputs into outputs using forecasting, inventory, production planning, and scheduling. Operation systems are concerned with a broad view of such conversions; they include strategic decisions such as product design and development, quality policies, logistical systems, facility location decisions, facility layout, human resources, supply chain management, quality control, reliability, and maintenance. Operation systems are also concerned with efficiently delivering quality products and services to customers in a timely and cost-effective manner. Supply chain management involves purchasing, storing, and distributing raw materials and semifinished and finished products through a network of suppliers, production facilities, and distributors. Production, operation, and manufacturing systems are also concerned with developing systems' capabilities and utilizing resources effectively to fulfill the needs of the customers.

In business, the primary objective is to maximize the net profit. However, measuring and predicting net profit are often difficult because of market fluctuations, uncertainties, risks, and the dynamic nature of most businesses. Predicting net profit becomes even more difficult as the planning periods are set further into the future. It is, however, easier to predict the

Note: Advanced material that can be omitted without loss of generality will be indicated by a dagger.

Operations and Production Systems with Multiple Objectives, First Edition. Behnam Malakooti.

TABLE 1.1 Possible Objectives (Criteria) in Design, Planning, and Control of Production and Operation Systems

• Minimize total cost	• Maximize employees' job satisfaction
• Minimize risk	• Maximize ease of change of systems
• Maximize quality (products and services)	• Maximize ease of use of systems
• Maximize productivity	• Maximize achievement of just-in-time
• Maximize flexibility	• Maximize agility
• Minimize adverse environmental impact	• Maximize simplicity of systems
• Maximize customer satisfaction	• Minimize variations/fluctuations
	• Minimize use of energy

factors that contribute to net profit. Experience has shown that long-term net profit depends upon some of the objectives shown in Table 1.1, where many organizations (including businesses, government, and nonprofit organizations) must consider these objectives in design and operations of systems. Most businesses cannot simply measure and maximize net profit directly. However, they can measure and optimize some of these objectives, which will lead to maximizing the net profit.

In the design of products, processes, operations, and facilities, one must consider some or all of the above objectives. It is more feasible to measure and optimize some of the above objectives, especially over a long period of time, instead of trying to quantify and optimize the net profit directly. The result of optimizing several objectives often leads in the direction of maximizing net profits. Such objectives, however, often conflict with each other, especially when resources are limited. For example, one cannot expect to buy a high-quality product at a low price. Multiple-criteria decision-making (MCDM) models are based on optimizing several objectives simultaneously, while traditional decision-making models only consider one objective (usually minimizing cost). An understanding of trade-offs among different objectives will allow a decision maker to arrive at the best compromise solution that balances competing objectives.

This book includes a comprehensive study of multiple-objective approaches for production, operation, and manufacturing systems. The most common objectives that are used in this book are the ones listed in the left column of Table 1.1.

This book also covers concepts and methods that can be used for effective decision making in businesses, manufacturing industries, process industries, government organizations, the military, and nonprofit organizations as well as for personal life decision problems.

Business organizations manage three important functions: marketing, operations, and finance/accounting. Decisions related to these three areas can be categorized as strategic, tactical, and operational. Table 1.2 illustrates these three decisions.

1.1.1 Overview of Input and Output Systems

One way to describe production and operation systems is from an input–output point of view. From this point of view production and operation systems transform inputs into useful outputs. For example, a university can be viewed as a production system where incoming freshmen are the inputs and educated students with degrees are the outputs. The educational activities (classes, projects, extracurricular activities, etc.) are the transformation processes. This input–output relation, as shown in Figure 1.1, can be used to describe every form of production, operation, and manufacturing systems.

TABLE 1.2 Strategic, Tactical, and Operation Decisions

Strategic Decisions	Tactical Decisions	Operations Decisions
• Long-term plans (years) • Long-term forecasting • Less structured decisions • Long-term consequences • Focus on entire organization • Cut across departments • More difficult to define and solve	• Medium-term plans (months) • Routine and repetitive • More structured decisions • Medium-term consequences • Focus on departments, teams, and tasks • Interrelated decisions	• Short term (weeks) • Immediate plans • Short-range consequences • Focus on details, workforce, inventory, etc. • Allocation of resources • Quality issues • Reliability issues

The integration of several interrelated production, operation, and manufacturing systems leads to a supply chain system. Supply chain management involves the integration of several phases of operations, including materials procurement, manufacturing processes, product assembly, and distribution systems. Supply chain management (Figure 1.2) integrates all aspects of a business in order to reduce costs and maximize speed of delivery. Generally the supply chain relies on a competitive and customized chain of suppliers. It is a generalization of the input–output model (Figure 1.1), incorporating all phases and cycles of production from the materials supplier to the customer.

1.1.2 Overview of the Chapters of This Book

A view of production and operation systems is presented in Figure 1.3. At the top level, the functional areas of production and operation systems are categorized as production and operations planning, process design and logistics, and quality, reliability, and measurement. the systems approaches, multiple-criteria decision analysis, and problem-solving tools are presented at the lower level of Figure 1.3. Sections 1.3 and 1.4 discuss each of these topics. The top level of Figure 1.3 is the subject of this book and the bottom level of Figure 1.3 is the subject of the forthcoming book (Malakooti, 2014).

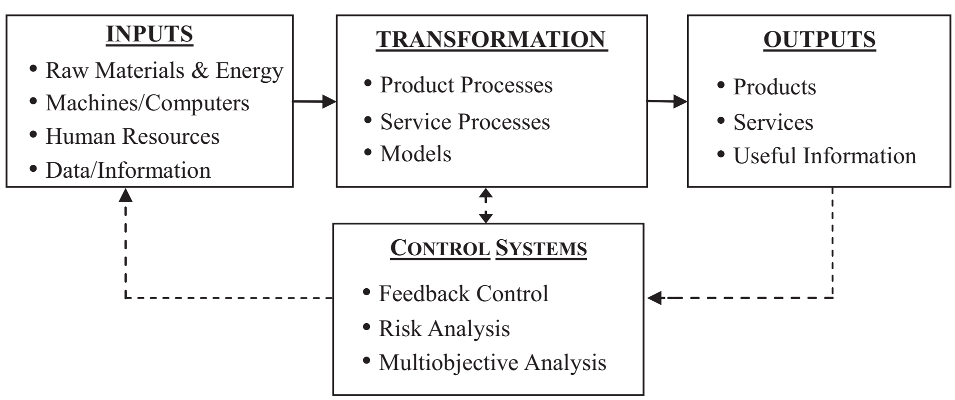

Figure 1.1 Input–output relation in production/operation systems with control systems feedback.

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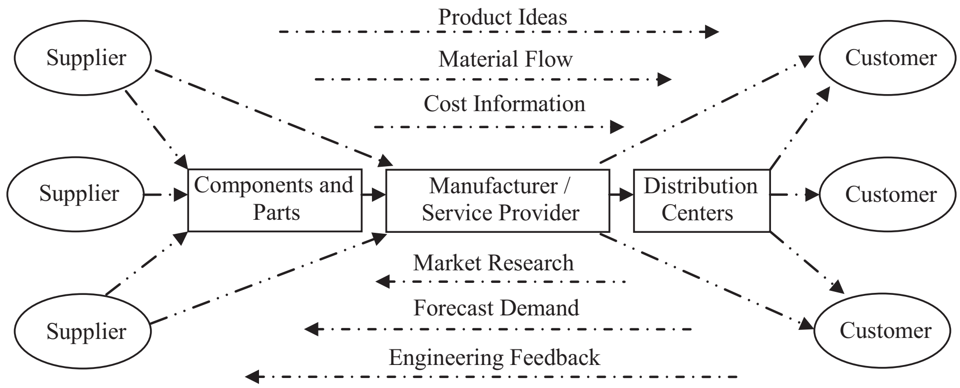

Figure 1.2 View of supply chain system and management.

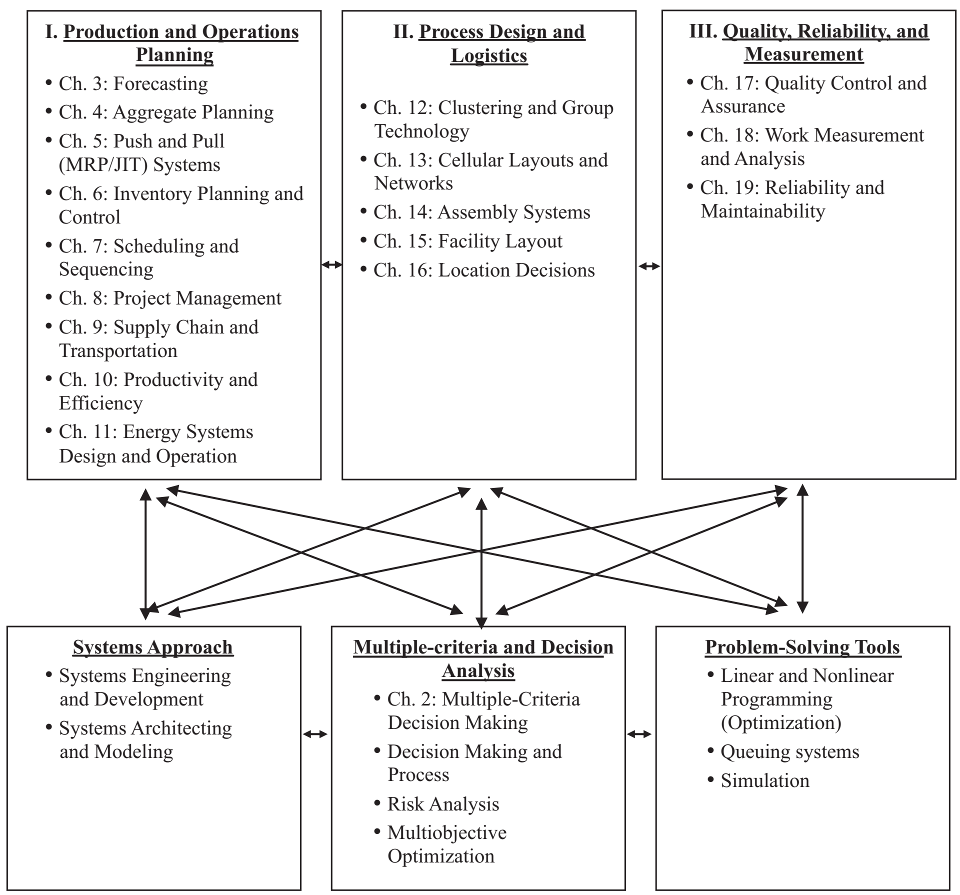

Figure 1.3 Functional areas of production and operation systems, along with systems approaches, multiple criteria and decision analysis, and problem-solving tools.

1.2 PRODUCTION AND OPERATIONS HISTORY AND PERSPECTIVE

The history of production and operation systems began around 5000 B.C. when Sumerian priests developed the *ancient system* of recording inventories, loans, taxes, and business transactions. The next major historical application of operation systems occurred in 4000 B.C. It was during this time that the Egyptians started using planning, organization, and control in large projects such as the construction of the pyramids. By 1100 B.C., labor was being specialized in China; by about 350 B.C., an archaic assembly line was formed in Greece.

In the Middle Ages, kings and queens ruled over large areas of land. Loyal noblemen maintained large sections of the monarch's territory. This hierarchical organization in which people were divided into classes based on social position and wealth became known as the *feudal system*. In the feudal systems, servants produced for themselves and people of higher classes by using the ruler's land and resources. The Renaissance brought about specialization in labor within the *European system*. This system had some of the first significant contributions that led to the industrial revolution. The industrial revolution occurred as the result of two conceptual phenomena: interchangeability of parts and division of labor. Division of labor was developed several centuries before interchangeability of parts. It was in the late eighteenth century when Eli Whitney popularized the concept of interchangeability of parts when he manufactured 10,000 muskets. Up to this point in history of manufacturing, each product (e.g., each gun) was considered a special order, meaning that parts of a given gun were fitted only for that particular gun and could not be used in other guns. Interchangeability of parts allowed the mass production of parts independent of the final products in which they will be used. This changed the factory layout from a job shop to a flow shop, which resulted in a substantial increase in product quality and speed of production.

In 1883, Frederick W. Taylor introduced the stopwatch method for accurately measuring the time to perform each single task of a complicated job. He developed the scientific study of productivity and identifying how to coordinate different tasks to eliminate wasting of time and increase the quality of work. The next generation of scientific study occurred with the development of (a) work sampling and (b) predetermined motion time systems (PMTSs). Work sampling is used to measure the random variable associated with the time of each task. PMTSs allow the use of standard predetermined tables of the smallest body movements (e.g., turning the left wrist by 90°) and integrating them to predict the time needed to perform a simple task. PMTSs have gained substantial importance due to the fact that they can predict work measurements without actually observing the actual work. The foundation of PMTSs was laid out by the research and development of Frank B. and Lillian M. Gilberth around 1912. The Gilberths took advantage of taking motion pictures at known time intervals while operators were performing the given task.

At the beginning of the twentieth century, *American Industry* invented the revolutionary idea of an assembly synchronized system. Henry Ford developed the first auto assembly system where a car chassis was moved through the assembly line while workers added components to it until the car was completed. During World War II, the growth of complex systems led to the development of efficient manufacturing methods and the use of advanced mathematical and statistical tools. This was supported by the development of academic programs in industrial and systems engineering disciplines as well as fields of operations research and management science (as multidisciplinary fields of problem solving). While systems engineering concentrated on the broad characteristics of the relationships between inputs and outputs of generic systems, operations researchers concentrated on solving specific and focused problems. The synergy of operations research and systems engineering allowed for the realization of solving large-scale and complex problems in the modern era. Recently, the development of faster and smaller computers, intelligent systems, and the World Wide Web (WWW) has substantially changed the nature of operations, manufacturing, production, and service systems.

Based upon this evolutionary history of production, operations, and manufacturing systems, it is clear that each era built upon the ideas of its predecessors. Table 1.3 shows a chronological display of this history and the major achievements for each period. The history and future of production and operation systems are divided into five phases. We believe that currently we are at the beginning of phase V.

I. Empiricism (learning from experience)
II. Analysis (scientific management)
III. Synthesis (development of mathematical problem-solving tools)
IV. Isolated systems with single objective (use of integrated and intelligent systems and WWW)
V. Integrated complex systems with multiple objectives (development of ecologically sound systems, environmentally sustainable systems, considering individual preferences)

As stated before, productions, operations, and manufacturing systems have been constantly changing over the past several thousand years. The initial production systems contained a significant amount of human insight and artistic creativity. However, the historical path of production systems has shifted more toward scientific models. Industrial engineering and management science were developed as a result of the industrial revolution, when the size and complexity of manufacturing increased significantly. These new complex systems, as well as the changes in the scale of businesses and organizations, have necessitated more precise and innovative models. The use of these modern models has resulted in highly efficient production and operations systems. Recent developments in computers, the Internet, and enhanced transportation systems led to the world becoming a “smaller place” with a global economy. Countries are no longer self-sufficient, and companies now produce for the world market. Therefore, it is necessary to view production, operation, and manufacturing systems from a global point of view, as opposed to the traditional regional or national perspective. Today, production, operation, and manufacturing systems face many new challenges. As a result, factors such as language barriers must be properly addressed. Large inventories are no longer feasible due to quick changes in demand and increases in holding costs. Designers must find new ways to design, manufacture, assemble, and transport products. As customized products and services replace standardized products and services, flexibility in manufacturing processes becomes more important.

Recent changes in the global market have changed the fields of production, operation, and manufacturing systems to handle the dynamic global needs. Information systems that were used to control, monitor, and maintain manufacturing and production systems no longer stop at the physical boundaries of the enterprise. They often interact with both clients and suppliers in order to more efficiently manage the supply chain system. Modern systems designers must overcome a multitude of challenges and problems. Considering

TABLE 1.3 Production, Operation, and Manufacturing System History and Perspective

Phase I: Empiricism	**Renaissance** • Double-entry bookkeeping and cost accounting **Industrial Revolution** • Began in the eighteenth century in British Isles • New technology, new forms of organization and management of production process • Replacement of people by machines • Improvements in machinery led to early mass production systems • Interchangeability of parts (Eli Whitney) • Specialization of labor (Adam Smith's "Wealth of Nations") • Dramatic reduction in unit cost of consumer products
Phase II: Analysis	**Scientific management** • "The Principles of Scientific Management," developed by Frederick Taylor (1895) • Scientific analysis and measurement of work • Emphasis on analysis (dissolving into basic elements) • Decomposition of a large problem into several smaller problems • Solving each smaller problem independently • Combining optimum results from small problems • Was criticized as an insult to human dignity—view man as a machine • Acknowledgment of human abilities and limitations • Development of more humane definition of role of people as elements in production process
Phase III: Synthesis	**Operations problem solving** • Developed after creation of "special teams" during World War II to solve problems related to war operations • Shifted focus from war tactical problems to industrial problems • Development of deterministic models • Development of stochastic models • Development of simulation models • Use of analytical models • Use of statistical models • Use of computers to solve problems • Synthesis aimed at producing balanced system solutions
Phase IV: Isolated systems with single objective	**Systems approach** • Complexity analysis • Structures, decomposition, and coordination of systems • Systems architecting • Identifying complex problems, variables, and their interactions • Looking at system as a whole with emphasis on integration **Globalization** • Global markets and global corporations • New international laws allowing global competition • Increase in choices and sensitivity to global markets

(*continued*)

TABLE 1.3 (*Continued*)

	Intelligent systems • Shift in emphasis from well-structured to ill-structured problems • Ability to integrate experience and intelligence with quantitative models • Learning from biological systems **World Wide Web and Internet** • Paperless communication and operations • Instant ordering and service • Worldwide collaboration and trade • Integrated supply chain management
Phase V: Integrated complex systems with multiple objectives	**Multiobjectives-based systems** • Developing methods for simultaneously optimizing quality, cost, productivity, flexibility, and ecological soundness of systems and products • Considering individual decision makers' multiple-criteria preferences • Development of customized products for massive-scale customers **Risk measurement and analysis** • Considering individual risk preferences in decision making • Measurement of risk for individual and organizational decision makers • Measurement and understanding of catastrophic risks **Ecological, biological and energy-aware systems** • Developing biologically inspired systems and products • Developing sustainable production, operations, and manufacturing systems • Developing environmentally friendly systems • Developing energy-efficient and renewable systems and products • Developing reusable/recyclable systems and products • Developing pollution and waste-free systems and products

ecological and human issues, a framework designed to optimize multiple objectives is essential.

While technology has been progressing at an amazing pace, centuries of abuse of natural resources, eradication of forests, and pollution of the whole Earth environment (air, soil, and oceans) are the dark sides of human advancements. A solution to these catastrophic human behaviors is to change unidimensional–single-objective consuming behavior to multidimensional–multiobjective behavior to develop environmentally friendly systems. Ecologically sound production and manufacturing systems can be developed to ensure that the natural environment is not negatively affected. “The ecologically sound systems” must be developed to allow life in all its forms to continue and thrive on Earth.

1.3 PRODUCTION AND OPERATIONS MODELS

In this section, we provide an overview of the production and operation problems and models and their objectives that are covered in this book.

1.3.1 Production and Operations Planning

Forecasting Forecasting can be used to predict future patterns of behavior—for example, predicting demands for a certain product for each of the next 12 months. While it is unreasonable to expect an exact prediction using forecasting models, a good estimate with some degree of confidence of its occurrence can be found. Usually, the forecasting of periods farther into the future is less accurate.

Models	Objectives
• Qualitative models • Time series models (a) Moving averages (b) Exponential smoothing (c) Cyclical/seasonal analysis • Regression (cause-and-effects) models (a) Linear regression (b) Nonlinear regression models (c) Multivariable regression models (d) Qualitative regression models	• Minimize risk associated with forecasting • Maximize confidence in forecasted values • Maximize accuracy in forecasted values • Maximize stability of forecasting

Aggregate Planning Aggregate planning is concerned with medium-range planning for several periods (e.g., months). The basis of this planning model is to simplify the problem formulation by forming cumulative units of several products. An aggregate plan is developed based on forecasted demands to determine the optimal resource utilization to meet a given demand. Resources include regular workforce, facility capacity, inventory level, outsourcing, and subcontracting.

Models	Objectives
• Tabular and graphical approaches • Linear programming approach for single product • Linear programming approach for multiproducts • Disaggregating and master scheduling • Multiple-objective linear programming approaches	• Minimize total cost • Minimize total backlog • Minimize total inventory • Minimize fluctuations in hiring and firing

Push-and-Pull Systems: MRP and JIT In push systems, the materials are produced and kept in inventory regardless of whether the downstream stations are ready to process them. The material requirements planning (MRP) model is a push scheduling that determines the time and the amount of the components of a product required in order to satisfy its demand for each given period of time. This model is dependent upon an accurate forecast, at which point the exact required quantities for all components or subassemblies can be determined. In material requirements planning, lot sizes for production of each component are determined based on forecasts, setup costs, and inventory costs. Just-in-time (JIT) is a pull system. In JIT, production planning of components is based on whether the downstream stations are ready for processing them. That is, the production scheduling is based on the internal demand of facilities that produce the items. In JIT, ideally no inventory is kept. In pull systems (JIT), materials are not shipped to downstream stations unless the downstream stations are ready to produce them.

Models	Objectives
• Tabular model for material requirements plan • Lot-sizing methods (a) Economic order quantity (b) Part period balancing (c) Least-unit cost • Material resource planning • Just-in-time production system • Multicriteria hybrid push-and-pull systems	• Minimize total inventory • Minimize total backorder • Minimize carrying costs • Maximize achieving JIT

Inventory Planning and Control Inventory systems are used to determine how much inventory should be stored for each period of time in order to meet future needs. Inventories are hedged against uncertainties for possible shortages. There are four types of inventories: raw materials, product components, work-in-process, and finished goods. Inventories tie up precious capital resources and do not produce any direct income. Therefore, inventories must be minimized. However, inventory holding costs must be balanced with the cost of possible backlogs and unsatisfied customers. To be conservative, one may keep more inventory than is needed to avoid possible shortages due to future demand fluctuations and variations in production planning.

Models	Objectives
• Economic order quantity model • Economic order quantity model with inventory discount • Economic production quantity model • Economic order quantity model allowing shortage • Inventory with probabilistic demand • Inventory of perishable items	• Minimize total inventory cost • Minimize possible shortages • Maximize achieving JIT inventory plan • Minimize risks • Maximize flexibility

Scheduling and Sequencing In order to produce a product, its components must be processed by a number of processors. Scheduling and sequencing are concerned with the optimal planning of a set of given tasks where each task must be processed by different processors (e.g., machines). Scheduling and sequencing can be used for repetitive products. Scheduling is an important tool in the control of production operations. Factors such as job arrival patterns, the variety of processors, processing time, the number of available processors, the labor force, and flow patterns are considered for determining a feasible schedule that minimizes total processing time.

Models	Objectives
• Sequencing *n* jobs on one processor	• Minimize tardiness
• Sequencing *n* jobs on two processor	• Maximize JIT
• Sequencing two jobs on *m* processors	• Minimize total processing time
• Sequencing *n* jobs on *m* processor	• Maximize machine utilization
• Sequencing flow shop problems	• Minimize work-in-progress inventory
• Sequencing job shop problems	

Project Management Project management is concerned with the planning of single large projects that consist of many activities. Projects are unique, that is, not repetitive in nature (e.g., building a stadium). To complete a project, many activities must be planned in a certain sequence. The traditional objective of project management is to sequence all project activities in such a way that the total project duration is minimized while the proper sequencing of activities is maintained.

Models	Objectives
• Critical-path method	• Minimize total cost of project
• Time and cost trade-offs	• Minimize total duration of project
• Project/program evaluation and review technique for probabilistic activities	• Maximize probability of completion
• Planning with resource constraints	• Minimize the required number of resources
	• Minimize risk of not meeting deadlines

Supply Chain and Transportation

Supply Chain As discussed before, the supply chain management system is an integrated system to manage the flow of materials from suppliers to the manufacturer and finally to the customer; see Figure 1.2. In supply chain management, the overall inventory is reduced at all levels, including raw materials inventory, work-in-progress inventory, and finished-goods inventory. Supply chain management is a model for efficiently managing a network of customers, retailers, distributors, suppliers, and manufacturers and effectively moving materials and information through the system.

Assignment The assignment problem is encountered in many applications: for example, to assign contractors to jobs, facilities to locations, and salespersons to territories.

Transportation The objective of transportation problems is to minimize the total cost of delivering a quantity of goods from a set of origin points (e.g., suppliers) to a set of destination points (e.g., customers) where there are different transportation costs associated with each pair of point of origin and point of destination.

Transshipment Transshipment is a broadening of the transportation problem where intermediate points (e.g., warehouses) are used between the origin points and destination points, creating a network of transportation problems.

Models	Objectives
• Supply chain management—network	• Minimize transportation costs
• Assignment methods	• Minimize transportation time
• Transportation methods	• Minimize assignment costs
• Transshipment method	• Maximize flexibility and agility
	• Maximize quality

Productivity and Efficiency Productivity is defined as the amount of output per input for production and service processes. It is commonly measured in terms of output per unit worker per unit hour, which is known as labor productivity. Productivity growth is a rate comparing the productivity of a given period to a base period. Generally, higher productivity (and productivity growth) is associated with a higher standard of living in a country. Efficiency is used when comparing the productivity of comparable processes.

Models	Objectives
• Single productivity indexes	• Minimize cost
• Multiple productivity indexes	• Maximize accuracy
• Single efficiency indexes	• Maximize quantity
• Multiple efficiency indexes–linear programming approach	• Maximize quality
• Productivity and efficiency of system of multiple processors	

Energy Systems: Design and Operation An energy system is defined based on the relationships of three entities: users, savers, and energy generators. A user is an entity that consumes energy for certain purposes. Examples of a user include cars, home appliances, and factory machinery. A user can receive energy from either a generator or a saver. A saver is a device that is able to store energy for future use. A generator is a device that generates energy. If a generator can produce energy faster than it is consumed, it can be saved by the saver for later use. This allows the saver to provide energy at a later time and prevents the generator from having to constantly produce energy. For different applications different energy systems can be designed and operated optimally.

Models	Objectives
• Energy conversion and types • Multicriteria energy selection • Energy routing optimization • Optimization for design and operation of energy systems • Optimization for multiperiod operation of energy systems • Multicriteria energy systems	• Minimize cost per unit of energy • Minimize environmental impact per unit of energy • Maximize rate of extraction of renewable energy (per unit) • Maximize JIT use of energy • Maximize efficiency of energy systems

1.3.2 Process Design and Logistics

Clustering and Group Technology Clustering methods can be used to cluster groups of objects based on their attributes for serving certain objectives. An example of clustering is group technology. Group technology is a strategy that combines the benefits of mass production with the high product variation characteristics of a job shop environment. Group technology strategy reduces production waste, material handling, production time, waiting time, and setup time. This leads to a streamlining of the production operations to achieve a flexible manufacturing system based upon grouping families of parts and clustering similar machines. Parts are generally grouped by similarity in use of production machinery. Machines that process similar parts are placed in the same cluster to maximize efficiency.

Models	Objectives
• Rank order clustering • Similarity coefficient clustering • *P*-median mathematical programming • *K*-means algorithm—iterative • Hierarchical clustering	• Minimize material flow (and cost) • Minimize setup time • Minimize cost of duplicated machines • Maximize flexibility • Maximize productivity

Cellular Layouts and Networks Many design (e.g., layout) problems can be formulated as a single-row network (e.g., layout). The materials (or information) flow can be either unidirectional or bidirectional. For practical purposes, manufacturing facilities usually divide their facilities into separate self-sufficient and self-contained cells. These areas are then designed in the form of a single row or U-shaped layout. These layouts are advantageous because they are easy to monitor, maintain, and utilize. The autonomous behavior of cells and their independence improves the workflow and reliability of the system. At times, however, the duplication of certain workstations (machines) may become necessary for the purpose of having independent cells where each cell operates independent of other cells.

Models	Objectives
• Single-row unidirectional layout • Single-row bidirectional layout • Head–tail heuristic • Integer programming—optimization	• Minimize material flow (and cost) • Maximize productivity • Maximize flexibility • Maximize agility

Assembly Systems Assembly systems are generally used for the assembly of high-volume and low-variation products. Assembly line balancing is used to design an effective arrangement of the workstations needed to assemble a product. This form of production became popular at the beginning of the twentieth century with automobile assembly line production systems. Several objectives must be considered when designing effective and flexible assembly lines.

Models	Objectives
• Single-product line balancing • Mixed-product line balancing • Stochastic assembly line balancing	• Minimize number of stations • Minimize cycle time (to maximize productivity) • Minimize operational cost

Facility Layout Layout design is concerned with identifying the optimal locations of machines and departments within a given facility such as factories, offices, schools, banks, airports, and nearly every type of business. Factors influencing the layout of a production facility include available space, material flow costs, mobility, and employee satisfaction with the work environment. Different types of facilities are product, process, fixed position, cellular, and group technology. In designing an effective layout, one should consider several objectives. In construction models a solution is constructed; in improvement models a given solution is improved.

Models	Objectives
• Systematic layout planning—construction • Pairwise exchange model—improvement • Qualitative-based model—construction • Head–tail model—construction • Relayout model—improvement	• Minimize total materials flow and cost • Minimize total transportation time • Maximize space utilization • Maximize flexibility • Maximize ease of use • Maximize ease of expansion

Location Decisions The process of determining a geographic site for a facility is an important aspect of strategic decision making. In determining a facility location, factors such as availability, cost of location, technology, labor, utilities, accessibility, environmental conditions, and interactions with suppliers and customers must be considered. Different mathematical and analytical models can be used to make this decision.

Models	Objectives
• Break-even analysis • Assignment model • Rectilinear distance measurement • Euclidean distance measurement • Single-facility location model • Multifacility location model	• Minimize fixed and variable costs such as transportation and distribution • Maximize future flexibility and expansion • Maximize proximity to suppliers, resources, facilities, and customers • Maximize quality of products

1.3.3 Quality, Reliability, and Measurement

Quality Control and Assurance Quality control methods can be used to identify quality problems during and after the production process. Efficient sampling plans are used to predict the quality of products or processes while using minimal inspection costs. For the determined level of quality, a proper sampling approach should be used to minimize the number of defective products shipped to customers. Quality function deployment is an approach for incorporating the customer voice into the manufacturing process.

Models	Objectives
• Control charts (continuous and discrete measurements) • Operating characteristic curve • Sequential sampling plans • Average outgoing quality • Quality function deployment (QFD) • Multicriteria QFD	• Minimize cost of quality control • Maximize average outgoing quality • Maximize accuracy of measurements • Maximize confidence in results • Minimize risk to consumer • Minimize risk to producer

Work Measurement and Analysis With many corporations and firms focusing on efficiency gains and cost reductions, statistical based work measurement methods are becoming popular. Work measurement involves the use of time studies to measure, predict, and set standards for the acceptable amount of time that specific tasks and jobs should take.

Work measurement and labor standards have applications in manufacturing operations, service industries, government, and educational institutes.

Models	Objectives
• Stopwatch studies—continuous time	• Minimize cost of measurement
• Work sampling—discrete time	• Maximize accuracy of measurement
• Predetermined time standards	• Maximize confidence in results
• Multicriteria sampling plans	• Minimize risk

Reliability and Maintainability Reliability refers to the likelihood that a product will perform up to its specifications for an expected period of time. It can also be used to predict future costs and to determine optimal maintenance and replacement policies. Proper maintenance policies can prolong the life of a system or product and minimize the failure rates. Replacement polices are used to identify when a component or a system should be replaced to minimize the total cost and the risk. A balanced decision between maintenance costs and replacement costs must be made while considering the required level of reliability.

Models	Objectives
• Reliability of single components	• Maximize total reliability of system
• Mean time between failure rates	• Minimize total cost
• Reliability measurement of sequential and parallel systems	• Minimize total number of breakdowns
• Maintenance policies	• Minimize total preventative and breakdown costs
• Replacement policies	• Minimize risk of failure

1.4 SYSTEMS APPROACH AND TOOLS

1.4.1 Systems Approach

Systems Engineering and Development Systems engineers use modeling to plan for the development and construction of a system. The systems engineering process encompasses the design, development, and construction of a system and tracking the progress through the system life cycle. Systems engineering also encompasses integration approaches and management throughout the entire life cycle of a system. Every system is different, but the fundamental steps involved in the systems engineering process remain the same for all systems. The systems engineering process is an iterative process. Based on such objectives, the system is constructed. Systems engineering is an evolving field which continues to grow as new complex problems are encountered.

Models	Objectives
• Physical systems (micro vs. macro) • Biological systems (micro vs. macro) • Man-made systems (conceptual vs. physical) • Environment-based systems (static vs. dynamic) • Conceptual systems (logical vs. intuitive) • Dynamic systems (nonadaptive vs. adaptive) • Mathematical systems (linear vs. nonlinear) • Boundary-based systems (closed vs. open) • Goal-seeking systems (single objective vs. multiobjectives)	• Maximize efficiency of systems • Maximize productivity of systems • Maximize quality of systems • Minimize cost of systems • Maximize ease of use • Maximize ease of modification • Maximize simplicity of models

Systems Architecting and Modeling Systems architecting is the art and science of designing complex systems, which are also called systems of systems. Systems architecting is based on multiple disciplines of art, science, management, and engineering. In the design of a system, the systems architect must consider the objectives of different stake holders. The systems architecting process creates a systems architectural design by using the customer's requirements to produce a conceptual model. This process is performed by the systems architect, but it has feedback from many parties, including clients, systems engineers, and the developers of subsystems and components.

Models	Objectives
• Analog models • Physical models • Analytical models • Formal models • Managerial models	• Maximize customer's satisfaction • Maximize simplicity of design • Maximize quality of systems • Minimize project duration • Minimize project cost • Maximize aesthetic of system

1.4.2 Multicriteria Decision Analysis

Multicriteria Decision Making The first step in solving a MCDM problem is to clearly define the problem and its constraints. Once the problem is understood and formulated, the next step is to determine the objectives associated with the problem. Then one should apply a proper model for solving and analyzing the problem. Then, a set of promising feasible alternatives satisfying constraints should be generated and analyzed. It is important to realize that there may be many different alternatives to a given problem.

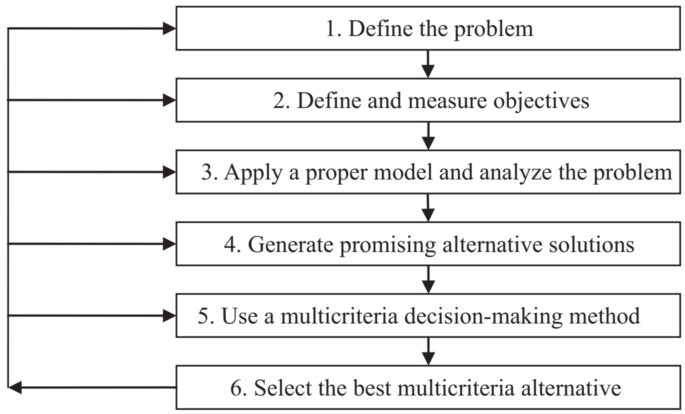

Figure 1.4 Flowchart of multicriteria problem-solving approach.

But, the set of promising alternatives is a small subset of alternatives. A MCDM approach (see Chapter 2) can be used to evaluate alternatives and choose the best multicriteria (also called the most compromised) alternative. This multicriteria process is shown in Figure 1.4. Each phase of decision making can be modified based on feedback from other phases.

Often, the decision-making process is complex and requires analyses of many different aspects, including several different objectives (criteria) and perspectives. The decision maker should always consider different alternatives and evaluate them based on given criteria. The MCDM methods can be used for evaluating, rating, and ranking alternatives while considering several conflicting objectives.

Models	Objectives
• Identifying efficient alternatives	• Minimize efforts of decision-making process
• Ranking by additive utility functions	• Maximize reliability of approach
• Ranking by Z utility theory functions	• Maximize simplicity of approach
• Ranking by closeness to goals	• Maximize robustness of approach
• Ranking by interactive methods	• Maximize accuracy of approach
• Ranking by paired comparisons of alternatives	

Decision Making and Process Understanding the decision process can provide insight into why people make decisions in certain ways. Decision makers who are conscious of their decision process and types can make more effective and balanced decisions. The decision process model is based on four dimensions, where each dimension has two opposing types: information processing (concrete and abstract), alternative generation (adaptive and constructive), alternative evaluation (risk averse and risk prone), and decision closure (decisive and tentative); see Chapter 2. We provide approaches for assessing and optimizing the decision process. In decision making, expected values are used to determine the best alternative while considering the payoffs associated with different probabilistic states of nature (of future events). Decision trees are one of the primary visual tools used in decision analysis. Decision trees can also be used to present multiphase or sequential decision-making problems. To estimate the value of additional information (to improve expected value result), Bayes's approach is used.

Models	Objectives
• Decision-making process and four types • Decision trees and tables • Sequential decision making • Expected value with partial information on probabilities • Worth of additional information (Bayesian approach)	• Maximize optimal value of having more information • Maximize optimal value of having more alternatives • Maximize expected value of payoffs • Maximize optimal timing of decision making • Maximize worth of additional information

Risk Analysis In risk analysis for decision making, consider two cases: decisions under risk (with known probabilities) and decisions under uncertainty (with unknown probabilities). Utility functions are used for presenting and reflecting the decision maker's risk attitude. Expected-utility theory is the classical approach for assessing utility function but it has its limitations. Z utility theory (Malakooti, 2014b) generalizes expected-utility theory and provides mechanisms to quantify risk as an objective measurement independent from the decision maker. Z utility theory functions can be easily assessed, verified, and graphically presented; they can be used for both risk and uncertainty. Z utility theory functions can also be used to identify the type of decision-making behavior: risk averse, risk prone, risk neutral, and mixed risk averse/prone. The picture depicted on the front cover of this book shows Z utility functions as birds that can fly nonlinearly in any direction and having different degrees of freedom.

Models	Objectives
• Decisions under risk • Expected utility theory • Z utility theory • Catastrophic risk measurement • Regret/reward theory • Multiplicative and feasible goal approaches • Decision making under uncertainty	• Maxmize expected value of (e.g., monetary) payoffs • Maximize qualitative payoffs • Minimize potential loss for risk averse • Maximize potential gain for risk prone

1.4.3 Problem-Solving Tools

Linear and Nonlinear Programming (Optimization) Optimization is a mathematical tool used to obtain the optimal solution (that optimizes an objective function) to a set of constraints on decision variables. The constraints are a set of equalities and/or inequalities that restrict the range of feasible alternatives. For example, in production problems, the objective is cost (to be minimized) subject to limited resources such as labor, materials, machines, and capital constraints. Optimization helps the decision maker plan and allocate resources effectively and efficiently. There are four classes of optimization problems:

- Linear programming (LP): linear objective and constraints
- Nonlinear programming (NLP): nonlinear objective and/or constraints
- Integer programming (IP): LP or NLP where some decision variables must assume integer values
- Combinatorial programming (CP): optimization problems where the set of alternatives is combinatorial

Models	Objectives
• Graphical solutions for two variables • Simplex method for solving LP • Feasible direction for solving NLP • Steepest descent methods • Constrained and unconstrained optimization • Computer-based algorithms for LP, NLP, IP, and CP • Sensitivity analysis of coefficients • Economic interpretations • Heuristics for combinatorial problems	• Maximize accuracy of presenting model • Minimize number of constraints, decision variables, and objectives • Maximize simplicity of model • Maximize ease of communication to decision maker • Maximize chance of finding optimal solution • Minimize computational effort to find optimal solution

Queuing Systems In most queuing problems, objects (customers or products) arrive to the queuing line in a random fashion. Similarly, the service time by the server (processor) to process each object is random. Based on the characteristics of a queuing line, many performance measurements, such as the average service time per object, can be found. There can be one or several channels of arrival to each processor. The service can occur in one phase or several phases. Queuing systems are used extensively in industry as well as service industries and organizations. Minimizing total cost, average service time, and waiting time is an important objective when designing a queuing system.

Models	Objectives
• Single server, single phase • Single server, multiphase • Multiple server, single phase • Multiple server, multiphase	• Minimize number of servers • Minimize waiting and service time • Minimize costs • Maximize quality of service • Maximize long-term productivity

Simulation Simulation is an important analytical tool for analyzing complex systems. Simulation can be used to assist decision makers in experimenting with different possible alternatives prior to choosing one. Simulation incorporates and performs many “runs” of a given scenario to achieve a realistic performance of the systems under study. Some complex systems can be modeled by simulation.

Models	Objectives
• Generating random numbers • Continuous-event simulation • Discrete-event simulation • Random-number generation • Inverse transformation functions • Learning in simulation • Multiobjective optimization in simulation	• Maximize accuracy of model • Minimize cost of modeling • Maximize validity of model • Minimize computational time

1.5 MULTICRITERIA PRODUCTION/OPERATION SYSTEMS

1.5.1 Pyramid of Multicriteria Production/Operations

There are five long-term objectives that should be considered in operational systems:

Cost Cost can be measured in terms of monetary units (e.g., dollars). It usually consists of fixed and variable costs. Generally, the present worth of costs can be calculated by considering relevant interest and inflation rates. Cost is the easiest objective to measure for the current time or the committed near future.

Productivity Productivity can be measured in terms of the number of products produced during a period of time (e.g., 100,000 products per 40 h).

Quality Quality can be measured in a variety of ways. In the broadest sense, it can be measured by the customer’s satisfaction for the intended use of the product. From a production standpoint, quality is a measure in terms of the conformation of a manufactured product to its design specifications. These measurements are discussed in Chapter 17.

Flexibility (Reconfigurable and Agility) Flexibility can be measured in a variety of ways. It may refer to what extent a system can be changed (reconfigured) to produce a different line of products. It may also refer to the ease of changing the layout for future expansion (or reduction) and technological upgrades. Agility may refer to the speed at which the changes may take place.

Ecological Soundness Ecological soundness refers to the biological and environmental impacts of the system under study. Ecologically sound systems support energy efficiency, sustainability, minimal hazardous by-products, and long-term buildup of the natural environment.

Multicriteria Pyramid of Production and Operation Systems Figure 1.5 shows the relationship between the five objectives of production and operation systems. The tip

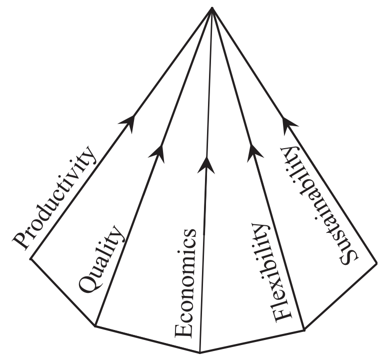

Figure 1.5 Multicriteria pyramid of production and operation systems shows feasible and efficient multicriteria alternatives; tip of pyramid can be achieved at the highest cost.

of the pyramid is associated with the highest productivity, the highest quality, the most economical, the most flexibility, and the most sustainability. The points inside the pyramid are associated with different combinations of the five criteria. The tip of this Pyramid is the ideal point, but it is infeasible. The base of this Pyramid consists of the worst points. Therefore, in practice, one should make a tradeoff among these five objectives to find a feasible solution closer to the tip of the Pyramid. In the next section, we discuss how to identify efficient alternatives which are not dominated by other points. This book provides an overall approach for maximizing these five objectives.

Trade-Off Analysis and Efficiency Once the target values for costs, productivity, quality, flexibility, and ecological soundness are set, strategic decisions and needed resources to achieve such objectives can be determined. In the following, the trade-offs between cost and the other four criteria are discussed; these are presented in Figures 1.6*a*, *b*, *c*, and *d*. In order to have consistent notation for maximizing all objectives, consider maximizing the inverse of cost (1/cost), which is the same as minimizing cost. Therefore, all these five objectives are maximized. To illustrate the concept of efficiency, for example, consider flexibility and the inverse of cost (1/cost). An alternative is inefficient (or dominated) if there exists another alternative that is better or equivalent in terms of both objectives. For example, in Figure 1.6*a*, alternative ($1/C_1$, F_1) is dominated by alternative ($1/C_1$, F_2); it is inefficient. The set of alternatives can be reduced to a set of efficient alternatives.

Cost versus Flexibility Strategies that heavily emphasize minimizing cost may lead to more rigid and inflexible systems. Likewise, the strategy that opts for more flexibility is associated with higher cost. Consider Figure 1.6*a*. All alternative strategies on the curve labeled as "current trade-off" are efficient with respect to each other. This is an indifference curve meaning that the feasible alternatives in terms of C and F are located on this curve. In order to have an increase in flexibility, the cost can be identified. Suppose that point ($1/C_1$, F_1) is selected as the operational system by a given industry. The operation system is then designed for this given flexibility and cost. However, with the progress of technology as time passes, improvements will shift the curve upward, labeled as "future trade-off." The

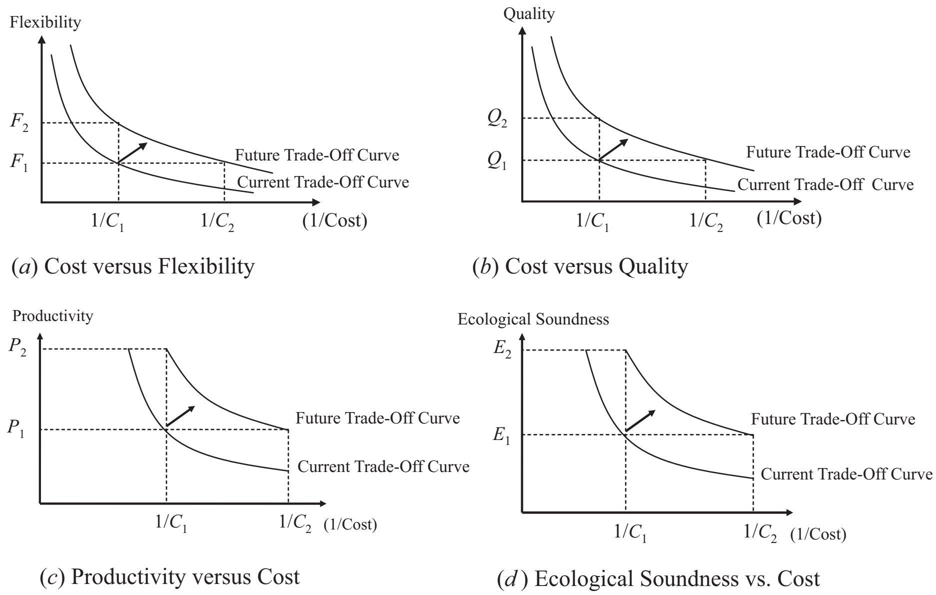

Figure 1.6 Current vs. future trade-off curves. Future trade-off curve will be better than current trade-off curve because of technological and process improvements. Also, one current alternative will lead to many improved alternatives in the future.

current point $(1/C_1, F_1)$ could be replaced by one of the choices between points $(1/C_2, F_1)$ and $(1/C_1, F_2)$ on the future trade-off curve. In making a strategic decision, one should design a system that considers the future improvement in cost and flexibility. That is, the future choices depend on the choice made at the current time. Therefore, at the current time, one should consider an alternative that provides the most choices for cost and flexibility in the future.

Cost versus Quality Now consider quality versus cost. Figure 1.6*b* demonstrates a similar relationship to Figure 1.6*a*. Once a strategy [e.g., a given cost and quality (C_1, Q_1)] is selected, the future improvements in cost and quality will render more choices on the future trade-off curve, that is, all points between $(1/C_2, Q_1)$ and $(1/C_1, Q_2)$ on the future curve.

Cost versus Productivity Similarly, Figure 1.6*c* shows the trade-off between cost and productivity. A higher cost (i.e., lower 1/cost) is associated with a higher productivity assuming everything else is constant. For example, for the same quality and flexibility, it will cost more to have a system with higher productivity.

Cost versus Ecological Soundness Similarly, Figure 1.6*d* shows the trade-off between cost and ecological soundness. There is a trade-off between cost and ecological impact. Currently, it costs more to develop systems that are more ecologically friendly. In the future, it may be possible to develop systems that are less costly and more ecologically friendly.

1.5.2 Hierarchical Multicriteria Planning

In this section, we propose a hierarchical framework for production and operation systems. See Figure 1.7. In this framework, six levels are considered based on the duration of the planning. Level 1 has the longest planning horizon, and level 6 has the shortest one. This hierarchical multilevel system is characterized by vertical (or top-down) decomposition

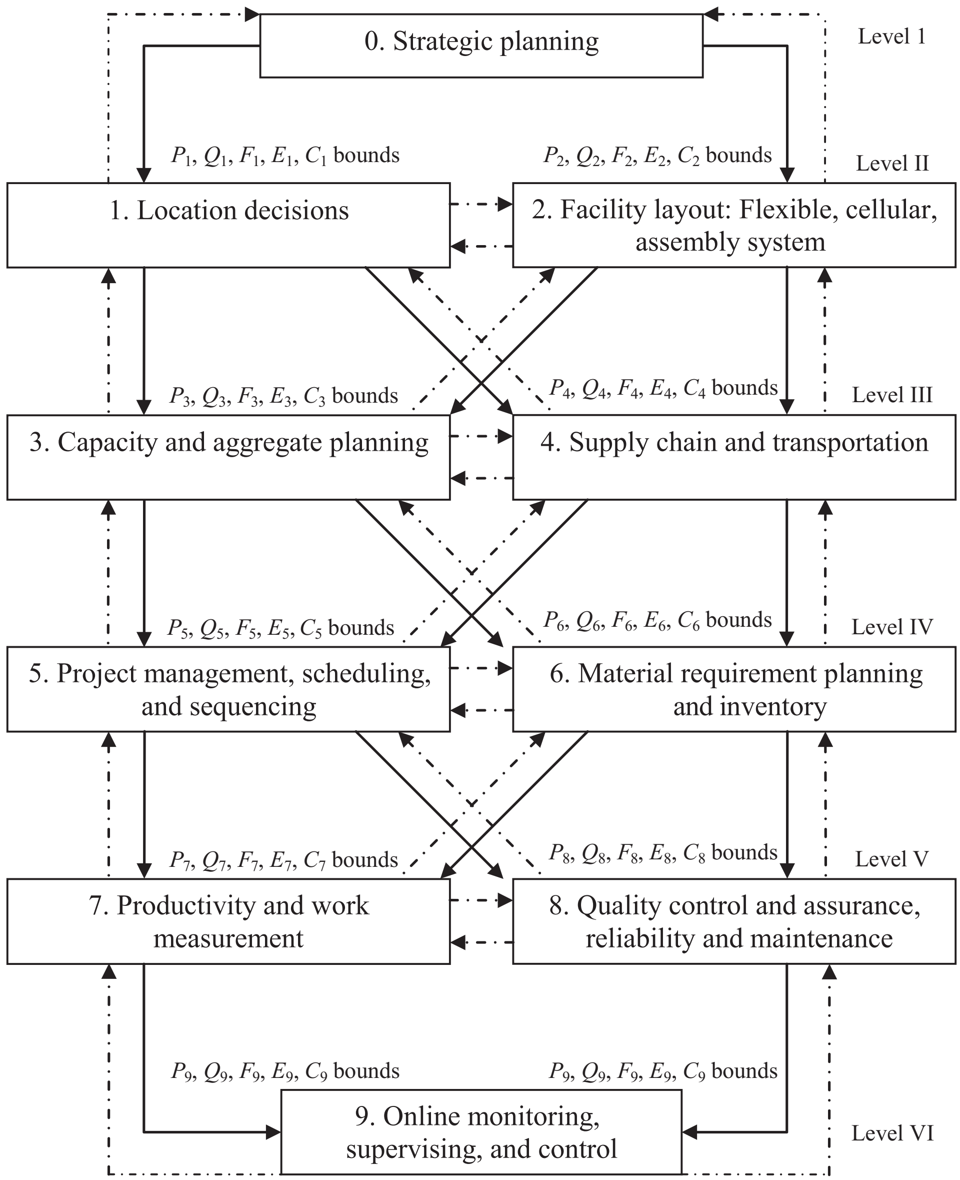

Figure 1.7 Hierarchical multilevel multiobjective system consisting of six levels. Each production planning function communicates to other functions based on their common objectives: productivity level (P), quality level (Q), flexibility (F), ecological soundness (E), and cost (C).

and the interdependence of adjacent levels. Higherlevel planning and decision making are usually associated with longer durations and more uncertainty compared to the lower levels. In this hierarchical formulation of production planning, the initial action starts with higher levels and bounds on objectives are given to lower levels. The objectives are:

- Maximize *P* (productivity)
- Maximize *Q* (quality)
- Maximize *F* (flexibility)
- Maximize *E* (ecological soundness)
- Minimize *C* (cost)

The information on objectives is provided in terms of lower and upper bounds where the bounds are iteratively reduced according to the interaction among connected subsystems. Figure 1.7 diagrams the interrelation of the six-level problems. A solid arrow indicates the dictation of bounds on objectives from a parent to children. Children provide feedback or make adjustments using a dashed arrow. For the same child, if the given bounds from two parents are not feasible, then negotiations should occur to find a feasible solution and the best compromise solution. Each level is discussed in the following.

Level I At the highest level strategic planning, bounds on all five objectives, *P*, *Q*, *F*, *E*, and *C*, are determined for a long period of time (e.g., for several years).

Level II In location decisions, the best locations of facilities are determined based on objectives such as minimizing transportation and distribution cost, maximizing proximity to suppliers, resources, and facilities, and maximizing proximity to customers. In the facility layout problem, the best arrangement and location of departments (or machines) within a given facility are determined. The objectives of the facility layout problem include minimizing the materials movement, maximizing the flexibility, and minimizing the materials movement cost.

Level III In capacity and aggregate planning, the optimal master schedule is determined. Based on this master schedule, broad planning in terms of aggregated units and the needed capacities is determined. Objectives include minimizing the production cycle or project duration, satisfying priorities on due dates, and minimizing the project cost such as resources, labor, and machinery. In supply chain and transportation, optimal plans to deliver materials to manufacturers and from manufacturers and suppliers to customers are determined. Objectives include minimizing transportation cost, minimizing transportation time, and maximizing the quality of transportation.

Level IV In project management, scheduling, and sequencing, the best ways to assign jobs to different departments, machines, or contractors are determined. Objectives include minimizing durations satisfying priorities (e.g., due dates) and minimizing cost. In material requirement planning and inventory, optimal plans to acquire necessary components and materials to manufacture the products based on the demands are determined. Objectives include minimizing total inventory, minimizing total backorder, and maximizing achievement of JIT.

Level V In productivity and work measurement, the best approaches for measuring productivity and work measurements are used. These measurements can help higher level decision-making units to be more realistic about their target objectives. Objectives include maximizing the accuracy of measurements, maximizing the confidence level in determined values, and minimizing the total cost (and time) of making the measurements. In quality control and assurance, the quality of products is measured in accordance with the required specifications. Objectives include maximizing the number of outgoing items, maximizing the quality of outgoing items, and minimizing the cost of quality control. In reliability, reliability of the system or product is measured. In maintenance, the best maintenance policy for the optimal performance of the system or product is determined. Objectives include minimizing cost, maximizing systems' life, and maximizing the quality of products.

Level VI In online monitoring, supervision, and control, the main concern is to adjust the system parameters automatically with respect to changes in raw materials and manufacturing dynamics. An automated system would simulate the decision maker's behavior (preferences) instantly. Objectives for online control are minimizing the time needed to stabilize the systems' behavior to achieve certain goals, minimizing the deviation from the goals, and minimizing the cost of production, operations, and monitoring.

1.6 PRODUCT AND PROCESS LIFE CYCLE

1.6.1 Product Life Cycle

The product life cycle is commonly used to describe the life of a product over time. This cycle consists of four stages: product introduction, growth, maturity, and decline. A product life-cycle curve is shown in Figure 1.8 where the annual sales volume of a product is plotted against time. The four phases are described below.

Phase I: Introduction During the introduction of a product, production and manufacturing facilities are designed to produce a small number of products. In this stage, manufacturing costs are high. Flexibility in production methods is needed in order to adapt to changes that will occur in the future. Marketing for the product is just beginning, and the sales volume slowly increases.

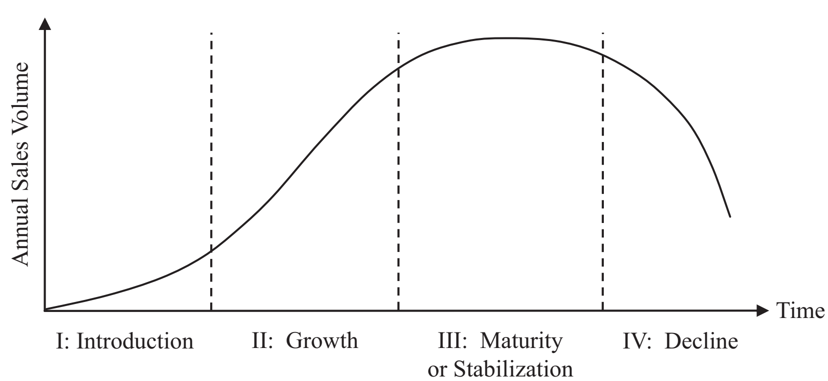

Figure 1.8 Product life-cycle curve.

Phase II: Growth In the growth phase, the sales volume increases rapidly. Improvement methods are introduced in this stage. Permanent equipment is acquired to plan for a stable system for the next stage. A concerted effort to gain market share is made in this stage as competing products emerge.

Phase III: Maturity The maturity phase is reached when demand for the product does not increase anymore and there is little room for improving the process. This phase is also referred to as stabilization. The focus for marketing the product relies on competitive pricing. In this phase, the most efficient and least expensive production method is used. The economy of scale substantially helps to keep the market price low and competitive.

Phase IV: Decline Finally, the product enters the fourth stage of its life cycle, the decline. At this point, the market becomes saturated and sales volume declines. Creative marketing techniques may be used to maximize the sales of products. The product may be modified in order to prolong its life cycle. In some cases, decline may occur after a long period of time.

Every product may have a different life cycle in terms of the duration of each of its four phases. The challenge for decision makers is to make production planning congruent with the product's life cycle. Each phase should be planned in terms of material procurements, labor hiring, production capacity, marketing, and sales. Most industries (such as auto industries) try to predict the life cycle of their products and begin new models even before the maturity of their current models occurs. In Figure 1.9 three curves for three generations of the same type of products are shown. When the decline of product *a* occurs, product *b* is at its maturity, and product *c* is being introduced. Following this strategy, a company will stay competitive and dynamic.

1.6.2 Process Life Cycle

The process life cycle refers to the development of process capability for a given line (type) of products. For example, in the auto industry, once the process capability of producing certain types of cars is stabilized, this process can be used to produce a variety of car models, including the new lines of cars that will be developed in the future. The life cycle of a process will usually outlast many generations of product lines. The process life cycle also consists of four phases; see Figure 1.10.

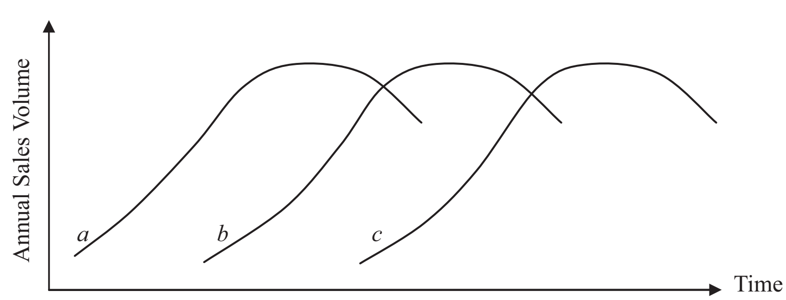

Figure 1.9 Product life cycle of different generation of same type of products, where product *b* replaces product *a*, product *c* replaces product *b*, and so on.

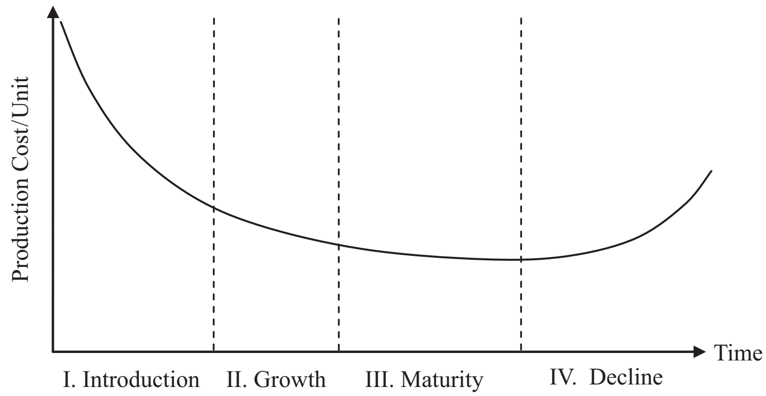

Figure 1.10 Process life cycle.

The basic idea behind the process life cycle is that as time goes on, manufacturing for mass production of a product becomes more efficient, skilled, and also automated, and products are produced more quickly and at a lower cost per unit. This is due in large part to the stabilization of the product's production capabilities and learning curves (discussed in the next section).

1.6.3 Product–Process Matrix

The relationship between the types of products and the types of processes can be shown through the use of the product–process matrix. The product–process matrix is a useful visual tool for providing information regarding the interaction of the product and process volume, flow, and flexibility. This matrix is shown in Figure 1.11. In Figure 1.11, by moving diagonally down from the upper left-hand corner to the lower right-hand corner, different

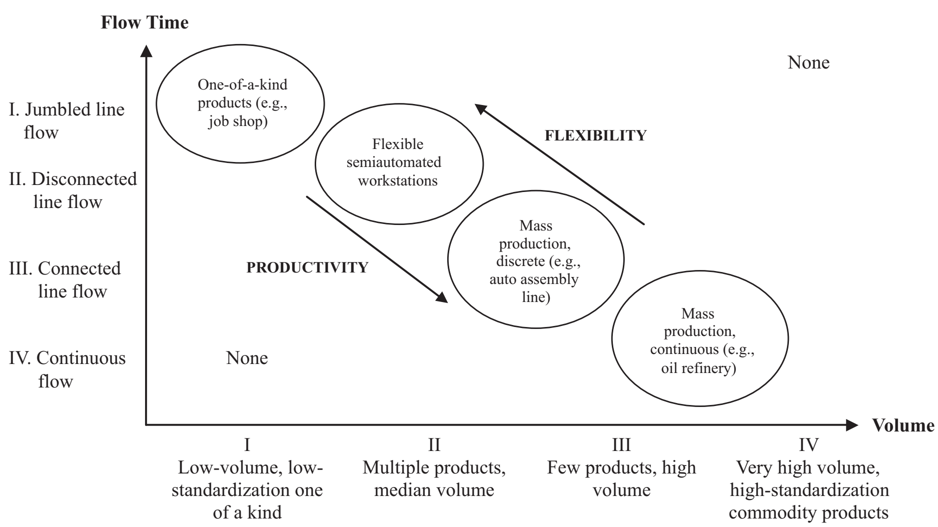

Figure 1.11 Product–process matrix classifying different products and process.

pairings of product and process types occur. In the upper left-hand corner, jobs are unique and manufacturing costs per unit are high. There is much flexibility in the production processes. Moving down the diagonal line, flexibility is reduced, but manufacturing costs per unit decrease. Product design and manufacturing processes become more standardized by moving toward the lower right-hand corner of the matrix. In this direction, production volume also increases. The top right and the bottom left are labeled as "none" because it is technologically and economically impossible to operate in these regions. For example, it is not economically feasible to develop an automated mass production system to only produce a few one-of-a-kind products (the bottom left).

1.7 LEARNING CURVES

Generally, with the passage of time, production systems become more efficient as workers and managers learn to become more effective. The learning process is especially rapid for repetitive systems (e.g., mass production and assembly systems). A famous learning curve is Moore's law, which regards the assembly time of computing hardware. It states that the number of transistors that can be placed on an IC doubles approximately every 18 months. For the past 50 years, this trend has been observed, but it is expected that this rate will start to flatten out in the next 10–15 years. Learning from experience is not the only reason for improved efficiency. Other factors are better machines and tools, streamlined production lines, automation, and improved products and processes. A learning curve is a graph that depicts labor hours required per unit of product versus the total number of units produced. For example, for a 60% learning rate, if the first unit takes 20 h, then the second unit will take $0.6 \times 20 = 12$ h, and the fourth unit will take $0.6 \times 12 = 7.2$ h. Continuing in the same manner, the 1024th unit will take only 0.12 h. As the number of units increase, the curve becomes flatter. This given example (learning rate of 0.6, or 60%) is very fast and not realistic for many industries. In practice, for most industries, the learning rate varies from 0.85 (or 85%) to 1 (or 100%). Three learning curves are presented in Figure 1.12 and Table 1.4.

Neglecting the learning curve for any labor-based organization will lead to overstaffing labor and additional cost. Learning curves are generated based on past experiences, so one

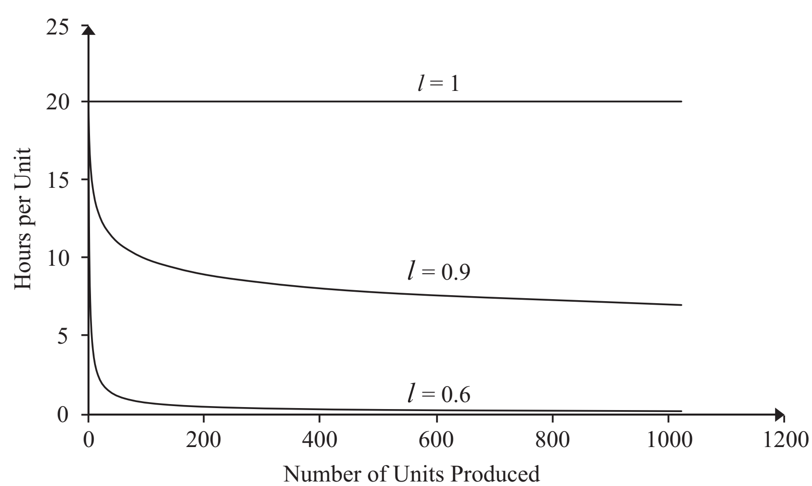

Figure 1.12 Learning curves for 60, 90, and 100% learning rates.

TABLE 1.4 Production Time for *n*th Unit for Learning Rates of 60, 90, and 100%, the Higher Learning Rate Associated with Less Productivity

	60% Rate		90% Rate		100% Rate	
n Units Produced	$0.6 \times T(n/2)$	Production time for *n*th unit, $T(n)$ (h)	$0.9 \times T(n/2)$	Production time for *n*th unit, $T(n)$ (h)	$1 \times T(n/2)$	Production time for *n*th unit, $T(n)$ (h)
1	—	20	—	20	—	20
2	(0.60) × 20	12	(0.90) × 20	18	1 × 20	20
4	(0.60) × 12	7.2	(0.90) × 18	16.2	1 × 20	20
8	(0.60) × 7.2	4.32	(0.90) × 16.2	14.58	1 × 20	20
16	(0.60) × 4.32	2.59	(0.90) × 14.58	13.12	1 × 20	20
32	(0.60) × 2.59	1.56	(0.90) × 13.12	11.81	1 × 20	20
1024	(0.60) × 0.20	0.12	(0.90) × 7.75	6.97	1 × 20	20

should make sure that the recorded information is accurate and relevant. The learning curve should be reevaluated when more recent data become available. Two different approaches, the arithmetic and the logarithmic, can be used to solve learning curve problems, that is, find the learning rate.

1.7.1 Arithmetic Approach

The arithmetic approach uses the following basic equation that defines learning curves:

$$T(2n) = lT(n) \tag{1.1}$$

where

n = number of units
$T(n)$ = production time for nth unit
l = learning rate, where $0 < l \leq 1$

When $l = 1$, no learning occurs, that is, the time to produce an item remains the same. As l decreases, the learning rate increases, and it takes less time to complete the same job.

Example 1.1 Aircraft Industry Using Arithmetic Approach In an aircraft industry it takes 1000 h to build the first aircraft and 700 h to build the second aircraft.

Find the learning rate l and the time it takes to produce the 4th, 8th, . . . , 1024th units.

First, find the learning rate l, where $T(1) = 1000$ and $T(2) = 700$. Consider Equation (1.1) where $n = 1$:

$$T(2) = lT(1) \qquad 700 = 1000\, l$$

$$l = \frac{700}{1000}$$

$$= 0.70$$

Therefore, use $T(2n) = 0.7T(n)$ to find the time it takes to build the products. These times are presented in the table below:

nth (aircraft)	1	2	4	8	16	32	64	128	256	512	1024
$T(n)$	1000	700	490	343	240	168	118	82.4	57.7	40.4	28.3

1.7.2 Logarithmic Approach

The arithmetic approach can be used to calculate the production time per unit for units $n = 2^k$, where k is a positive integer. However, the arithmetic approach cannot be used to predict the production time for any arbitrary number (e.g., 25th or 341th). The logarithmic approach can be used to find the value of $T(n)$ for any given n (the time it takes to produce the nth item) as follows:

$$T(n) = T(1)n^{-b} \tag{1.2}$$

where

$T(1)$ = production time for 1st unit
b = coefficient exponent of learning curve

Relationship of b to Learning Rate l Consider two numbers, n and $2n$. From Equations (1.1) and (1.2), the equation can be written as

$$l = \frac{T(2n)}{T(n)} = \frac{T(1)(2n)^{-b}}{T(1)n^{-b}} = 2^{-b} \qquad \text{or} \qquad l = 2^{-b} \tag{1.3}$$

Solving for b,

$$l = 2^{-b} \qquad \log(l) = -b\log(2) \qquad b = -\frac{\log(l)}{\log(2)} \tag{1.4}$$

Example 1.2 Logarithmic Approach: Detail Example Consider Example 1.1, where the learning rate is 70% (i.e., $l = 0.70$) and the time it takes to produce the first unit is 1000 h, that is, $T(1) = 1000$.

(a) Find the time required to produce the 600th unit.
(b) Find the time it takes to produce unit number 50, 100, 500, 1000, 2000, and 5000.
(c) Do parts (a) and (b) if the learning rate is 90%.

Solution

(a) First, find the value of b by using Equation (1.4):

$$b = -\frac{\log(0.70)}{\log(2)}$$
$$= 0.515$$

Using Equation (1.2),

$$T(n) = 1000(n)^{-0.515}$$

Therefore, the production time for the 600th unit is

$$T(600) = 1000(600)^{-0.515} = 37.1 \text{ h}$$

(b) For $l = 0.70$ and $b = 0.515$, use Equation (1.2) to find $T(n)$ for different values of n:

n (aircrafts)	1	50	100	500	1000	2000	5000
$T(n)$	1000	133.36	93.325	40.741	28.51	19.951	12.446

(c) For $l = 0.90$, using Equation (1.4), $b = 0.152$. Using Equation (1.2), we find:

n (aircrafts)	1	50	100	500	1000	2000	5000
$T(n)$	1000	551.76	496.59	388.83	349.95	314.95	274

1.7.3 Deteriorating Curves

In certain applications, the productivity (or quality or efficiency) of some systems decreases as the system gets older. For example, due to older age, a machine may require more shutdowns for needed repairs. Another example is how the output of a battery may decrease due to deterioration with age. In this case, Equations (1.1), (1.2), and (1.4) can be used where the learning rate $l > 1$, that is, over 100%. An example of a deteriorating curve is shown in Figure 1.13.

Example 1.3 Deteriorating Curve As time passes, a given machine will deteriorate and will require more shutdowns for needed repairs. Suppose that for this machine it takes 1000 h to produce the first unit, and the learning rate is 110% (i.e., $l = 1.1$). Respond to parts (a) and (b) of Example 1.2.

Solution

(a) First, find the value of b using Equation (1.4):

$$b = -\frac{\log(1.1)}{\log(2)}$$
$$= -0.138$$

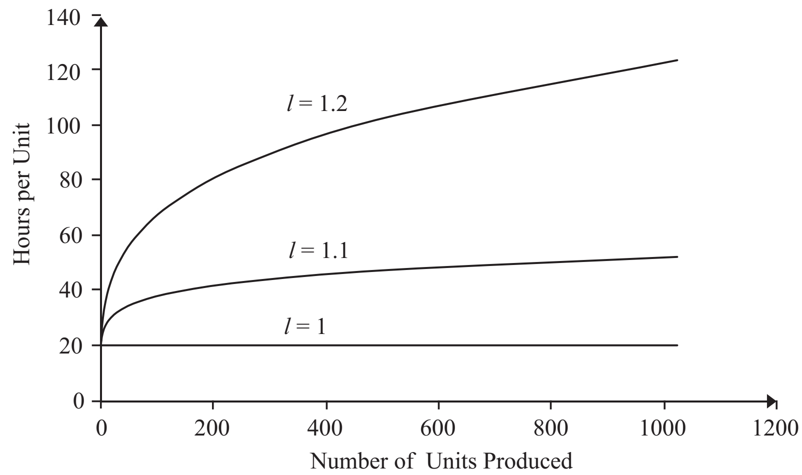

Figure 1.13 Deteriorating curve for 110, 120, and 100% deteriorating rates.

Using Equation (1.2),

$$T(n) = 1000(n)^{0.138}$$

Therefore, to produce the 600th unit, it will take

$$T(600) = 1000(600)^{0.138} = 2418 \text{ h}$$

(b) For $l = 1.1$ and $b = -0.138$, use Equation (1.2) to find $T(n)$ for different values of n:

n (aircrafts)	1	50	100	500	1000	2000	3000	4000	5000
$T(n)$	1000	1716	1888	2358	2594	2855	3019	3141	3239

1.8 CAPACITY PLANNING

1.8.1 Capacity Strategies

Capacity changes (growth or decline) must be continuously reevaluated by different organizations. This decision is based on the long-term forecasting of demand for products and services. Capacity planning is based on considering future (predicted) demands, technological changes, changes in construction costs, interest rate fluctuations, and the prediction of strategies employed by competitors. The relationship between capacity growth and future (predicted) demands can be categorized into three general strategies which are illustrated in Figure 1.14.

(a) *Capacity Leads Demand* In Figure 1.14*a*, planned capacity growth exceeds the predicted demand. This strategy allows a company to meet the demands without having shortages when there are unexpected increases in demand. The more than needed capacity in terms of facility, manpower, and inventory costs makes this plan

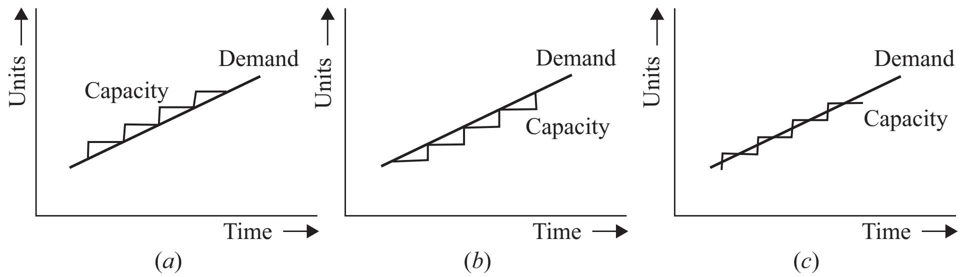

Figure 1.14 Capacity-planning strategies: (*a*) capacity leads demand; (*b*) capacity lags demand; (*c*) capacity matches demand.

less advantageous. This strategy is conservative in terms of consumer satisfaction but risky because of a possible loss of income from the excess capacity.

(b) *Demand Leads Capacity* In Figure 1.14*b*, capacity growth lags the demand. Demand is greater than the capacity for this case. The capacity is being fully utilized, but there will be shortages. In this case, the company will lose some of its future income. The risk of this strategy is that it may result in permanent loss of the market share.

(c) *Capacity Matches Demand* In Figure 1.14*c*, the capacity growth closely matches the demand. Minor shortages or excess accumulations may occur, but generally demands are met. This is a risk-neutral strategy compared to the other two options.

1.8.2 Break-Even Analysis

Economies of scale are the most significant considerations regarding capacity growth. Economies of scale can be used to justify greater capacity growth, because a larger facility will be able to produce units at a lower unit cost when demand is high. As the number of units increases, the average cost per unit decreases. A fundamental problem when considering capacity expansion is to what extent the organization can rely on outsourcing to meet demands. In order to analyze this problem, break-even curves can be used. However, break-even curves are only based on rough estimates of the demand, the time value of money, and learning curves. Breakeven curves can also be used for comparing alternatives when the total cost can be presented as a function of the volume of demand.

Suppose the unit cost is denoted by C_I if it is produced internally and by C_O if it is outsourced. The initial cost of producing the item internally is I_I, and the initial cost of outsourcing is I_O. Let x be the number of units produced (to be determined). The cost of the two alternative methods (producing internally or outsourcing) can be set equal to each other to find x^*, the break-even point.

$$\begin{gathered}\text{Cost of producing internally} = \text{cost of outsourcing} \\ I_I + C_1 x = I_O + C_O x\end{gathered} \tag{1.5}$$

Equation (1.5) can be solved to find the break-even quantity (x^*):

$$x^* = \frac{I_I - I_O}{C_O - C_I} \tag{1.6}$$

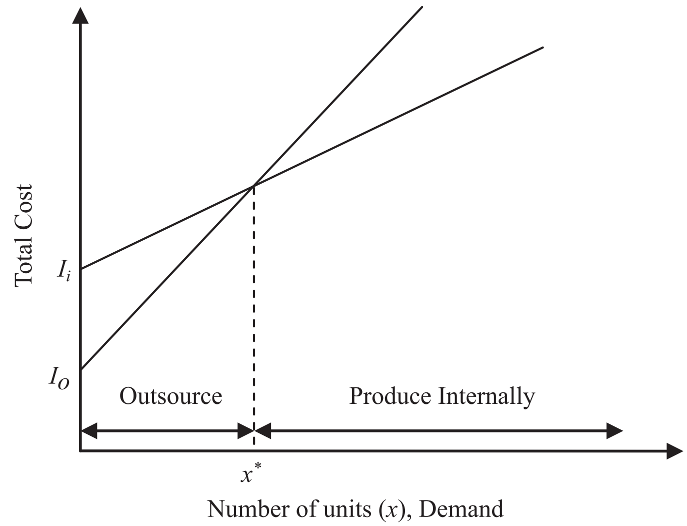

Figure 1.15 Break-even analysis for finding break-even quantity.

Note that generally $I_I > I_O$ and $C_I < C_O$. Figure 1.15 illustrates break-even curves and the break-even point quantity x^*. When the total quantity is less than x^*, one should choose outsourcing; when the total quantity is more than x^*, one should choose producing internally.

Example 1.4 Break-Even Analysis with Three Alternatives Consider the following three alternatives:

I. Full internal production at \$14 per unit with \$20,000 invested
II. Full outsourcing at \$18 per unit with \$0 invested
III. Partial internal production and partial outsourcing at \$16 per unit with \$12,000 invested

Identify which alternatives should be selected for different demand quantities.

To solve this problem, we need to find the break-even points for each pair of alternatives. The three different break-even points are shown in Figure 1.16. For example,

$$x_1^* = \frac{20{,}000 - 12{,}000}{16 - 14} = 4000 \text{ units}$$
$$x_3^* = \frac{12{,}000 - 0}{18 - 16} = 6000 \text{ units}$$

In this example:

If the quantity x is less than $x_1^* = 4000$, choose alternative II.
If the quantity x is more than $x_3^* = 6000$, choose alternative I.
If the quantity x is between 4000 and 6000, choose alternative III.

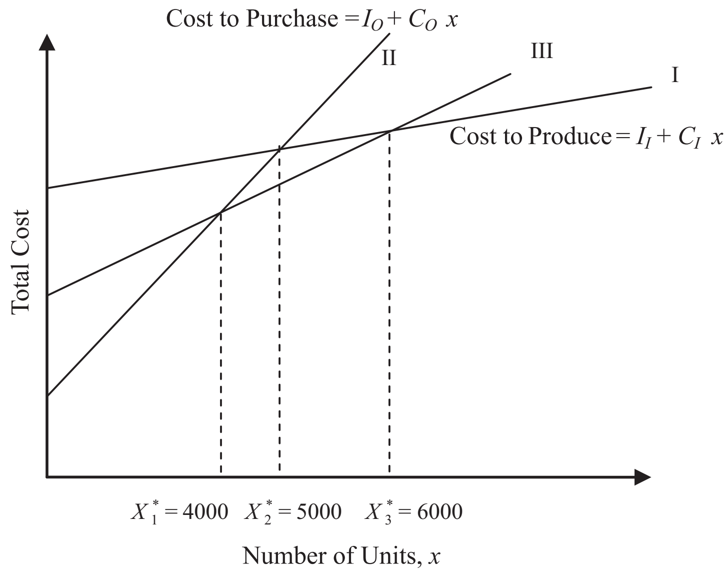

Figure 1.16 Break-even analysis for three alternatives.

Note that the break-even point of alternatives I and II, x_2^*, is not used as it is inferior to alternative III.

1.9 MACHINING/OPERATION OPTIMIZATION

In the last section, the importance of capacity planning as a key strategic decision making was discussed. The capacity of a given process is directly proportional to the speed at which the process is operated. Increasing the production rate, however, usually increases the cost of operations and machinery maintenance and may also impact the quality of the product. Production systems consist of production departments, workstations, and machines. The smallest component of a production system is a machine. In this section, we discuss how to optimize the setup of a machine by considering both production rate and the cost of operation. For the purpose of illustration, the optimization for metal cutting/machining and tool replacements is presented here. However, the same basic idea can be applied to production departments and workstations.

In metal cutting/machining (such as turning, drilling, milling, and grinding), a higher cutting speed costs more because the cutting tools wear faster. Replacing cutting tools more frequently translates into a higher maintenance cost for the company. Alternatively, the company can buy more expensive cutting tools that last longer, but this also translates into a higher cost. Therefore, the production manager must choose an operating speed of the machines that balances the conflicting goals of increasing production rate and minimizing costs given that the quality of products are unchanged for the range of changes in production rate. In this section, we discuss the basics of machine setup and tool life optimization using the well-known Frederick W. Taylor tool life equation developed in the late nineteenth century. We also demonstrate the trade-off between the productivity and cost for machining optimization.

1.9.1 Taylor's Tool Life Equation

Taylor's equation, developed by Frederick W. Taylor (the father of scientific management), shows the basic relationship between machine speed and tool life for machinery processes:

$$vt^n = C \tag{1.7}$$

where

v = speed of cutting (inches per minute)
t = tool life (minutes)

In Taylor's equation, the parameters n and C are found for the given machine, tool, and type of materials being cut. The parameters of this equation (n and C) can be derived by cutting materials at different speeds and recording the tool life for each given speed. Then, a linear regression method (covered in Chapter 3) can be used to estimate n and c. In the following we show how to find these parameters by solving two equations with two unknowns. To verify Taylor's equation, one can experimentally generate several points and check if speeds and tool life match the generated Taylor equation.

Example 1.5 Taylor's Equation Parameters Identification The table below shows the results of two experiments for a lathe cutting machine using a specific type of cutting tool for a given type of steel material.

(a) Derive the tool life equation for this tool.
(b) Find the tool life if the speed is 18 in./min; also find the speed which has a tool life of 120 min.
(c) Verify if the equation is valid.

	Experiment 1	Experiment 2
Speed (in./min), v	10	13
Tool life (min), t	150	50

Solution

(a) The following two equations can be written based on Equation (1.7) using the data from experiments 1 and 2, respectively:

$$10 \times 150^n = C \qquad 13 \times 50^n = C$$

Equating the left-hand sides of the above two equations yields

$$10 \times 150^n = 13 \times 50^n \qquad \text{or} \qquad \frac{10}{13} = \left(\frac{50}{150}\right)^n$$

Taking the log of both sides gives

$$\ln 0.769 = n \ln 0.333 \qquad \text{or} \qquad n = 0.24$$

Now, the value of C can be obtained by substituting the value of n in one of the above equations:

$$C = 10 \times 150^n = 10 \times 150^{0.24} = 33.29$$

Therefore, the tool life equation is

$$vt^{0.24} = 33.29$$

Figure 1.17 shows Taylor's equation for this example.

(b) Examples of how to find t (or v) for given v (or t) are shown in the table below.

Speed (in./min)	Tool Life (min)	n	C	Solution
18	$t = ?$	0.24	33.29	$18 \times t^{0.24} = 33.29$ or $t = 12.96$ min
$v = ?$	120	0.24	33.29	$v \times 120^{0.24} = 33.29$ or $v = 10.51$ in./min

(c) To verify Taylor's equation, more experiments must be conducted to verify if the derived equation closely matches the data from the experiments. For example, at speed $v = 18$ in./min, use a new tool and measure its life. Also, at speed $v = 10.51$ in./min, run the experiment with a new tool and measure the tool life. According to the obtained Taylor equation, the tool lives should be about 12.96 and 120 min, respectively. If the results of experiments are approximately close to these numbers, the model is valid.

1.9.2 Multicriteria of Machining Operation

Consider the following two objectives for the tool life/machining problem introduced in the last section:

Minimize f_1 = total cost (measured by the total cost of replacing all tools during a production period)

Maximize f_2 = productivity (measured by the total number of parts produced per period)

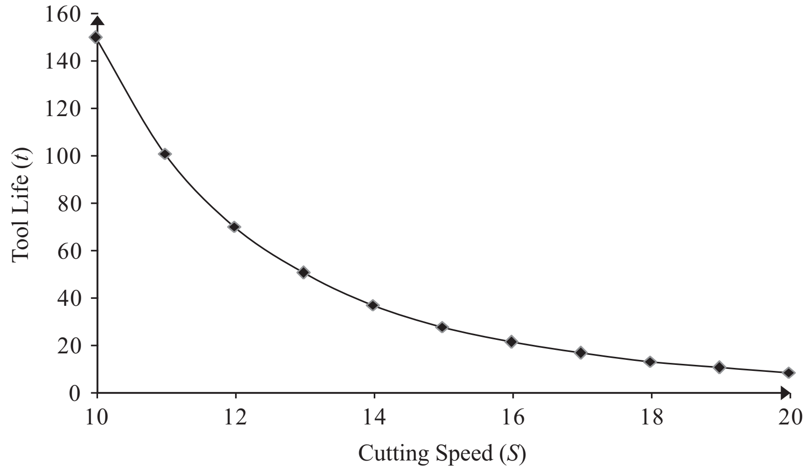

Figure 1.17 Taylor's Tool Life for Example 1.5.

Based on Taylor's equation for tool life, these two objectives can be presented as follows:

$$f_1 = c_t N \tag{1.8}$$

where c_t is the cost of replacing one tool in dollars and N is the number of times the tool is replaced per production period. The value of N can be found by dividing the production period (T) by the tool life:

$$N = \frac{T}{t}$$

To find the productivity, consider the total cutting length required for one part, denoted as L. Then, obtain the total number of parts produced per period for the given speed:

$$f_2 = \frac{vT}{L} \tag{1.9}$$

To generate multiple-criteria alternatives, consider the given minimum and maximum cutting speeds. Then, consider several equally distributed points between the given minimum and maximum speeds. For each given speed, derive the tool life, number of tool changes, total costs, and total production per production period.

Example 1.6 Multicriteria of Maching Operation Consider Taylor's equation in Example 1.5; that is,

$$vt^{0.24} = 33.29$$

Suppose that the production period is four weeks and there are 40 h per week. Also suppose that the total cost of replacing each tool is \$30 (the cost of a new tool and the labor cost of replacing it). Also suppose that each part requires a total of 200 in. of cutting, and the cutting speed v can vary from 10 to 15 in./min. Generate six multicriteria alternatives and identify whether they are efficient. Rank all alternatives.

We know $c_t = \$30$ and $L = 200$. We also know from Equation (1.9) that the total production time is

$$T = 4 \times 40 \times 60 = 9600 \text{ min}$$

We can consider six equally distributed cutting speeds: 10, 11, 12, 13, 14, and 15. The six multicriteria alternatives are stated in the table below. For each given speed v, find the tool life t, the number of tool life changes (N), the total cost f_1, and the total productivity f_2. All these alternatives are efficient in terms of optimizing both objectives simultaneously. More alternatives can be generated by considering additional cutting speeds. The ranking of these alternatives by a hypothetical decision maker is shown in the following table. Therefore, the decision maker will use the third alternative, cutting speed $v = 12$, which will result in a tool life $t = 70$, productivity of 576 parts per period, and total cost of \$4102 per period.

	a_1	a_2	a_3	a_4	a_5	a_6
Cutting speed, v	10	11	12	13	14	15
Tool life, t	150	101	70	50	37	28
Number of tool changes, N	64	95	137	191	260	346
Minimum cost (\$), $f_1 = c_t N$	1919	2855	4102	5726	7797	10,394
Maximum number of parts, $f_2 = vT/L$	480	528	576	624	672	720
Efficient?	Yes	Yes	Yes	Yes	Yes	Yes
Ranking by the decision maker	3	2	1	4	5	6

WWW **See Supplement S1.1.xls.**

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EXERCISES

Introduction (Section 1.1)

1.1 Describe characteristics of each of the following types of decisions:
- **(a)** Strategic decisions
- **(b)** Tactical decisions
- **(c)** Operational decisions

1.2 For a given industry (e.g., automobile):
- **(a)** Provide strategic, tactical, and operation decisions.
- **(b)** What are the inputs, outputs, and transformation processes?
- **(c)** What are the supply chain characteristics?

1.3 Provide an example for each of the following systems. For each example, identify inputs, transformation, and outputs.
- **(a)** Systems with tangible inputs and outputs (e.g., a physical product)
- **(b)** Systems with intangible inputs and outputs (e.g., a service)
- **(c)** Systems with intangible inputs but tangible outputs (e.g., an information system)

Production and operations history and perspective (Section 1.2)

2.1 Describe the major historical events that have changed the way operations, manufacturing, and production systems operate.

2.2 Describe the characteristics and differences of the five phases of operations, manufacturing, and production systems history.

Production and operations Models (Section 1.3)

3.1 Provide an example and its characteristics for each of the following problems. (You may use the Internet to find examples.)
- **(a)** Location decisions
- **(b)** Layout design
- **(c)** Supply chain

(d) Transportation
(e) Clustering and group technology
(f) Assembly systems

3.2 Provide an example and its characteristics for each of the following problems. (You may use the Internet to find examples.)
(a) Forecasting
(b) Aggregate planning
(c) Push-and-pull systems: MRP and JIT
(d) Inventory planning and control
(e) Project management
(f) Scheduling and planning

3.3 Provide an example and its characteristics for each of the following problems. (You may use the Internet to find examples.)
(a) Quality control and assurance
(b) Reliability, maintenance, and replacement
(c) Work measurement and analysis
(d) Productivity and efficiency
(e) Energy systems

Systems Approach and Tools (Section 1.4)

4.1 Provide an example and its characteristics for each of the following problems. (You may use the Internet to find examples.)
(a) Systems engineering and development
(b) Systems architecting and modeling
(c) Multi objective perspective

4.2 Provide an example and its characteristics for each of the following problems. (You may use the Internet to find examples.)
(a) Optimization
(b) Decision analysis
(c) Queuing systems
(d) Simulation

Multiple-Criteria Production/Operation Systems (Section 1.5)

5.1 Consider a decision-making problem (either a personal or a business decision). For this problem, define and apply each of the six steps of solving multiple-criteria problems. Justify why the selected alternative is the best.

5.2 Describe the difference between efficient and inefficient alternatives. Give examples of efficient and inefficient alternatives for exercise 5.1.

5.3 Provide an example (e.g., choose an industry or a business) where each of the five strategic criteria are used. Also discuss the trade-offs for pairs of criteria for the selected example. (You may use the Internet to find examples.)

5.4 Choose a business. *Hint:* You can search the Internet.

(a) Provide an example where the six levels of production planning are used.

(b) Describe each level and show how each level interacts with other levels.

(c) Describe the objectives of each level and the objectives of the whole system.

5.5 Choose a manufacturing industry. (You may use the Internet to find examples.) Respond to questions (a) (b) and (c) of exercise 5.4.

Product and Process Life Cycle (Section 1.6)

6.1 Choose a product. For this product, briefly describe the four stages of the product life cycle. (You may use the Internet to find examples.)

6.2 **(a)** Describe two products that would experience a sharp decline on the life-cycle curve in the fourth stage.

(b) Describe two types of products for which sales would remain steady for a long period after maturation.

6.3 Choose a process (e.g., an industry or a business). For this process industry, briefly describe the four stages of the product life cycle. (You may use the Internet to find examples.)

6.4 Give an example (the name of the products and the name of the manufacturing) for each of the following product/process types. (You may use the Internet to find examples.)

(a) Jumbled flow/low volume

(b) Disconnected flow/multiple products

(c) Connected line flow/high volume

(d) Continuous flow/higher volume

Learning Curves (Section 1.7)

7.1 Provide an example for each of the following organizations with respect to learning curves. (You may use the Internet to find examples.)

(a) Manufacturing company

(b) Governmental organization

(c) Nonprofit organization

7.2 Draw learning curves for each of the following learning rates assuming the first unit takes 20 h to produce:

(a) 25% **(b)** 50% **(c)** 75% **(d)** 100%

7.3 If it takes 10 h to make the 1st car and 8 h to produce the 2nd car:

(a) Find the learning rate l and the learning curve exponent b.

(b) Find the time required to produce 5th unit, 16th unit, and 1000th unit.

7.4 The following table shows the time to produce the nth units for three cases:

	Hours for nth unit		
Unit n	Case I	Case II	Case III
1	50	50	50
5	12	10	14

(a) Consider case I. Find the learning rate, the exponent of the learning curve, and the time needed to produce the 8th, 10th, and 90th units.

(b) Consider case II. Find the learning rate, the exponent of the learning curve, and the time needed to produce the 8th, 10th, and 90th units.

(c) Consider case III. Find the learning rate, the exponent of the learning curve, and the time needed to produce the 8th, 10th, and 90th units.

7.5 Suppose that the exponent of the learning curve is $b = 0.24$, and it takes 30 h to produce the 1st unit.

(a) How long will it take to produce the 50th and 1500th units?

(b) Find the learning rate l.

(c) Find the total time it takes to produce 50 and 1500 units.

7.6 The following table shows the times to produce the nth units.

Unit n Produced	Hours for nth unit
1	40
2	x
4	16.9

(a) How many hours will it take to produce the 2nd unit?

(b) Find the learning rate and the exponent of the learning curve coefficient.

(c) How long will it take to produce the 64th, the 70th, and the 3000th units?

7.7 If it takes 33.75 h to produce the 1st unit and 40 h to produce the 5th unit:

(a) Find the learning (deteriorating) rate and the exponent of the learning curve coefficient.

(b) How long will it take to produce the 2nd, 15th, and 200th units?

7.8 If it takes 100 h to produce the 1st unit and 120 h to produce the 30th unit:

(a) Find the learning (deteriorating) rate and the exponent of the learning curve coefficient.

(b) How long will it take to produce the 100th, 1000th, and 10,000th units?

Capacity Planning (Section 1.8)

8.1 Provide an example (e.g., choose an industry or a business) where each of the following cases has occurred. Discuss the risks (advantages/disadvantages) associated with each case. (You may use the Internet to find examples.)

(a) Capacity leads demand.
(b) Capacity lags demand.
(c) Capacity matches demand.

8.2 A fast food restaurant expects to cook 600 hamburgers per hour.

(a) The current grill's capacity is 2 hamburgers per minute. How many grills does the restaurant need?
(b) The owners can replace the current grills with a new model that can cook three hamburgers per minute where each new grill costs $1500. Alternatively, the restaurant can buy supergrills that cook seven hamburgers per minute where each costs $3300. Which one of the new grills is the better alternative?
(c) If demand is increased to 800 hamburgers per hour, does your answer to part (b) change? Explain why.

8.3 Suppose a computer company can internally produce processors for $10 per processor, but this requires some initial investment in setting up the system. An outside vendor can make the same processor for $13 per processor. If the company needs to produce 6000 processors, what is the maximum amount of investment the company should be willing to spend to produce the product internally (instead of outsourcing).

8.4 An electric company can make its own oscillating fans for $4.50 per unit after making an $1800 investment. An outside vendor will make the oscillating fans for $5.25 per unit.

(a) What is the break-even quantity of oscillating fans for the company?
(b) Show this result graphically

Machining Optimization (Section 1.9)

9.1 A cutting tool life is 40 min if the cutting speed is 120 in. /min; its life is 60 min if the cutting speed is 100 in./min

(a) What is the tool life equation for this tool?
(b) What is the tool life if the cutting speed is 110 in./min?
(c) What cutting speed will result in a tool life of 30 min?

9.2 Consider Taylor's equation where $n = 0.40$ and $C = 50$.

(a) What cutting speed should be used to have a tool life of 70 min?
(b) What is the tool life if the cutting speed is 15 in./min?

9.3 Consider the following equations for cost and production time.

$$f_1(v) = 5 + 220v^{-1} + 0.134v^{0.678} \qquad \text{production cost}$$
$$f_2(v) = 1.7 + 40v^{-1} + 0.0103v^{0.678} \qquad \text{production time}$$

(a) Find the multicriteria alternatives for speeds of 100, 125, 150, 175, and 200.
(b) Identify efficient and inefficient alternatives.

9.4 Consider the following tool life equation:

$$vt^{0.4} = 50$$

Suppose the minimum cutting speed is 80 in./min and the maximum cutting speed is 120 in./min. The total production time is 100 h, the total cutting length per part is 40 in., and the cost to replace each tool is $16.

(a) Generate five equally distributed alternatives based on cutting speed.

(b) Measure total cost and total productivity for each alternative.

(c) Identify inefficient and efficient alternatives. Show the multicriteria alternatives graphically.

9.5 Consider the following tool life equation:

$$vt^{0.65} = 24$$

Suppose the minimum cutting speed is 20 in./min and the maximum cutting speed is 28 in./min. The total production time is 80 h, the total cutting length per part is 20 in., and the cost to replace each tool is $6. Respond to parts (a), (b), and (c) of exercise 9.4.