APPLIED OPERATIONS MANAGEMENT: MANAUFACTURING AND SERVICES

PREFACE

Applied Operations Management provides a clear and concise introduction to *operations management,* which involves the planning, coordinating, and executing of all activities that create goods or services. The course *operations management* is offered in a variety of titles including *production/operations management*, *analysis for production systems*, *design and engineering of production systems*, etc.

This course focuses on the fundamentals and essentials needed to understand how operations strategies are carried out and they are tackled using new concepts and tools. It illustrates decisions with many solved problems to test and help students reinforce their understanding of the subject. It covers many application-oriented problems that help readers to relate, to integrate, to discover, and, in general, to gain useful insights. Further, many business professionals can benefit from this up-to-date course containing the latest techniques and methods.

The course presents, in an integrated fashion, much of the material covered in the exams leading to professional status as a Certified Production and Inventory Manager (CPIM). The CPIM exams and certification are administered by the American Production and Inventory Control Society (APICS).

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CHAPTER 1
WHAT IS PRODUCTION /OPERATIONS MANAGEMENT?

LEARNING OBJECTIVES:
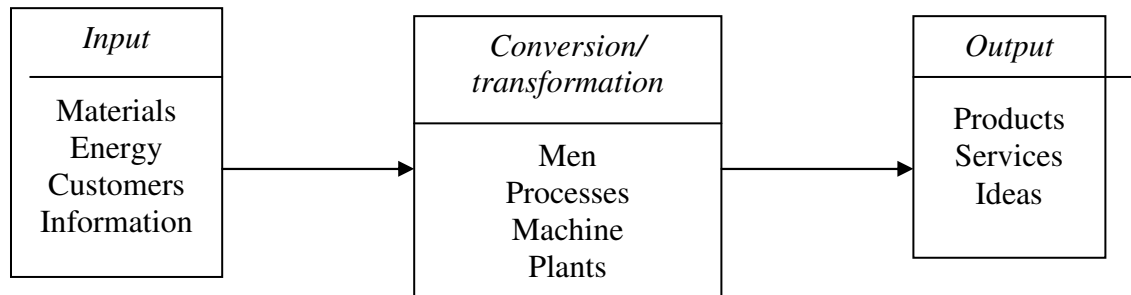
After studying this chapter you will be able to:

1. Define *operations.*
2. Define the term *production and operations management*
3. Compare service and manufacturing.
4. Discuss what operation strategies consist of.
5. Outline a production system.
6. Formulate a guideline to increase productivity.
7. Implement a process for quality control.
8. Construct a quality circle.
9. Discuss the concept of *continuous improvement (CI).*
10. Improve quality costs.
11. Explain the ISO-9000 Series Standards.
12. Diagram a fishbone diagram.
13. Explain and initiate The 5W2H approach
14. Describe the Deming Prize.
15. Explain the Taguchi quality loss function.
16. Establish benchmarking.
17. Distinguish between Total Quality Management (TQM) and Business Process Reengineering (BPR)

The term *production* typically means factories, machinery, and equipment. The subject of what has been known as *production management* has expanded in scope to cover management of service or nonmanufacturing activities such as insurance, banking, hotel management, transportation, and education. Because of this wide scope, the field has taken a new designation, *production/operations management (POM)* or simply *operations management (OM).*

Production/operations is the process by which goods and services are created. We find productive processes in all kinds of organized activities, as in factories, offices, supermarkets, schools, and hospitals. POM or OM deals with decision making related to productive processes to ensure that the resulting goods or services are produced according to specifications, in the amounts and by the schedule required, and at minimum cost. Inputs of materials, labor, and resources are used to obtain goods or services using one or more conversion/transformation processes, thereby adding value. Figure 1 depicts this process.

FIGURE 1

THE TRANSFORMATION OF INPUTS TO OUTPUTS

Input	*Conversion/ transformation*	*Output*
Materials Energy Customers Information	Men Processes Machine Plants	Products Services Ideas

Operations management begins with high-level business plans and strategies, short-run and long-run. These plans and strategies are based on careful and sound projection of demand for the product or service. Operating plans are derived from the long-term or short-term strategy and are translated into master schedules, which, in turn, form production and purchasing plans. Production planning and material control interact continuously with manufacturing in the execution of the plan. Finished goods are distributed geographically as required by the markets served by the business.

OM is divided broadly into the following four sections:

1. Decision Making Tools and Demand Management

2. Planning Systems
   - Capacity Planning
   - Aggregate Production Planning and Master Scheduling
   - Facility Location Planning

3. Operating and Controlling the System
   - Inventory Management and Material Requirement Planning
   - Project Management and Control
   - Scheduling
   - Waiting Lines and Queuing
   - Quality Control and Continuous Improvement

4. Designing Systems
   - Product/Service Design and Process Selection

- Facilities Positioning
- Design of Work Systems

GENERAL DESCRIPTION OF PRODUCTION AND OPERATIONS SYSTEMS

Production/operations systems have inputs, which represent the material, parts, paperwork, forms, customers, and patients, as the case may be. These inputs are processed in some way by a series of operations whose sequence and number are specified for each input. The number of operations required may vary from one to any number and may take on any desired characteristics; that is, they may be mechanical, chemical, assembly, inspection and control, dispatching, receiving, shipping, personal contact, such as an interview, and paperwork operations.

The outputs of a production system are completed parts, products, chemicals, service to customers or patients, completed paperwork, etc. There is normally provision for storage after the receipt of the input and between each operation in the system. The storage time may vary from zero to any finite value. Inputs are transported between all operations in the system, and any means of transportation may be used, including self-transportation in the case of clients and customers. An information system and decision maker interconnects the physical activities and provides a basis for management decisions. These functions provide the equivalent of a "nervous system." Such production systems may occur in series or in parallel.

CONTINUOUS VERSUS INTERMITTENT SYSTEMS

Continuous flow production systems are those where the facilities are standardized as to routings and flow since the inputs are standardized. Therefore, a standard set of processes and sequence of processes can be adopted. Continuous systems are represented in practice by production and assembly lines, large-scale office operations processing forms by some standard procedure, continuous flow chemical operations, etc.

Intermittent production systems are those where the facilities must be flexible enough to handle a wide variety of products and sizes or where the basic nature of the activity imposes change of important characteristics of the input (change in product design). In such instances there is no single sequence pattern of operations which is appropriate, so the relative location of the process centers or departments must be a compromise that is satisfactory for all inputs considered together. Transportation facilities between operations must also be flexible to accommodate a wide variety of input characteristics as well as a wide variety of routes through the system. Intermittent systems are called such because the flow is intermittent.

PRODUCTION OF PRODUCTION SYSTEMS

The problems which occur in production systems require two major types of decisions: those that relate to the design of the systems and those that relate to the operation and control of the systems (short-run and long-run decisions).

Short-run decisions related to operation and control:
- Inventory and production control.

- Maintenance and reliability of the system.
- Quality control.
- Labor control.
- Cost control and improvement.

Long-run decisions related to system design:
- Selection and design of inputs (products).
- Selection of equipment and processes.
- Production design of items processed. (Production cost interacts strongly with the design of the item being processed.)
- Job design.
- System location.
- Facility layout.

The relative importance of these problems of production management varies considerably, depending on the nature of individual production systems. Nonetheless, each system has these problems to some degree. Part of the art of production management involves sensing the relative importance of the various problems in a given situation.

MANUFACTURING OPERATIONS VERSUS SERVICE OPERATIONS
Distinction between manufacturing and service operations is based on the following features:

- The nature and consumption of output.
- Nature of work (jobs).
- Degree of consumer contact.
- Uniformity of output.
- Quality assurance.
- Measurement of performance.

Table 1 provides an overview of the different manufacturing and service operations.

TABLE 1
DIFFERENCES BETWEEN MANUFACTURING AND SERVICE OPERATIONS

Characteristic	*Manufacturing*	*Service*
Output	Tangible	Intangible
Consumer contact	Low	High
Nature of work	Capital intensive	Labor intensive
Uniformity of output	High	Low
Difficulty of quality assurance	Low	High
Measurement of performance	Easy	Difficult

OPERATIONS STRATEGY

Operations strategy is concerned with setting broad policies and plans for using the production resources of the firm to best support the firm's long-term competitive strategy. Typical operations strategy issues include

- Capacity requirements: amount, timing, and type.
- Facilities: size, location, and specialization.
- Technology: equipment, automation, and linkages.
- Vertical integration: extent of use of outside suppliers.
- Workforce: skill level, wage policies, employment security.
- Quality: defect prevention, monitoring, and intervention.
- Production planning/materials control: sourcing policies, centralization, decision rules.
- Organization: structure, control/reward systems, role of staff groups.

Each of these issues is discussed in detail in later chapters.

Four basic operations strategies were identified: cost, quality, speed of delivery, and flexibility. These four strategies translate directly into characteristics used to direct and measure manufacturing performance.

COST

Within every industry, there is usually a segment of the market that buys strictly on the basis of low cost. To successfully compete in this niche, a firm must be the low-cost producer. But even doing this does not always guarantee profitability and success. Products sold strictly on the basis of cost are typically commodity-like in nature. In other words, customers cannot distinguish the products of one firm from those of another. As a result, customers use cost as the primary determinant for making a purchase. However, this segment of the market is frequently very large and many companies are lured by the potential for significant profits, which they associate with the large unit volumes of product. As a consequence, competition in this segment is fierce—and so is the failure rate. After all, there can only be one low-cost producer, which usually establishes the selling price in the market.

QUALITY

Quality can be divided into two categories: product quality and process quality. The level of quality in a product's design will vary as to the market segment it is aimed for. Obviously, a child's first two-wheel bicycle is of significantly different quality than the bicycle of a world-class cyclist. One advantage of offering higher-quality products is that they command higher prices in the marketplace. The goal in establishing the proper level of product quality is to focus on the requirements of the customer. Overdesigned products with too much quality will be viewed as being prohibitively expensive. Underdesigned products, on the other hand, will lose customers to products that cost a little more but are perceived by the customers as offering much greater benefits. Process quality is critical in every market segment. In general, customers want products without defects. Thus, the goal of process quality is to produce error-free products through *total quality management (TQM).*

SPEED OF DELIVERY

Another market niche considers speed of delivery to be an important determinant in its purchasing decision. Here, the ability of a firm to provide dependable and fast delivery allows it to charge a premium price for its products.

FLEXIBILITY

Flexibility, from a strategic perspective, refers to the ability of a company to offer a wide variety of products to its customers. Flexibility is also a measure of how fast a company can convert its process(es) from making an old line of products to producing a new product line. Product variety is often perceived by the customer to be a dimension of' speed of delivery.

PRODUCTIVITY

Productivity is a ratio of outputs to inputs. Productivity can be expressed on *a partial factor basis* or on a *total factor* basis. Total factor productivity is the ratio of outputs to all inputs.

$$\text{Productivity} = \frac{\text{Outputs}}{\text{Labor} + \text{Capital} + \text{Materials} + \text{Energy}}$$

Outputs relative to one, two, or three of these inputs labor, capital, materials, or energy-- are *partial* measures of productivity. Output per labor hour, often called *labor productivity or labor efficiency*, use probably the most common partial measure of productivity. Productivity measures are relative measures. To be meaningful, it needs to be compared with something else such as similar operations within its industry or over time within the same operation.

EXAMPLE 1

Given output in finished units = $10,000 and inputs = $9,000 broken down into: labor = $3,000, materials = $200, capital = $5,000, and energy = $800

Then Total measure: Output/input = $10,000/$9,000 = 1.11

Multifactor measures:
Output/(labor + material) = $10,000/($3,000 + $200) = 3.13
Output/(labor + material + capital) = $10,000/($3,000 + $200 + $5,000) = 1.22

Partial measures:
Output/labor = $10,000/$3,000 = 3.33
Output/energy = $10,000/$800 = 12.5

NOTE:
The terms *productivity, efficiency*, and *performance* are terms used interchangeably.

Table 2 presents some examples of partial productivity measures.

TABLE 2
SOME EXAMPLES OF PARTIAL PRODUCTIVITY MEASURES

Business	*Productivity Measure*
Retail business	Sales per square foot
Utilities	Kilowatts per ton of coal
Lumber mill	Board feet per cord of wood
Restaurant	Customers per labor hour

TOTAL QUALITY MANAGEMENT AND QUALITY COSTS

In order to be globally competitive in today's world-class manufacturing environment, firms place an increased emphasis on quality and productivity. Total quality management (TQM) is an effort in this direction. Simply put, it is a system for creating competitive advantage by focusing the organization on what is important to the customer. Total quality management can be broken down into: "Total": that is the whole organization is involved and understands that customer satisfaction is everyone's job. "Quality": the extent to which products and services satisfy the requirements of internal and external customers. "Management": the leadership, infrastructure and resources that support employees as they meet the needs of those customers.

QUALITY DEFINED

A quality product or service is one that conforms to customer satisfaction. Generally, there are two types of product quality — quality of design and quality of conformance. Quality of design measures the functionality of a product or service. It is the decision of a designer to include or exclude certain features from a product. It is really measured by the customer through appearance, operation, and reliability. Quality of performance measures how closely products and services match the intent of the design. This traditionally has been the focus of a quality management program. In this regard, quality refers to doing it right the first time.

TOTAL QUALITY MANAGEMENT (TQM)

TQM is supported by two key beliefs that quality is what the customer says it is, and that it must be thoroughly integrated into the very fabric of the organization, including its basic strategies, culture, and management systems. It is essentially an endless quest for perfect quality. It is a *zero-defects* approach. It views the optimal level of quality costs as the level where zero defects are produced. This approach to quality is opposed to the traditional belief, called *acceptable quality level (AQL)*, which allows a predetermined level of defective units to be produced and sold. AQL is the level where the number of defects allows for the minimization of total quality costs. The rationale behind the traditional view is that there is a tradeoff between prevention and appraisal costs and failure costs. As you increase prevention and appraisal costs, you expect to see failure costs decrease.

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Figure 2 graphically illustrates the relationship between these two cost components under two different views.

Studies indicate that the total cost of poor quality, or the cost of not doing the right things right the first time, is 20 percent of gross sales for manufacturing companies and 30 percent for service industries. If U.S. production of goods and services is estimated at $4.5 trillion, then the potential for savings from improved quality is a staggering almost $1 trillion that can be saved or redirected for better use. Quality experts maintain that the optimal quality level should be about 2.5% of sales. The accounting department should be a major force in the firm that keeps track of and reports on quality costs.

PRINCIPLES OF TQM

Making a product right the first time is one of the principal objectives of TQM. Implementing a successful TQM program will in fact reduce costs rather than increase them. There is no question that better quality will result in better productivity. This is based on the principle that when less time is spent on rework or repair, more time is available for manufacturing, which will increase productivity.

When an organization maintains accurate records of its cost of quality, TQM will demonstrate that effective quality assurance geared towards prevention versus correction will pay for itself. A good example of this is the situation where it is possible to eliminate 100% inspection with a good statistical process control (SPC) program. Elimination of high reject rates results in fewer products being repaired, reworked or scrapped with the obvious reductions in cost.

Tying the cost of quality to TQM is necessary in order to motivate management who is cost motivated in both industry and government. In a TQM environment, management will start utilizing the cost data to measure the success of the program. The corporate financial planner can determine that overall product costs are being reduced by the TQM program. Given this success in the prevention of defects, the following failure costs will be reduced or eliminated:

1. Rework or repair
2. Inspection of rework
3. Testing of rework
4. Warranty costs
5. Returned material
6. Discounts, adjustments and allowances

It is quite obvious that the cost of prevention in TQM is minor when taken against the above listed failure costs.

FIGURE 2

TRADITIONAL VIEW VERSUS WORLD-CLASS VIEW
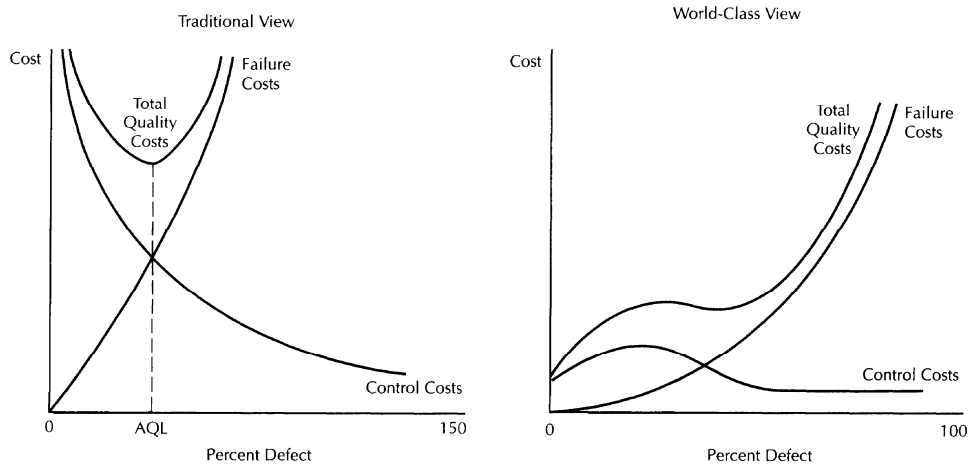
A checklist of TQM features follows:

.A systematic way to improve products and services
.A structured approach in identifying and solving problems
.A long-term method of quality control
.A process supported by management's actions
.A process that is supported by statistical quality control
.A technique that is practiced by everyone

ELEMENTS OF TQM

The principle elements of TQM are straightforward and embrace a common-sense approach to management. However, each of the individual elements must be integrated into a structured whole to succeed. The elements are as follows:

1. A Focus on the Customer

Every functional unit has a customer, whether it be an external consumer or an internal unit. TQM advocates that managers and employees become so customer-focused that they continually find new ways to meet or exceed customers' expectations. We must accept the

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concept that quality gets customer order and meets the customer's needs and expectations. This is the strategic goal of TQM.

2. A Long Term Commitment

Experience in the U.S. and abroad shows that substantial gains come only after management makes a long-term commitment, usually five years or more, in improving quality. Customer-focus must be constantly renewed to keep that goal foremost.

3. Top Management Support and Direction

Top management must be the driving force behind TQM. Senior managers must exhibit personal support by using quality improvement concepts in their management style, incorporating quality in their strategic planning process, and providing financial and staff support.

4. Employee Involvement

Full employee participation is also an integral part of the process. Each employee must be a partner in achieving quality goals. Teamwork involves managers, supervisors, and employees in improving service delivery, solving systemic problems, and correcting errors in all parts of work processes.

5. Effective and Renewed Communications

The power of internal communication, both vertical and horizontal, is central to employee involvement. Regular and meaningful communication from all levels must occur. This will allow an agency to adjust its ways of operating and reinforce the commitment of TQM at the same time.

6. Reliance on Standards and Measures

Measurement is the springboard to involvement, allowing the organization to initiate corrective action, set priorities and evaluate progress. Standards and measures should reflect customer requirements and changes that need to be introduced in the internal business of providing those requirements. The emphasis is on "doing the right thing right the first time."

7. Commitment to Training

Training is absolutely vital to the success of TQM. The process usually begins with awareness training for teams of top level managers. This is followed by courses for teams of mid-level managers, and finally by courses for non-managers. Awareness training is followed by an identification of areas of concentration, or of functional areas where TQM will first be introduced. Implementing TQM requires additional skills training, which is also conducted in teams.

8. Importance of Rewards and Recognition

Most companies practicing TQM have given wide latitude to managers in issuing rewards and recognition. Here, a common theme is that individual financial rewards are not as appropriate as awards to groups or team members, since most successes are group achievements.

COSTS OF QUALITY

Market shares of many U.S. firms have eroded because foreign firms have been able to sell higher-quality products at lower prices. In order to be competitive, U.S. firms have placed an increased emphasis on quality and productivity in order to:

     1. produce savings such as reducing rework costs, and
     2. improve product quality

     Studies indicate that costs of quality for American companies are typically 20-30% of sales. Quality experts maintain that the optimal quality level should be about 2.5% of sales.

     Costs of quality are costs that occur because poor quality may exist or actually does exist. More specifically, quality costs are the total of the costs incurred by (1) investing in the prevention of nonconformance to requirements; (2) appraising a product or service for conformance to requirements; and (3) failure to meet requirements.

     Quality costs are classified into three broad categories: prevention, appraisal, and failure costs. *Prevention costs* are those incurred to prevent defects. Amounts spent on quality training programs, researching customer needs, quality circles, and improved production equipment are considered in prevention costs. Expenditures made for prevention will minimize the costs that will be incurred for appraisal and failure. *Appraisal costs* are costs incurred for monitoring or inspection; these costs compensate for mistakes not eliminated through prevention. *Failure costs* may be *internal* (such as scrap and rework costs and reinspection) or *external* (such as product returns due to quality problems, warranty costs, lost sales due to poor product performance, and complaint department costs).

TWO DIFFERENT VIEWS CONCERNING OPTIMAL QUALITY COSTS

There are two views concerning optimal quality costs:
    1.   the traditional view that uses an acceptable quality level
    2.   the world-class view that uses total quality control

Optimal Distribution of Quality Costs: Traditional View

The traditional approach uses an acceptable quality level (AQL) that permits a predetermined level of defective units to be produced and sold. AQL is the level where the number of defects allowed minimizes total quality costs. The reasoning of the traditional approach is that there is a tradeoff between failure costs and prevention and appraisal costs. As prevention and appraisal costs increase, internal and external failure costs are expected to decrease. As long as the decrease in failure costs is greater than the corresponding increase in prevention and appraisal costs, a company should continue increasing its efforts to prevent or detect defective units.

Optimal Distribution of Quality Costs: World-Class View

The world-class view uses total quality control and views the optimal level of quality costs as the level where zero defects are produced. The zero-defects approach uses a quality performance standard that requires:

1.   all products to be produced according to specifications and
2.   all services to be provided according to requirements

Zero defects reflects a total quality control philosophy used in just-in-time (JlT) manufacturing.

NOTE:
Quality refers to doing it right the first time. TQM is a system for creating competitive advantage by focusing on what is important to the customer. It can be broken down into: "Total": that is the whole organization is involved and understands that customer satisfaction is everyone's job. "Quality": the extent to which products and services satisfy the requirements of internal and external customers. "Management": the leadership, infrastructure and resources that support employees as they meet the needs of those customers.

Quality cost reports can be used to point out the strengths and weaknesses of a quality system. Improvement teams can use them to describe the monetary benefits and ramifications of proposed changes. Return-on-investment (ROI) models and other financial analyses can be constructed directly from quality cost data to justify proposals to management. In practice, quality costs can define activities of quality program and quality improvement efforts in a language that management can understand and act on -- dollars.

The negative effect on profits, resulting from product or service of less than acceptable quality or from ineffective quality management, is almost always dynamic. Once started, it continues to mushroom until ultimately the company finds itself in serious financial difficulties due to the two-pronged impact of an unheeded increase in quality costs coupled with a declining performance image. Management that clearly understands this comprehends the economics of quality.

CONTINUOUS IMPROVEMENT

Continuous improvement (CI) is a management philosophy that seeks endless pursuit of improvement of machinery, materials, labor utilization, and production methods through application of suggestions and ideas of team members. The need for continuous improvement within companies has come about because

- Global development and more open trade have resulted in more companies with which each company must compete.
- The companies with which a company has competed have become better.
- Customer expectations have increased.

The CI utilizes many different approaches, including:

1. 5W2H (5 whys, 2 hows) approach: asking various questions about the current process and how it can be improved.

2. Statistical process control: using traditional statistical control charts, which is covered in depth in Chapter 14.

3. *Pareto* analysis: focusing attention on the most important problem areas. It is based on the concept that about 80 percent of the problems come from 20 percent of the items.

4. PDCA (*p*lan-*d*o-*c*heck-*a*ct) cycle: a framework for improvement activities.

5. Quality circles: tapping employees for ideas concerning quality and productivity improvement. The circles are a voluntary group of workers who meet regularly to identify and solve problems of quality and productivity.

6. *Fishbone* (or *Ishikawa*) diagrams: identifying potential causative factors for the problem areas. They use a chart resembling the skeleton of a fish in which the spine bone represents the major cause of quality problems and connecting bones, contributing causes, revealing cause-effect linkages. This a tool that is most useful in brainstorming to the root cause of a problem.

7. *Benchmarking*. Examining excellent performers outside the industry and seeing how you can use their best practices. Benchmarking typically involves the following steps:
   (a) Identify those practices needing improvement.
   (b) Identify a company that is the world leader in performing the process.
   (c) Interview the managers of the company and analyze data obtained.

QUALITY CERTIFICATIONS, REGISTRATIONS, AND AWARDS
In order to recognize a variety of achievements in quality assurance, there are different types of certifications, registrations, and awards.

Supplier Certification
Your suppliers are an important part of your process. Firms using TQM soon learn that they need much better suppliers. They wish to use more suppliers that are "certified" by setting very rigorous certification standards, and provide help and training in how to achieve those standards. The reward to the supplier is a much larger and stable volume of business with the customer. A secondary reward is that they become better suppliers to their other customers.

ISO-9000 Series Standards
ISO-9000 is a series of quality standards, which the European Community (EU) has adopted for producers worldwide.

Quality Awards
Beyond supplier certification and ISO-9000, prestigious awards have been developed for outstanding achievement in TQM:
   (a) Deming Prize—Japan (named after W. Edwards Deming)
   (b) Malcolm Baldrige National Quality Award—U.S.
   (c) Canada Awards for Business Excellence—Canada

TAGUCHI METHOD OF QUALITY CONTROL

Taguchi method of quality control is a method of controlling quality, developed by Genich Taguchi, a past winner of the Deming Award, that emphasizes robust quality design and the *quality loss function* (QLF). Taguchi claims that quality is greatly determined at the design level. In addition to quality control in production, he emphasizes quality control in four other functions: (1) product planning, (2) product design, (3) process design, and (4) production service after purchase. Further, Taguchi's QLF quantitatively measures the success or failure of quality control. The traditional view is that any product that measures within the upper and lower specification limits is "good," and a product outside the limits is "bad." In contrast, the QLF presumes that *any* deviation from the target specification is important since it means economic losses for the customer. Furthermore, the economic losses increase quadratically as the actual value deviates from the target value. The QLF can be described by the following equation:

$$L(y) = k(y - T)^2$$

where   L = Quality loss
          y = Actual value of quality characteristic
          k = A proportionality constant dependent upon the firm's external failure cost structure.
          T = Target value of quality characteristic

EXAMPLE 2

Davidson Company has decided to estimate its quality loss using the Taguchi loss function. After some study, it was determined that $k = \$400$ and $T = 10$ inches in diameter. Table 3 illustrates the computations of the quality loss for a sample of 4 units.

TABLE 3
QUALITY-LOSS COMPUTAUION

Unit	Actual Diameter (y)	y – T	$(y - T)^2$	$k(y - T)^2$
1	9.9	-0.10	0.010	$4.00
2	10.1	0.10	0.010	4.00
3	10.2	0.20	0.040	16.00
4	9.8	-0.20	0.040	16.00
Total			0.100	$40.00
Average			0.025	$10.00

Note that the average loss per unit is $10. The total expected loss for, say, 1,000 units would be $10,000 ($10 x 1,000 units).

BUSINESS PROCESS REENGINEERING (BPR)

TQM seeks evolutionary changes in the processes while the practice *called business process reengineering (BPR)* seeks to make revolutionary changes. BPR does this by taking a fresh look at what the firm is trying to do in all its processes, and then eliminating nonvalue-added steps and computerizing the remaining ones to achieve the desired outcome.

SUPPLY CHAIN MANAGEMENT

To remain competitive, companies are continually faced with challenges to reduce product development time, improve product quality, speed delivery time to customers, and reduce production costs and lead times. Increasingly, these challenges cannot be effectively met by isolated change to specific organizational units, but instead depend critically on the relationships and interdependencies among different firms (or subunits).

With the movement toward a global market economy, companies are increasingly inclined toward specific, high-value-adding manufacturing niches. This, in turn, increasingly transforms the above challenges into problems of establishing and maintaining efficient material flows along product supply chains. The ongoing competitiveness of a company is tied to the dynamics of the supply chain(s) in which it participates, and recognition of this fact is leading to considerable change in the way organizations interact with their supply chain partners.

AGILE TECHNOLOGY

Strategic planning has traditionally relied on forecasts of market conditions and customer needs. But in today's uncertain business environment, it is difficult for companies to look far into the future. Instead, they have to spot trends early and respond more quickly than competitors to opportunities and threats.

The "Sense-and-Respond" Model — A New Operating Model
The logic of "make-and-sell" still dominates the thinking of large industrial groups. It assumes that competitive advantage comes from economies of scale, that customer needs can be predicted and even influenced by the company, and that operations should be designed to maximize efficiency and utilization of fixed assets.

The make-and-sell model works well when markets are stable and change is slow. However, when change is rapid and markets are volatile, companies need a different operating model that values flexibility over efficiency and speed over scale. This "sense-and-respond" model is about anticipating customer needs and swiftly responding with the appropriate capabilities and customer offerings. This creates a "unique value proposition" of rapid response and reliable delivery times that gives it an edge over competitors.

Modularity and Agility
How does a company become agile without destroying its scale advantages? In the make-and-sell model, variety is an evil because choice is the enemy of scale. Customers now demand variety but this comes at a cost. So how can a company become agile without compromising its cost position? The key is modularity of products and information technology systems, and decoupling of business processes and value chains.

To increase the agility of offerings, companies are embracing modularity in their product platforms, which allows them to create a diverse array of products with a relatively small number of components and sub-systems.

Business processes can also be made more agile and more effective by decoupling the front-end of the business process (the end closer to customers and markets) from the back-end of

the business process (the back-office processes that support the front-end). The back-end can then be centralized to create shared services, and it can also be relocated to places where resources are more cost-effective.

Companies that have learned to exploit technology can respond more flexibly than competitors to new trends and threats.

- A "sense-and-respond" organizational model has replaced a "make-and-sell" model at cement companies, which tracks deliveries via satellite to increase efficiency.
- Modularity increases the diversity of products, while limiting the components. Nissan shares engine components across a broad range of vehicles.
- Leaders of agile businesses must cope with letting go of outsourced operations while managing across borders.

QUESTIONS

1. What is production/operations?
2. What factors distinguish between production and service operations?
3. What are the major decision areas in P/OM?
4. What are the major components of a production system? Give two examples.
5. List four basic operations strategies.
6. Explain the difference between total and partial productivity.
7. What is *continuous improvement* (CI)? What are the major tools for this philosophy?
8. How does productivity measurement differ between manufacturing and service operations?
9. Contrast the world class view with the traditional view in quality control.
10. List the types of quality costs.
11. Describe *total quality management* (TQM).
12. What is ISO-9000 Series Standards? List key quality awards.
13. What is the logic of Taguchi methods?

PROBLEMS

1. Donovan Furniture Company provided the following data. Compare the labor, materials, and total productivity of 20X1 and 20X2.

		20X1	*20X2*
Output:	Sales	$22,000	$35,000
Inputs:	Labor	10,000	15,000
	Materials	8,000	12,500
	Capital equipment	700	1,200
	Energy	2,200	4,800

2. Identify specific productivity and quality measures that would be useful in each of the following operations:
   (a) bus system
   (b) department store
   (c) post office
   (d) hotel

ANSWERS

1. Production/operations is the process by which goods and services are created.
2. Distinction between manufacturing and service operations is based on the following features: the nature and consumption of output; nature of work (jobs); degree of consumer contact; uniformity of output; quality assurance; measurement of performance.
3. Major decision areas in P/OM include: capacity planning, aggregate production planning and master scheduling, locational planning, material requirement planning and inventory management, project management and control, scheduling, queuing, quality assurance, product and service design, facilities layout, design of work systems
4. The major components of the production system are inputs, a conversion or creation process, and outputs. Examples are as follows:

System	Inputs	Conversion Process	Outputs
Auto assembly plant	Labor Energy Robots Parts	Welding Manual assembly Painting	Automobiles
Hospital	Patients Staff Beds Drugs Medical equipment Doctors	Operations Drug administration Health-status monitoring	Healthy individuals Lab results

5. Four basic operations strategies are: cost, quality, speed of delivery, and flexibility.
6. Total productivity is the ratio of total output to all resources used in production: labor, capital, material, management, energy, while partial productivity centers on only a single or a subset of these input variables.
7. Continuous improvement (CI) is a management philosophy that seeks endless pursuit of improvement of machinery, materials, labor utilization, and production methods through application of suggestions and ideas of team members. The CI utilizes two major approaches:
   Internal tools. Using very structured programs such as Statistical Process Control (SPC)
   Benchmarking. Examining excellent performers outside the industry and seeing how you can use their best practices.

8. In manufacturing, physical input and outputs are easy to identify and quantity. For services, intangibles such as health, social benefits, and customer satisfaction are more difficult to define and measure. Quality measures such as waiting time per patient and response to treatment are often used as surrogates.

9. The traditional approach uses an *acceptable quality level* (AQL) that permits a predetermined level of defective units to be produced and sold, whereas the world-class view uses total quality control and views the optimal level of quality costs as the level where zero defects are produced.

10. Quality costs are classified into three broad categories: prevention, appraisal, and failure costs.

11. Total quality management (TQM) is a system for creating competitive advantage by focusing the organization on what is important to the customer. Total quality management can be broken down into: "Total": that is the whole organization is involved and understands that customer satisfaction is everyone's job. "Quality": the extent to which products and services satisfy the requirements of internal and external customers. "Management": the leadership, infrastructure and resources that support employees as they meet the needs of those customers.

12. They are Deming Prize—Japan (named after W. Edwards Deming); Malcolm Baldrige National Quality Award—U.S.; Canada Awards for Business Excellence—Canada.

13. The Taguchi method focuses on assuring quality through proper process and product design. Taguchi views any deviation from the "ideal quality" as a loss to society. Taguchi emphasizes minimization of variability in processes and robust design.

SOLUTIONS TO PROBLEMS

1.

	20X1	20X2
Partial productivities:		
Labor	2.20	2.33
Materials	2.75	2.80
Total productivity	1.05	1.04

2.
    (a) bus system: passengers per route, percent on schedule
    (b) department store: sales per week, mistagged merchandise
    (c) post office: delivery days per letter, percent lost items
    (d) hotel: rooms cleaned, complaints per guest

CHAPTER 2
TOOLS FOR DECISION MAKING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Outline the steps in the decision making process.
2. Discuss a decision making under uncertainty.
3. Construct a decision matrix and a payoff table and use it to solve a problem.
4. Diagram a decision tree.
5. Explain and give examples of optimization models.
6. Describe the uses of statistical models.
7. Develop and implement a simulation model.
8. Develop and solve a linear programming (LP) model.

Operations managers are decision-makers. They may have to make choices among various alternatives. This chapter focuses on basic concepts of decision making, i.e.,

1. the types of decision making
2. the decision making process
3. the use of information systems for decision making
4. decision tools or models available to operations managers

DECISION MAKING UNDER UNCERTAINTY

The common basis for classifying a decision in decision theory is the amount of information available concerning the probability of occurrence of basic alternatives.

There are two major classes of decision problems in this structure: decision making under certainty and decision making under risk or under uncertainty. Decision making under certainty means that for each decision there is only one event and therefore only one outcome for each action. Decision making under risk or uncertainty, which is more common in reality, involves several events for each action with its probability of occurrence. The decision problem can best be approached using what is called *decision theory*. Decision theory is a systematic approach to making decisions especially under uncertainty.

The basic steps that are taken in any decision process include:

Step 1 Definition of the problem. When management concludes that a problem exists, it should prepare a specific definition or exact statement of the problem.

Step 2 Select a goal. The identification of problems as a gap between a desired result and a present or anticipated result indicates the importance of objectives or goals. Increased profits is an example of an operational goal.

Step 3 Identify any constraints. Management's choice is always limited to some extent by law, regulatory action, moral values, resources available, or management preferences. Any constraints which might exist need to be identified.

Step 4 Identify alternative courses of action. Once a problem has been defined, then the alternative actions that might be taken should be identified.

Step 5 Forecast the environmental conditions. The environmental conditions, or states of nature, should be estimated for each alternative course of action. The states of nature are the uncontrollable variables affecting the decision.

Step 6 Determine the potential outcomes or payoffs. The alternative courses of actions and the states of nature should be considered along with the relevant revenues and costs to determine the financial consequences of each alternative course of action, i.e., a decision matrix.

Step 7 Selections and application of decision rules. Once a payoff table has been constructed, the management accountant must apply a decision rule. A decision rule is a set of instructions for analyzing the data to choose a course of action which will meet the company's objectives. The decision rule to be applied is to select the course of action which maximized the expected monetary profit.

DECISION MATRIX

Decision theory utilizes an organized approach such as a *decision matrix* (or *payoff table*). It is characterized by:

(1) the *row* representing a set of alternative courses of action available to the decision maker;

(2) the *column* representing the state of nature or conditions that are likely to occur and the decision maker has no control over; and

(3) the *entries* in the body of the table representing the outcome of the decision, known as payoffs which may be in the form of costs, revenues, profits or cash flows. By computing expected value of each action, we will be able to pick the best one.

EXAMPLE 1
Assume the following probability distribution of daily demand for a product:

Daily demand	0	1	2	3
Probability	.2	.3	.3	.2

Also assume that unit cost =$3, selling price=$5 (i.e., profit on sold unit = $2), and salvage value on unsold units =$2 (i.e., loss on unsold unit =$1). We can stock either 0, 1, 2, or 3 units. The question is:

How many units should be stocked each day? Assume that units from one day cannot be sold the next day.

Then the payoff table can be constructed as follows:

State of Nature

Demand	0	1	2	3	Expected value
Stock (probability)	(.2)	(.3)	(.3)	(.2)	
0	$0	0	0	0	$0
Actions 1	-1	2	2	2	1.40
2	-2	1*	4	4	1.90**
3	-3	0	3	6	1.50

*Profit for (stock 2, demand 1) equals (no. of units sold)(profit per unit) - (no. of units unsold)(loss per unit) = (1)($5 - 3) - (1)($3 - 2)= $1

**Expected value for (stock 2) is: -2(.2) + 1(.3) + 4 (.3) + 4 (.2) =$1.90

The optimal stock action is the one with the highest expected monetary value i.e., stock 2 units.

<u>Expected Value of Perfect Information</u>

Suppose the decision maker can obtain a perfect prediction of which event (state of nature) will occur. The expected value with perfect information would be the total expected value of actions selected on the assumption of a perfect forecast. The expected value of perfect information can then be computed as:

Expected value with perfect information minus the expected value with existing information

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NOTE:

Decision making under uncertainty is a decision made when the state of nature is unknown and the probability of occurrence of the different states of nature is *unknown*. Common decision selection guides include:

(a) The *maxmax* criterion selects the alternative with the maximum possible monetary payoff. This is a criterion of extreme optimism.

(b) The *maxmin* is a more pessimistic criterion, under which you examine only the worst possible outcome of each act and select the alternative that will give the largest payoff if the worst circumstance occurs.

EXAMPLE 2
From the payoff table in Example 1, the following analysis yields the expected value with perfect information:

State of Nature

Demand	0	1	2	3	Expected value
<u>Stock</u>	(.2)	(.3)	(.3)	(.2)	
0	$0				$0

	Actions 1	2		0.6
	2		4	1.2
	3		6	1.2
				$3.00

Alternatively,

$$\$0 \,(.2) + 2\,(.3) + 4\,(.3) + 6\,(.2) = \$3.00$$

With existing information, the best that the decision maker could obtain was select (stock 2) and obtain $1.90. With perfect information (forecast), the decision maker could make as much as $3. Therefore, the expected value of perfect information is $3.00 - $1.90 = $1.10. This is the maximum price the decision maker is willing to pay for additional information.

> **NOTE:**
> The fact that you can forecast perfectly does not mean that you can control demand. It simply means that you have perfect knowledge of demand and you are right all the time so that you would make the best decision in each case.

DECISION TREE

Decision tree is another approach used in discussions of decision making under uncertainty. It is a pictorial representation of a decision situation. As in the case of the *decision matrix* approach discussed, it shows decision alternatives, states of nature, probabilities attached to the state of nature, and conditional benefits and losses. The decision tree approach is most useful in a sequential decision situation. The decision tree approach enjoys the following advantages:

(a) It structures the decision process, making use of decision making in an orderly, sequential fashion.
(b) It forces use to examine all possible outcomes.
(c) It communicates the decision making process to others.
(d) It allows a group to discuss alternatives one at a time.
(e) It can be used with a computer.

EXAMPLE 3
Assume XYZ Corporation wishes to introduce one of two products to the market this year. The probabilities and present values (PV) of projected cash inflows are given below:

Product	Initial investment	PV of cash inflows	Probabilities
A	$225,000		1.00
		$450,000	0.40
		200,000	0.50
		-100,000	0.10
B	80,000		1.00
		320,000	0.20

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100,000	0.60
-150,000	0.20

 • A decision tree analyzing the two products is given in Figure 1.

FIGURE 1

DECISION TREE

	Initial Investment (1)	Probability (2)	PV of Cash Inflows (3)	PV of Cash Inflows (2) X (3) = (4)
		0.40	$450,000	$180,000
	$225,000	0.50	$200,000	100,000
Product A		0.10	-$100,000	-10,000
			Expected PV of Cash Inflows	$270,000
Choice A or B				
Product B		0.20	$320,000	$64,000
	$80,000	0.60	$100,000	60,000
		0.20	-$150,000	-30,000
			Expected PV of Cash Inflows	$ 94,000

Based on the expected NPV, choose product A over product B. This analysis fails to recognize the risk factor in project analysis.

NOTE:
     Decision trees are a kind of road map of a decision problem that lays out in schematic form, the alternative decisions, events, and outcomes that face the decision maker.

MODELING A REAL LIFE SYSTEM
     Many decision making systems are model-based. The real world is complex, dynamic, and expensive to deal with. For this reason, we use models instead of real life systems. A model is an abstraction of a real life system that is used to simulate reality. Especially in a computing environment we live in, operations managers find use of models easy and less expensive to understand what is happening and to make better decisions.
     There are many different types of models. Common model types are briefly described below.

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NARRATIVE MODELS

A narrative model is either written or oral. The narrative represents a topic or subject. In an organization, reports, documents, and conversations concerning a system are all important narratives. Examples include the following: a salesperson verbally describing a product's competition to a sales manager, and a written report describing the function of a new piece of manufacturing equipment.

PHYSICAL MODELS

The fashion model is an example of physical models, as are dolls and model airplanes. Many physical models are computer designed or constructed. An aerospace engineer may develop a physical model of a shuttle to gain important information about how a large-scale shuttle might perform in space. A marketing department may develop a prototype of a new product.

GRAPHICAL MODELS

A graphical model is a pictorial representation of reality. Lines, charts, figures, diagrams, illustrations, and pictures are all types of graphical models. Graphical models assist decision makers in designing, developing, and using graphic displays of data and information. In addition, sophisticated graphic design and analysis such as computer-assisted design (CAD) is widely available. A graph that shows budget and financial projections and a break-even chart are good examples of graphic models.

MATHEMATICAL MODELS

A mathematical model is a quantitative representation of reality. These models are most popular for decision making in all areas of business. Any mathematical formula or equation is a model that can be used for simulation or "what-if" analysis purposes. Once properly constructed, management can experiment with them just as physical scientists do a controlled experiment in their laboratory. In a sense, mathematical models are the managers' laboratory.

STATISTICAL MODELS

Statistical models can be used to develop demand forecasts for capacity and production planning. Regression analysis is an example of statistical models. Other uses of statistical models in production and operations management are the techniques of work sampling and statistical quality control.

OPTIMIZATION MODELS

Optimization models refer to techniques for establishing complex sets of mathematical equations and inequalities that represent objectives and constraints. These models are "prescriptive" in that they try to provide the best possible solution to the problem at hand. They include mathematical programming such as linear programming (LP).

PROJECT PLANNING AND MANAGEMENT MODELS

Project planning and management models are used to navigate and coordinate large projects, and to discover critical paths that could delay or jeopardize an entire project if they are

not completed in a timely and cost-effective fashion. *Program Evaluation and Review Technique (PERT)* is widely used for this purpose.

SIMULATION MODELS

The primary use of a simulation model is to respond to "what if . . . " questions. These descriptive models can produce large amounts of detailed output because they work by mimicking many parts of the real-world system. One major weakness is that no automatic searching or optimizing is done by the model. (Any such features must be built on top of the simulation model and must be used as a submodel.) In such cases, the simulation may have to be performed many, many times while a search for the best decision parameters is under way. This can be quite expensive if the simulation is complex.

NOTE:
Simulation is descriptive while optimization models such as LP are prescriptive.

LINEAR PROGRAMMING

Linear programming (LP) is a mathematical technique designed to determine an optimal decision (or an optimal plan) chosen from a large number of possible decisions. The optimal decision is the one that meets the specified objective of the company, subject to various restrictions or constraints. It concerns itself with the problem of allocating scarce resources among competing activities in an optimal manner. The optimal decision yields the highest profit, contribution margin (CM), or revenue, or the lowest cost. A linear programming model consists of two important ingredients:

1. *Objective function*. The company must define the specific objective to be achieved.
2. *Constraints*. Constraints are in the form of restrictions on availability of resources or meeting minimum requirements. As the name linear programming indicates, both the objective function and constraints must be in *linear* form.

EXAMPLE 4

A firm wishes to find an optimal product mix. The optimal mix would be the one that maximizes its total profit or contribution margin (CM) within the allowed budget and production capacity. Or the firm may want to determine a least-cost combination of input materials while meeting production requirements, employing production capacities, and using available employees.

APPLICATIONS OF LP

Applications of LP are numerous. They include:
1. Selecting the least-cost mix of ingredients for manufactured products
2. Scheduling jobs to machines
3. Determining a least-cost shipping pattern
4. Scheduling flights
5. Gasoline blending
6. Optimal manpower allocation
7. Selecting the best warehouse location to minimize shipping costs.

FORMULATION OF LP
1. Decide what your variables should be-- units of some output commodity like widgets.
2. Decide whether you wish to maximize (e.g. profit) or minimize (e.g. cost), if information is given on both cost and revenue, you will generally wish to work with profit figures.
3. Construct an objective function as a sum of the variables times their respective unit profit or cost. Include all-variables.
4. Express the constraints as functions of the variables you choose. In how many ways can each particular type of capacity be used up? That is the number of variables which should appear in each constraint equation.
5. Beware of inequalities. If your constraint is not to exceed some amount of productive capacity or warehouse space, the appropriate constraint inequality is $\leq$. If you must satisfy some level of demand, the appropriate constraint Inequality is $\geq$.
6. Always include a statement that you cannot have negative production or shipments, i.e. all variables take on nonnegative values (≥ 0).

In the following example, we will use this technique to find the optimal product mix.

EXAMPLE 5
The Omni Furniture Manufacturing Company produces two products: desk and table. Both products require time in two processing departments, Assembly Department and Finishing Department. Data on the two products are as follows:

| | *Products* | | Available |
Processing	Desk	Table	Hours
Assembly	2	4	100 hours
Finishing	3	2	90
Profit per unit	$25	$40	

The company wants to find the most profitable mix of these two products.
Define the decision variables as follows:
x_1 = Number of units of desk to be produced
x_2 = Number of units of table to be produced

The objective function to maximize total profit (Z) is expressed as:
$Z = 25x_1 + 40x_2$

Then, formulate the constraints as inequalities:
$2x_1 + 4x_2 \leq 100$ (Assembly constraint)
$3x_1 + 2x_2 \leq 90$ (Finishing constraint)

In addition, implicit in any LP formulation are the constraints that restrict x_1 and x_2 to be nonnegative, i.e.,
$x_1, x_2 \geq 0$
Our LP model is:
Maximize: $Z = 25x_1 + 40x_2$
Subject to: $2x_1 + 4x_2 \leq 100$

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$$3x_1 + 2x_2 \leq 90$$
$$x_1, x_2 \geq 0$$

COMPUTATION METHODS OF LP

There are solution methods available to solve LP problems. They include:

1. The graphical method
2. The simplex method

The graphical solution is easier to use but limited to the LP problems involving two (or at most three) decision variables. The graphical method follows the steps:

Step 1: Change inequalities to equalities.
Step 2: Graph the equalities. To graph the equality, (1) set one variable equal to zero and find the value of the other and connect those two points on the graph and (2) mark these intersections on the axes and connect them with a straight line.
Step 3: Identify the correct side for the original inequalities by shading. Repeat steps 1-3 for each constraint.
Step 4: After all this, identify the feasible region, the area of *feasible solutions*.
Step 5: Solve the constraints (expressed as equalities) simultaneously for the various corner points of the feasible region.
Step 6: Determine the profit or contribution margin at all corners in the region.

NOTE:

Feasible solutions are values of decision variables that satisfy all the constraints simultaneously. They are found on and within the boundary of the feasible region. The graphical approach is based on two important LP properties:

1. The optimal solution lies on the boundary of the feasible region, which implies that one can ignore the (infinitely numerous) interior points of the feasible region when searching for an optimal solution.

2. The optimal solution occurs at one of the corner points (basic feasible solutions) of the feasible region.

EXAMPLE 6

Using the data and the LP model from Example 5, follow steps 1 through 6. We obtain the following feasible region (shaded area).

Step 1: Change inequalities to equalities.
$$2x_1 + 4x_2 = 100$$
$$3x_1 + 2x_2 = 90$$

Step 2: Graph the equalities. To graph the equality, set one variable equal to zero, find the value of the other, mark the points on the axes, and connect those two points with a straight line.

For equation 1: If $x_1=0$, $x_2=25$; if $x_2=0$, then $x_1=50$, connect $x_2=25$ and $x_1=50$.
For equation 2: If $x_1=0$, $x_2=30$; if $x_2=0$, then $x_1=45$, connect $x_2=30$ and $x_1=45$.

Step 3: Identify the correct side for the original inequalities. The correct side is the line and the area below it for less-than or equal-to constraints.

Step 4: After all this, identify the feasible region, the area of feasible solutions. The area of feasible solutions is the duplicated area as indicated by the shaded area in Figure 3.

Step 5: Solve the constraints (expressed as equalities) simultaneously for the various corner points of the feasible region.

Step 6: Determine the profit or contribution margin at all corners in the feasible region.
We evaluate all of the corner points as follows:

	Corner Points		*Profit*
	x_1	x_2	$\$25x_1 + \$40x_2$
(a)	30	0	$\$25(30) + \$40(0) = \$750$
(b)	20	15	$25(20) + 40(15) = 1{,}100$
(c)	0	25	$25(0) + 40(25) = 1{,}000$
(d)	0	0	$25(0) + 40(0) = 0$

The corner point (b) ($x_1 = 20$, $x_2 = 15$) produces the most profitable solution ($Z^* = \$1{,}100$). This point can be found by solving two equations that created it simultaneously, as shown below.

$$2x_1 + 4x_2 = 100 \qquad (1)$$
$$3x_1 + 2x_2 = 90 \qquad (2)$$

Multiplying the second equation (2) through by 2 and subtract from (1), we obtain
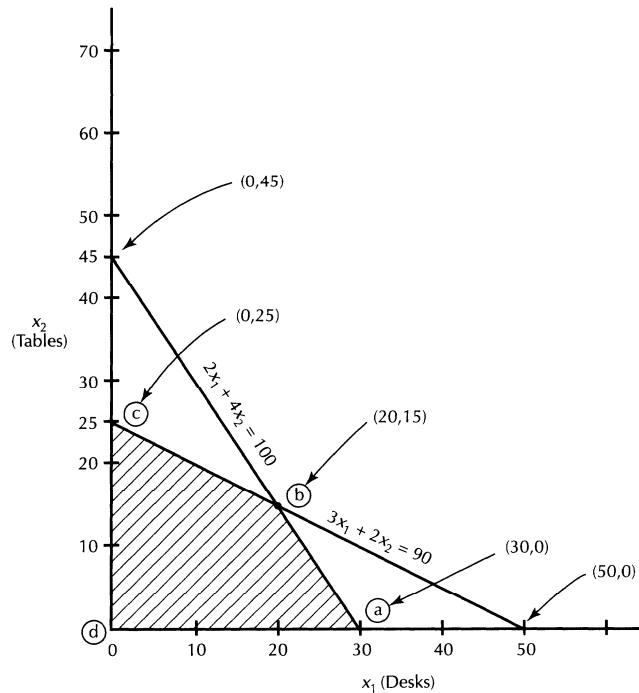
$$2x_1 + 4x_2 = 100 \qquad (1)$$
$$- \quad \underline{6x_1 + 4x_2 = 180} \qquad (2)$$
$$-4x_1 = -80$$
$$x_1 = 40$$

Substituting $x_1 = 40$ into (10) or (2) yields $x_2 = 15$.

FIGURE 3
THE FEASIBLE REGION AND CORNER POINTS

THE FEASIBLE REGION AND CORNER POINTS

THE SIMPLEX METHOD

The simplex method is the technique most commonly used to solve LP problems. It is an algorithm, which is an iteration method of computation, to move from one solution to another until it reaches the best solution. LP computer software uses this approach, which will be illustrated later. *Note:* Slack, surplus, and artificial variables must be employed in order to convert inequalities to equalities. For example, to convert inequalities of the $\leq$ type to equalities, slack variables are added to account for the unused capacity. Detailed steps in the simplex procedure are not covered in this course.

ASSUMPTIONS

Four basic assumptions are fundamental to the general linear programming problem:

1. *Linearity: the objective function* and the *constraint equations* are assumed to be linear (straight lines).
2. *Certainty:* the method does not have provisions for probability. The stated conditions are assumed to follow precisely the given mathematical expressions.
3. *Divisibility:* the values of the decision variable may take on fractional or integer values (e.g., it is possible to produce 58.6 gallons of a product).
4. *Nonnegativity:* the values of the variables that the method selects (decision variables) must be greater than or equal to zero.

CAN THE COMPUTER HELP?

We can use a computer LP software package such as *LINDO (Linear Interactive and Discrete Optimization)* and *What's Best!* to quickly solve an LP problem.

The following shows LINDO output for Example 5

COMPUTER PRINTOUT FOR LP

```
                    VARIABLE    ORIGINAL     COEFF.
VARIABLE             VALUE       COEFF.       SENS.
  X 1                 20          25            0 Note:X1 = 20
  X 2                 15          40            0     X2 = 15


CONSTRAINT          ORIGINAL    SLACK OR    SHADOW
NUMBER                RHS       SURPLUS     PRICE
  1                   100          0           8.75 Note:u1 = $8.75
  1                    90          0           2.50     u2 = $2.50
 OBJECTIVE FUNCTION VALUE:  1100                  Note: Z = $1,100

        SENSITIVITY ANALYSIS

    OBJECTIVE FUNCTION COEFFICIENTS

            LOWER     ORIGINAL        UPPER
VARIABLE    LIMIT    COEFFICIENT      LIMIT

 X 1         20         25             60
 X 2        16.67       40             50

     RIGHT HAND SIDE

CONSTRAINT   LOWER    ORIGINAL     UPPER
NUMBER       LIMIT     VALUE       LIMIT

  1           60        100         180
  2           50         90         150
```

QUESTIONS
1. What is the decision making process?
2. Differentiate among decision making under certainty, risk, and uncertainty.
3. List the types of models that are useful to operations managers.
4. What is a decision matrix? What are the major components of this matrix?
5. What is the expected value of perfect information? How is it computed?

6. What are project planning and management models used for? Give a popular technique for this.
7. What is a popular statistical model used by operations managers?
8. What is linear programming? Why is it called linear?
9. List four popular applications of LP for operations decisions.
10. What are the two ingredients of LP?
11. What are two major computational methods of LP? Briefly describe the pro and con of each.

PROBLEMS

1. The manager of a restaurant must place his order for hot dogs weekly. A review of his sales records for the past 50 weeks reveals the following frequency of hot dogs sold:

Hot Dogs	Number of Weeks
2000	15
3000	20
4000	15
	50 weeks

Hot dogs sell for $1.00 each and cost $0.60 each. Unsold hot dogs are donated to a nearby orphanage.
     1. Construct the payoff table and determine the optimal number of hot dogs to order each week.
     2. Compute the expected value of perfect information.

2. Based on the industry supply and demand analysis, Madden Corporation wishes to build a full-scale manufacturing facility. It is considering:
    A. Build a large plant, costing $6 million.
    B. Build a small plant, costing $2 million.
The probabilities of various demands and present values of projected cash inflows for these demand situations are given below.

Action	Demand Conditions	PV of Cash Inflows ($)	Probabilities
A	High	$8 million	0.5
	Medium	4 million	0.3
	Low	1.5 million	0.2
B	High	$3 million	0.5
	Medium	2 million	0.3
	Low	1.5 million	0.2

Construct a decision tree to analyze the two options.
(a) Which option would you choose? Comment on your decision.

3. The Carson Company makes two products, X and Y. Their contribution margins are $50 and $90, respectively. Each product goes through three processes: cutting, finishing, and painting. The number of hours required by each process for each product and capacities available are given below:

<center>Hours Required in Each Process</center>

Product	Cutting	Finishing	Painting
X	2	4	3
Y	1	6	2
Capacities in Hours	300	500	250

Formulate the objective function and constraints to determine the optimal product mix.

4. A company fabricates and assembles two products, A and B. It takes three minutes to fabricate each unit of A, and six minutes to fabricate each unit of B. Assembly time per unit for product A is one minute, and for product B, nine minutes. Six hundred minutes of fabrication time and 1,800 minutes of assembly time are available. The company makes a contribution margin of $2 on each unit of A it sells, and $1 on each unit of B.
   (a) Express the problem as an LP model.
   (b) What quantities of A and B should be produced in order to maximize profits? What will be the profits earned at these production levels?

ANSWERS

1. The decision making process is the process of defining a problem and its environment, identifying alternatives, evaluating alternatives, selecting an alternative, and implementing the decision.
2. Decision making under certainty means that for each decision there is only one event and therefore only one outcome for each action. Decision making under risk or uncertainty, which is more common in reality, involves several events for each action with its probability of occurrence. Decision making under uncertainty is a decision made when the probability of occurrence of the different states of nature is *unknown.*
3. Models can be narrative, graphical, statistical, mathematical, optimization, and simulation.
4. A decision matrix is an organized approach to decision making under risk. It is characterized by: (1) the *row* representing a set of alternative courses of action available to the decision maker; (2) the *column* representing the state of nature or conditions that are likely to occur and the decision maker has no control over; and (3) the *entries* in the body of the table representing the outcome of the decision, known as payoffs which may be in the form of costs, revenues, profits or cash flows. By computing expected value of each action, we will be able to pick the best one.
5. It is the value of a perfect forecast. The expected value of perfect information can be computed as: expected value with perfect information minus the expected value with existing information.
6. Project planning and management models are used to navigate and coordinate large projects, and to discover critical paths that could delay or jeopardize an entire project if they are not completed in a timely and cost-effective fashion. *Program Evaluation and Review Technique (PERT)* is widely used for this purpose.
7. Regression analysis is an example. It can be used to develop demand forecasts for capacity and production planning.
8. Linear programming (LP) is a mathematical technique designed to determine an optimal decision (or an optimal plan) chosen from a large number of possible decisions. The

optimal decision is the one that meets the specified objective of the company, subject to various restrictions or constraints. It is linear because we assume both the objective function and constraints are linear.

9. Four popular applications of LP are: selecting the least-cost mix of ingredients for manufactured products; determining the most profitable mix of products; scheduling jobs to machines; determining a least-cost shipping pattern.

10. Two ingredients of LP are the objective function and inequality constraints (including nonnegativity constraints).

11. Two major computational methods of LP are: (1) the simplex method and (2) the graphical method. The simplex method is the technique most commonly used to solve LP problems. It is an algorithm, which is an iteration method of computation, to move from one solution to another until it reaches the best solution. The graphical approach is easier to use but limited to the LP problems involving two (or at most three) decision variables.

SOLUTIONS TO PROBLEMS

1.
(a)
The payoff table follows:

		State of Nature			
		Demand	2,000	3,000	4,000	
	Stock	(Probability)	(0.3)	(0.4)	(0.3)	Expected Profit
	2,000		$800	$800	$800	$800
Action	3,000		200*	1,200	1,200	900**
	4,000		(400)	600	1,600	600***

*2,000 units sold Profit: 2,000 x $0.40 = $800
 1,000 units unsold Cost: 1,000 X $0.60 = (600)
$200

**Expected profit for 3,000 hot dogs:
   ($200)(0.3) + ($1,200)(0.4) + ($1,200)(0.3) = $60 + $480 + $360 = $900
***Expected profit for 4,000 hot dogs:
   (-$400)(0.3) + ($600)(0.4) + ($1,600)(0.3) = -$120 + $240 + $480 = $600

Therefore, the manager should order 3,000 hot dogs weekly, which will maximize the expected profit, i.e., $900.

(b). The expected value with perfect information is:
   ($800)(0.3) + ($1,200)(0.4) + ($1,600)(0.3) = $240 + $480 + $480 = $1,200
   Thus, the expected value of perfect information is
                $1,200 - $900 = $300
which is the maximize amount of money the manager would be willing to pay for perfect information.

2.

(a) Expected NPVs for A and B are as follows:

Action	Demand Conditions	PV of Cash Inflows ($) (1)	Probabilities (2)	(1)x (2)
A	High	$8 million	0.5	$4 million
	Medium	4 million	0.3	1.2 million
	Low	1.5 million	0.2	0.3 million
			PV	$5.5 million
			I	6 million
			Expected NPV =	-0.5 million
B	High	$3 million	0.5	$1.5 million
	Medium	2 million	0.3	.6 million
	Low	1.5 million	0.2	.3 million
			PV	$2.4 million
			I	2 million
			Expected NPV =	0.4 million

(b) Choose Option B since its expected NPV is greater than Option A's. This approach does not tell us how risky each option is.

3.
Let   X = Number of units of product X to be produced
        Y = Number of units of product Y to be produced
Then, the LP formulation is as follows:

$$\text{Maximize:} \quad Z = \$50X + \$90Y$$

$$\text{Subject to:} \quad 2X + 1Y \leq 300$$
$$4X + 6Y \leq 500$$
$$3X + 2Y \leq 250$$
$$X, Y \geq 0$$

4.
(a) Let A = Number of units of product A to produce
    Let B = Number of units of product B to produce

$$\text{Maximize: } Z = \$2A + \$1B$$

$$\text{Subject to:} \quad 3A + 6B \leq 600 \text{ (fabrication)}$$
$$1A + 9B \leq 1{,}800 \text{ (assembly)}$$
$$A, B \geq 0$$

(b)

1.	A = 0,	B = 100	Z = $100
2.	A = 200,	B = 0	Z = $400

Thus, 200 units of A should be produced and no units of B. Profit will be $400 at this level.

CHAPTER 3
DEMAND MANAGEMENT AND FORECASTING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Explain how the Delphi method works.
2. Compute a moving average.
3. Differentiate between a weighted moving average and exponential smoothing
4. Explain and illustrate trend analysis.
5. Perform a simple regression.
6. Outline the least-squares method.
7. Interpret a variety of regression statistics such as the correlation coefficient, the standard error of the estimate, and the t-value.
8. Discuss classical decomposition.
9. Compute various measures of forecasting performance such as the mean absolute deviation (MAD) and the mean squared error (MSE).
10. Define and illustrate a tracking signal.

The most important function of business is probably forecasting. A forecast is a starting point for planning. The objective of forecasting is to reduce risk in decision making. In business, forecasts are the basis for capacity planning, production and inventory planning, manpower planning, planning for sales and market share, financial planning and budgeting, planning for research and development, and top management's strategic planning. In this chapter, we examine several aspects of forecasting and we present some popular forecasting models. Demand is a key determinant in two major categories of decisions that are discussed throughout the course: decisions about the design of the production system and decisions about how to operate the production system.

WHO USES FORECASTS?

Forecasts are needed for marketing, production, purchasing, manpower, and financial planning. Further, top management needs forecasts for planning and implementing long-term strategic objectives and planning for capital expenditures. More specifically, production planners need forecasts in order to: (1) schedule production activities, (2) order materials, (3) establish inventory levels, and (4) plan shipments. Some other areas that need forecasts include material requirements (purchasing and procurement), labor scheduling, equipment purchases, maintenance requirements, and plant capacity planning.

As soon as the company makes sure that it has enough capacity, the production plan is developed. If the company does not have enough capacity, it will require planning and budgeting decisions for capital spending for capacity expansion. Figure 1 displays the relationship between demand forecasting and production/operations systems.

FORECASTING METHODS

There is a wide range of forecasting techniques which the company may choose from. There are basically two approaches to forecasting: qualitative and quantitative. They are as follows:

1. Qualitative approach - forecasts based on judgment and opinion.
   - Expert opinions
   - Delphi technique
   - Sales force polling
   - Consumer surveys

2. Quantitative approach
   - Moving averages and weighted moving averages
   - Exponential smoothing
   - Simple regression
   - Multiple regression
   - Trend analysis and classical decomposition

FIGURE 1
RELATIONSHIP BETWEEN DEMAND FORECASTING
AND PRODUCTION/OPERATIONS SYSTEMS.
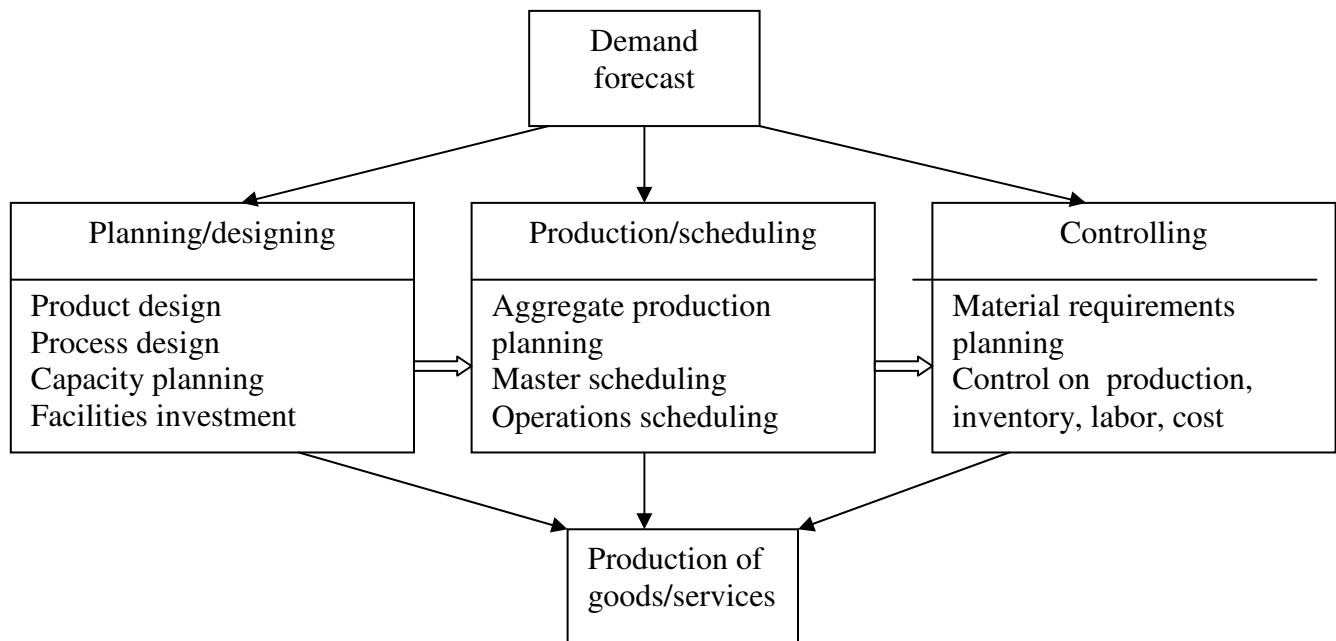
SELECTION OF FORECASTING METHOD

The choice of a forecasting technique is significantly influenced by the stage of the product life cycle, and sometimes by the firm or industry for which a decision is being made.

In the beginning of the product life cycle, relatively small expenditures are made for research and market investigation. During the first phase of product introduction, these expenditures start to increase. In the rapid growth stage, considerable amounts of money are involved in the decisions; therefore a high level of accuracy is desirable. After the product has entered the maturity stage, the decisions are more routine, involving marketing and manufacturing. These are important considerations when determining the appropriate sales forecast technique.

After evaluating the particular stages of the product, and firm and industry life cycles, a further probe is necessary. Instead of selecting a forecasting technique by using whatever seems applicable, decision makers should determine what is appropriate. Some of the techniques are quite simple and rather inexpensive to develop and use, whereas others are extremely complex, require significant amounts of time to develop, and may be quite expensive. Some are best suited for short-term projections, whereas others are better prepared for intermediate-term, or long-term forecasts.

What technique or techniques to select depends on the following criteria:

1. What is the cost associated with developing the forecasting model compared with potential gains resulting from its use? The choice is one of benefit-cost trade-off.
2. How complicated are the relationships that are being forecasted?
3. Is it for short-run or long-run purposes?
4. How much accuracy is desired?
5. Is there a minimum tolerance level of errors?
6. How much data is available? Techniques vary in the amount of data they require.

THE QUALITATIVE APPROACH

The qualitative (or judgmental) approach can be useful in formulating short-term forecasts and also can supplement the projections based on the use of any of the qualitative methods. Four of the better known qualitative forecasting methods are Executive Opinions, the Delphi Method, Sales Force Polling, and Consumer Surveys.

EXPERT OPINIONS

The subjective views of executives or experts from sales, production, finance, purchasing and administration are averaged to generate a forecast about future sales. Usually this method is used in conjunction with some quantitative method such as trend extrapolation. The management team modifies the resulting forecast based on their expectations.

THE DELPHI METHOD

It is a group technique in which a panel of experts are individually questioned about their perceptions of future events. The experts do not meet as a group in order to reduce the possibility that consensus is reached because of dominant personality factors. Instead, the forecasts and accompanying arguments are summarized by an outside party and returned to the experts along

with further questions. This continues until a consensus is reached by the group, especially after only a few rounds. The experts are not influenced by peer pressure to forecast a certain way, as the answer is not intended to be reached by consensus or unanimity.

SALES-FORCE POLLING
Some companies use as a forecast source sales people who have continual contacts with customers. They believe that their sales force, which is closest to the ultimate customers, may have significant insights regarding the state of the future market. Forecasts based on sales-force polling may be averaged to develop a future forecast. Or they may be used to modify other quantitative and/or qualitative forecasts that have been generated internally in the company.

CONSUMER SURVEYS
Some companies conduct their own market surveys regarding specific consumer purchases. Surveys may consist of telephone contacts, personal interviews, or questionnaires as a means of obtaining data. Extensive statistical analysis is usually applied to survey results in order to test hypotheses regarding consumer behavior.

MOVING AVERAGES AND SMOOTHING METHODS
This section discusses several forecasting methods that fall in the quantitative approach category. The discussion includes the naive approach, moving averages, exponential smoothing, time series analysis, and regression analysis.

THE NAIVE APPROACH
The naive forecasting approach is based exclusively on historical observation of data. It does not attempt to explain the underlying causal relationships which produce the variable being forecast. A simplest example of a naive model type would be to use the actual sales of the current period as the forecast for the next period. Let us use the symbol Y'_{t+1} as the forecast value and the symbol Y_t as the actual value. Then, $Y'_{t+1} = Y_t$

MOVING AVERAGES
Moving averages are averages that are updated as new information is received. With the moving average, a manager simply employs the most recent observations to calculate an average, which is used as the forecast for the next period.

EXAMPLE 1
Assume that the marketing manager has the following sales data.

Date		Actual Sales (Y_t)
Jan.	1	46
	2	54
	3	53
	4	46
	5	58
	6	49
	7	54

In order to predict the sales for the seventh and eighth days of January, the manager has to pick the number of observations for averaging purposes. Let us consider two cases: one is a six-day moving average and the other is a three-day average.

Case 1

$$Y'_7 = \frac{46 + 54 + 53 + 46 + 58 + 49}{6} = 51$$

$$Y'_8 = \frac{54 + 53 + 46 + 58 + 49 + 54}{6} = 52.3$$

where Y' = predicted

Case 2

$$Y'_7 = \frac{46 + 58 + 49}{3} = 51$$

$$Y'_8 = \frac{58 + 49 + 54}{3} = 53.7$$

MOVING AVERAGE CALCULATIONS

Predicted Sales(Y'_t)

Date	Actual Sales	Case 1	Case 2
Jan. 1	46		
2	54		
3	53		
4	46		
5	58		51
6	49		53.7
7	54	51	
8		52.3	

In terms of weights given to observations, in case 1, the old data received a weight of 5/6, and the current observation got a weight of 1/6. In case 2, the old data received a weight of only 2/3 while the current observation received a weight of 1/3.

Thus, the marketing manager's choice of the number of periods to use in a moving average is a measure of the relative importance attached to old versus current data.

ADVANTAGES AND DISADVANTAGES

The moving average is simple to use and easy to understand. However, there are two shortcomings.

- It requires you to retain a great deal of data and carry it along with you from forecast period to forecast period.

- All data in the sample are weighted equally. If more recent data are more valid than older data, why not give it greater weight?

The forecasting method known as exponential smoothing gets around these disadvantages.

WEIGHTED MOVING AVERAGE

A weighted moving average allows any weights to be placed on each sales figure. providing the sum of all weights equal 1.

EXAMPLE 2

In Example 1, in Jan., the best forecast is derived by using 50 percent of the actual sales for the most recent day, 40 percent of two days ago, and 30 percent of three months ago. Then the forecast for day 8 would be

$Y'_8 = 0.50(54) + 0.40(49) + 0.30(58) = 27 + 19.6 + 17.4 = 64$

NOTE:

Experience and trial and error are the simplest ways to chose weights. If the most recent past is believed to be the most reliable indicator of what to expect in the future, it should get higher weighting.

EXPONENTIAL SMOOTHING

Exponential smoothing is a popular technique for short-run forecasting by operations managers. It uses a weighted average of past data as the basis for a forecast. The procedure gives heaviest weight to more recent information and smaller weights to observations in the more distant past. The reason for this is that the future is more dependent upon the recent past than on the distant past. One disadvantage of the method, however, is that it does not include industrial or economic factors such as market conditions, prices, or the effects of competitors' actions.

NOTE:

Exponential smoothing is known to be effective when there is randomness and no seasonal fluctuations in the data.

THE MODEL

The formula for exponential smoothing is:

$$F_t = F_{t-1} + \alpha(A_{t-1} - F_{t-1}) \ or \ \alpha A_{t-1} + (1 - \alpha) F_{t-1}$$

or in words,

$F_{new} = F_{old} + \alpha(A_{old} - F_{old})$

where F_{new} = Exponentially smoothed average to be used as the forecast.

A_{old} = Most recent actual data.

F_{old} = Most recent smoothed forecast.

α = Smoothing constant.

The higher the α, the higher the weight given to the more recent information.

EXAMPLE 3

The following data on sales are given below.

Time period (t)	Actual sales (000)(A_t)
1	$60.0
2	64.0
3	58.0
4	66.0
5	70.0
6	60.0
7	70.0
8	74.0
9	62.0
10	74.0
11	68.0
12	66.0
13	60.0
14	66.0
15	62.0

To initialize the exponential smoothing process, we must have the initial forecast. The first smoothed forecast to be used can be
1. First actual observations.
2. An average of the actual data for a few periods

For illustrative purposes, let us use a six-period average as the initial forecast F_7 with a smoothing constant of $\alpha = 0.40$.

$$Then\ F_7 = (A_1 + A_2 + A_3 + A_4 + A_5 + A_6)/6$$
$$= (60 + 64 + 58 + 66 + 70 + 60)/6 = 63$$

Note that $A_7 = 70$. Then F_8 is computed as follows:

$$F_8 = F_7 + \alpha(A_7 - F_7)$$
$$= 63 + (0.40)(70 - 63)$$
$$= 63 + 2.80 = 65.80$$

Similarly,

$$F_9 = F_8 + \alpha(A_8 - F_8)$$
$$= 65.8 + (0.40)(74 - 65.80)$$
$$= 65.8 + 3.28 = 69.08$$
and

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$$F_{10} = F_9 + \alpha(A_9 - F_9)$$
$$= 69.08 + (0.40)(62 - 69.08)$$
$$= 69.08 - 2.83 = 66.25$$

By using the same procedure, the values of F_{11}, F_{12}, F_{13}, F_{14}, and F_{15} can be calculated. Table 1 shows a comparison between the actual sales and predicted sales by the exponential smoothing method.

Due to the negative and positive differences between actual sales and predicted sales, the forecaster can use a higher or lower smoothing constant (α), in order to adjust his/her prediction as quickly as possible to large fluctuations in the data series. For example, if the forecast is slow in reacting to increased sales, (that is to say, if the difference is negative), he/she might want to try a higher value. For practical purposes, the optimal α may be picked by minimizing what is known as the *mean squared error* (MSE), which is a popular measure of forecasting performance.

$$MSE = (A_t - F_t)^2 / (n - i)$$
where i = the number of observations used to determine the initial forecast (in our example, $i=6$).

TABLE 1
COMPARISON OF ACTUAL SALES AND PREDICTED SALES

Time period (t)	Actual sales (A_t)	Predicted sales (F_t)	Difference ($A_t - F_t$)	Difference^2 ($A_t - F_t)^2$
1	$60.0			
2	64.0			
3	58.0			
4	66.0			
5	70.0			
6	60.0			
7	70.0	63.00	7.00	49.00
8	74.0	65.80	8.20	67.24
9	62.0	69.08	-7.08	50.13
10	74.0	66.25	7.75	60.06
11	68.0	69.35	-1.35	1.82
12	66.0	68.81	-2.81	7.90
13	60.0	67.69	-7.69	59.14
14	66.0	64.61	1.39	1.93
15	62.0	65.17	-3.17	10.05
				307.27

In our example,
$$MSE = 307.27 / (15 - 6) = 307.27 / 9 = 34.14$$

The idea is to select the α that minimizes MSE, which is the average sum of the variations between the historical sales data and the forecast values for the corresponding periods. An α value that yields an approximately equivalent degree of smoothing as a moving average of n periods is:

$$\alpha = \frac{2}{n+1}$$

REGRESSION ANALYSIS

Regression analysis is a statistical procedure for estimating mathematically the average relationship between the dependent variable and the independent variable(s). *Simple regression* involves one independent variable, price or advertising in a demand function, whereas *multiple regression* involves two or more variables, that is price and advertising together.

In this chapter, we will discuss only *simple (linear) regression* to illustrate the *least-squares method*, which means that we will assume the $Y = a + bX$ relationship.

THE LEAST-SQUARES METHOD

The least-squares method is widely used in regression analysis for estimating the parameter values in a regression equation. The regression method includes all the observed data and attempts to find a line of best fit. To find this line, a technique called the least-squares method is used.

To explain the least-squares method, we define the error as the difference between the observed value and the estimated one and denote it with u. Symbolically,

$$u = Y - Y'$$

where Y = observed value of the dependent variable
       Y' = estimated value based on $Y' = a + bX$

The least-squares criterion requires that the line of best fit be such that the sum of the squares of the errors (or the vertical distance in Figure 2 from the observed data points to the line) is a minimum, i.e.,

$$\text{Minimum: } \Sigma u^2 = \Sigma(Y-a-bX)^2$$

FIGURE 2
Y AND Y'
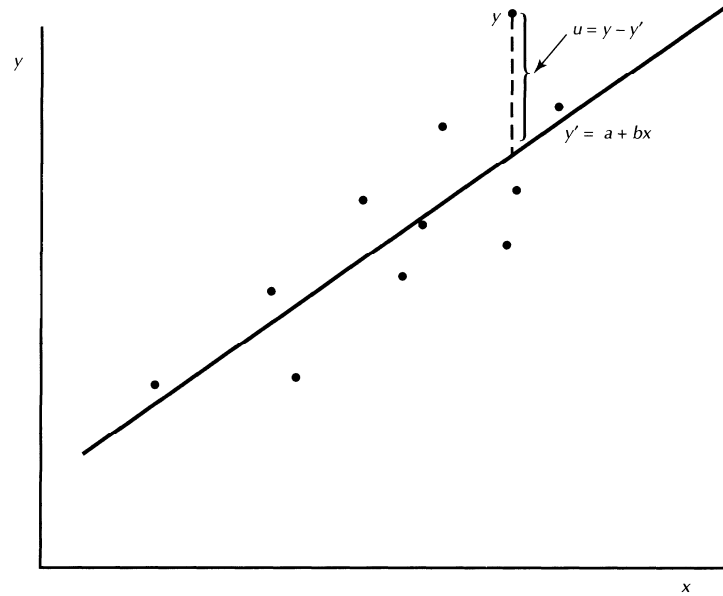
Using differential calculus we obtain the following equations, called normal equations:

$$\Sigma Y = na + b\Sigma X$$
$$\Sigma XY = a\Sigma X + b\Sigma X^2$$

Solving the equations for b and a yields

$$b = \frac{n\Sigma XY - (\Sigma X)(\Sigma Y)}{n\Sigma X^2 - (\Sigma X)^2}$$

$$a = \overline{Y} - b\overline{X}$$

where $\overline{Y} = \Sigma Y/n$ and $\overline{X} = \Sigma X/n$

EXAMPLE 5

   To illustrate the computations of b and a, we will refer to the data below.   All the sums required are computed and shown below.

COMPUTED SUMS				
Advertising X (in thousands)	Sales Y (in millions)	XY	X^2	Y^2
$77	$ 5.5	423.5	5,929	30.25
75	5.1	382.5	5,625	26.01
72	4.7	338.4	5,184	22.09
73	4.8	350.4	5,329	23.04
71	4.6	326.6	5,041	21.16
$368	24.7	1,821.4	27,108	122.55

From the table above:

$\Sigma X = 368$; $\Sigma Y = 24.7$; $\Sigma XY = 1,821.4$; $\Sigma X^2 = 27,108$.

$X = \Sigma X/n = 368/5 = 73.6$; $Y = \Sigma Y/n = 24.7/5 = 4.94$.

Substituting these values into the formula for b first:

$$b = \frac{n\Sigma XY - (\Sigma X)(\Sigma Y)}{n\Sigma X^2 - (\Sigma X)^2} \doteq \frac{(5)(1,821.4) - (368)(24.7)}{(5)(27,108) - (368)^2} = \frac{17.4}{116} = 0.15$$

$$a = \overline{Y} - b\overline{X} = 4.94 - (0.15)(73.6) = -6.10$$

Thus, Y' = -6.10 + 0.15 X

Note that ΣY^2 is not used here but rather is computed for r and r-squared (r^2).

NOTE:
Before attempting a least-squares regression approach, it is extremely important to plot the observed data on a diagram, called the scattergraph (See Figure 2). The reason is that you might want to make sure that a linear (straight-line) relationship existed between Y and X in the past sample. If for any reason there was a nonlinear relationship detected in the sample, the linear relationship we assumed -- Y = a + bX -- would not give us a good fit.

REGRESSION STATISTICS
Regression analysis is a statistical method. Hence, it uses a variety of statistics to tell about the accuracy and reliability of the regression results. They include:

1. Correlation coefficient (r) and coefficient of determination (r^2)
2. Standard error of the estimate (S_e) and prediction confidence interval

Correlation Coefficient (r) and Coefficient of Determination (r^2)

In order to obtain a good fit and achieve a high degree of accuracy, you should be familiar with a statistic known as correlation coefficient. The correlation coefficient r measures the degree of correlation between Y and X. The range of values it takes on is between -1 and +1. More widely used, however, is the coefficient of determination, designated r^2 (read as r-squared). Simply put, r^2 tells us how good the estimated regression equation is. In other words, it is a measure of "goodness of fit" in the regression. Therefore, the higher the r^2, the more confidence we have in our estimated equation. More specifically, the coefficient of determination represents the proportion of the total variation in Y that is explained by the regression equation. It has the range of values between 0 and 1.

EXAMPLE 6

The statement "Sales is a function of advertising expenditure with $r^2 = 75$ percent," can be interpreted as "75 percent of the total variation of sales is explained by the regression equation or the change in advertising and the remaining 25 percent is accounted for by something other than advertising, such as price and income."

The coefficient of determination is computed as

$$r^2 = 1 - \frac{\sum (Y - Y')^2}{\sum (Y - \overline{Y})^2}$$

In a simple regression situation, however, there is a short-cut method available:

$$r^2 = \frac{[n\sum XY - (\sum X)(\sum Y)]^2}{[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]}$$

The coefficient of correlation r is the *square root* of the coefficient of determination:

NOTE:
1. Comparing this formula with the one for b, we see that the only additional information we need to compute r^2 or r is ΣY^2.
2. $r^2 = (r)^2$ or r = the square root of $r^2 \neq r$

EXAMPLE 7

To illustrate the computations of various regression statistics, we will refer to the data in Example 5.

Using the shortcut method for r^2,

$$r^2 = \cfrac{(17.4)^2}{(116)\ [\,(5)\,(122.55) - (24.7)^2\,]} = \cfrac{302.76}{(116)\,(612.75 - 610.09)}$$

$$= \cfrac{302.76}{308.56} = 0.9812 = 98.12\%$$

This means that about 98.12 percent of the total variation in sales is explained by advertising and the remaining 1.88 percent is still unexplained. A high r^2 indicates an excellent fit in our estimated forecasting model. Advertising turns out to be an important factor.

$$r = \cfrac{17.4}{\sqrt{(116)\ [\,(5)\,(122.55) - (24.7)^2\,]}} = \cfrac{17.4}{\sqrt{308.56}} = 0.9905$$

or $r^2 = (0.9905)^2 = 0.9812 = 98.12\%$

Standard error of the estimate (S_e) and prediction confidence interval
The standard error of the estimate, designated S_e, is defined as the standard deviation of the regression.

It is computed as:

$$S_e = \sqrt{\cfrac{\sum (Y - Y')^2}{n - 2}} = \sqrt{\cfrac{\sum Y^2 - a\sum Y - b\sum XY}{n - 2}}$$

This statistic can be used to gain some idea of the accuracy of our predictions.

EXAMPLE 8

Going back to our example data, S_e is calculated as :

$$S_e = \sqrt{\cfrac{(122.55) - (-6.10)(24.7) - (0.15)(1821.4)}{6 - 2}}$$

$$= \sqrt{\frac{122.55 + 150.67 - 273.21}{4}} \qquad = .05$$

Suppose you wish to make a prediction regarding an individual Y value--such as a prediction about the sales when advertising is \$70. Usually, we would like to have some objective measure of the confidence we can place in our prediction, and one such measure is a *confidence (or prediction) interval* constructed for Y.

A confidence interval for a predicted Y can be constructed in the following manner.

$$Y' \pm t \, S_e$$

where Y' = the predicted value of Y given a value for X;
Note: t is the critical value for the level of significance employed. For example, for a significance level of 0.025 (which is equivalent to a 95% confidence level in a two-tailed test), the critical value of t for 4 degrees of freedom is 2.776. See Table 3 (t-table) in the Appendix.

EXAMPLE 9
If you want to have a 95 percent confidence interval of your prediction, the range for the prediction, given an advertising expense of \$70 (in thousands) would be between \$4.24 and \$4.56 (in millions):

Note that , Y' = -6.10 + 0.15 X = -6.10 + 0.15 (\$70) = \$4.4.

The confidence interval is therefore established as follows:
$$= \$4.4 \pm (2.776)(.0577) = \$4.4 \pm 0.16$$

which means the range for the prediction, given an advertising expense of \$70 would be between \$4.24 (\$4.4 - 0.16) and \$4.56 (\$4.4 + 0.16).

USE OF COMPUTER SOFTWARE FOR REGRESSION

Spreadsheet programs such as Microsoft's *Excel, Lotus 1-2-3,* and *Quattro Pro* have a regression routine which you can use without any difficulty. As a matter of fact, in reality, you do not compute the values a, b, r, and r^2 manually. The following shows a portion of the *Excel* regression output for the previous example.

SUMMARY OUTPUT

Regression Statistics

Multiple R	0.990557

	Coefficients	Standard Error	t Stat
R Square	0.981203		
Adjusted R Square	0.974937		
Standard Error	0.057735		
Observations	5		

	Coefficients	Standard Error	t Stat
Intercept	-6.1	0.88259	-6.911475
X Variable 1	0.15	0.011987	12.513992

MULTIPLE REGRESSION

Multiple regression analysis is a powerful statistical technique that is perhaps the one most widely used by forecasters. Multiple regression attempts to estimate statistically the average relationship between the dependent variable (e.g., sales) and two or more independent variables (e.g., price, advertising, income, etc.).

> **NOTE:**
> In reality, forecasters will face more multiple regression situations than simple regression, which is beyond the scope of this course.

COMPUTER SOFTWARE FOR FORECASTING

Forecasters in the real world of business use computers to do their calculations. Besides spreadsheet software illustrated earlier, there are numerous user-friendly software available for use in forecasting. Some are briefly explained below.

1. Statistical packages such as SPSS, SAS, and MINITAB.
2. American Software Inc.'s *ForeThought* .
3. General Electric's *Time Series Forecasting* program *FCST1*, a linear regression trend-analysis, seasonalized forecasting model. Its *FCST2* program creates several forecasts with four different methods of exponential smoothing.
4. IBM's *Consumer Goods System (COGS),* a forecasting and inventory control information system which is specifically oriented to the manufacturing process and distribution industries.
5. IBM's *Inventory Management Program and Control Technique (IMPACT),* an information system for wholesale and other users in distribution systems.

EVALUATION OF FORECASTS

The cost of a prediction error can be substantial. The forecaster must always find the ways to improve his forecasts. That means that he might want to examine some objective evaluations of alternative forecasting techniques. The performance of a forecast should be checked against its own record or against that of other forecasts. There are various statistical measures that can be used to measure performance of the model. Of course, the performance is

measured in terms of forecasting error, where error is defined as the difference between a predicted value and the actual result.

Error (e) = Actual (A) - Forecast (F)

MAD and MSE

The commonly used measures for summarizing historical errors include the *mean absolute deviation* (MAD) and the *mean squared error* (MSE). The formulas used to calculate these are

$MAD = \Sigma |e| / n$
$MSE = \Sigma e^2 / (n - 1)$

The following example illustrates the computation of MAD and MSE.

EXAMPLE 10

Sales data of a microwave oven manufacturer are given below:

Period	Actual(A)	Forecast(F)	e=(A-F)	$|e|$	e^2
1	217	215	2	2	4
2	213	216	-3	3	9
3	216	215	1	1	1
4	210	214	-4	4	16
5	213	211	2	2	4
6	219	214	5	5	25
7	216	217	-1	1	1
8	212	216	-4	4	16
			-2	22	76

Using the figures,

$MAD = \Sigma |e| /n = 22/8 = 2.75$
$MSE = \Sigma e^2 / (n - 1) = 76/7 = 10.86$

One way these measures are used is to evaluate forecasting ability of alternative forecasting methods. For example, using either MAD or MSE, a forecaster could compare the results of exponential smoothing with alphas and elect the one that performed best in terms of the lowest MAD or MSE for a given set of data. Also, it can help select the best initial forecast value for exponential smoothing.

CONTROL OF FORECASTS

It is important to monitor forecast errors to insure that the forecast is performing well. If the model is performing poorly based on some criteria, the forecaster might reconsider the use of

the existing model or switch to another forecasting model or technique. The forecasting control can be accomplished by comparing forecasting errors to predetermined values, or limits. Errors that fall within the limits would be judged acceptable while errors outside of the limits would signal that corrective action is desirable.

Forecasts can be monitored using either tracking signals or control charts.

TRACKING SIGNALS

A tracking signal is based on the ratio of cumulative forecast error to the corresponding value of MAD.

Tracking signal = Σ(A - F) / MAD

The resulting tracking signal values are compared to predetermined limits. These are based on experience and judgment and often range from plus or minus 3 to plus or minus 8. Values within the limits suggest that the forecast is performing adequately. By the same token, when the signal goes beyond this range, corrective action is appropriate.

EXAMPLE 11

Going back to Example 10, the deviation and cumulative deviation have already been computed:

MAD = Σ |A - F| / n = 22 / 8 = 2.75

Tracking signal = Σ (A - F) / MAD = -2 / 2.75 = - 0.73

A tracking signal is as low as -0.73, which is substantially below the limit (-3 to -8). It would not suggest any action at this time.

Note: After an initial value of MAD has been computed, the estimate of the MAD can be continually updated using exponential smoothing.

$MAD_t = \alpha(A - F) + (1 - \alpha) MAD_{t-1}$

CONTROL CHARTS

The control chart approach involves setting upper and lower limits for individual forecasting errors instead of cumulative errors. The limits are multiples of the estimated standard deviation of forecast, S_f, which is the square root of MSE. Frequently, control limits are set at 2 or 3 standard deviations.

$\pm$ 2(or 3) S_f

Note: Plot the errors and see if all errors are within the limits, so that the forecaster can visualize the process and determine if the method being used is in control.

EXAMPLE 12

For the sales data below, using the naive forecast, we will determine if the forecast is in control. For illustrative purposes, we will use 2 sigma control limits.

Year	Sales	Forecasts	Error	Error^2
1	320			
2	326	320	6	36
3	310	326	-16	256
4	317	310	7	49
5	315	317	- 2	4
6	318	315	3	9
7	310	318	- 8	64
8	316	310	6	36
9	314	316	- 2	4
10	317	314	3	9
			- 3	467

FIGURE 3

Control Chart for Forecasting Errors
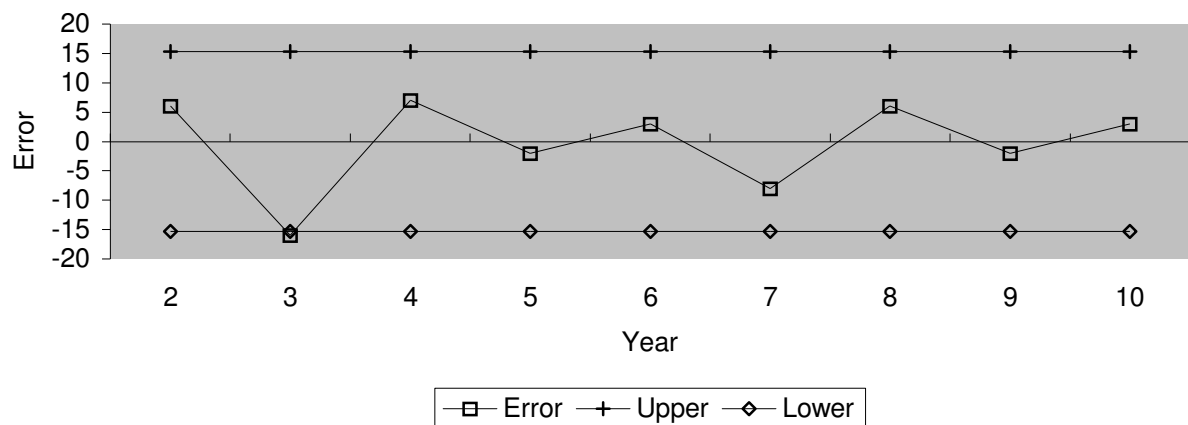
First, compute the standard deviation of forecast errors

$$S_f = \sqrt{e^2 / (n - 1)} = \sqrt{467/(9 - 1)} = 7.64$$

Two sigma limits are then plus or minus $2(7.64) = -15.28$ to $+15.28$

Note that the forecast error for year 3 is below the lower bound, so the forecast is not in control (See Figure 3). The use of other methods such as moving average, exponential smoothing, or regression would possibly achieve a better forecast.

NOTE:
A system of monitoring forecasts needs to be developed. The computer may be programmed to print a report showing the past history when the tracking signal "trips" a limit.

QUESTIONS
1. Discuss the difference between quantitative and qualitative (judgmental) forecasting methods. What circumstances would warrant one over the other?
2. Discuss the role of forecasting in production/operations management.
3. Illustrate, by examples of typical applications, the various types of qualitative forecasting techniques often used.
4. What are the basic steps in forecasting? Discuss each.
5. Define a time series.
6. How are moving averages calculated?
7. What is exponential smoothing and when it is most effective?
8. List the basic approaches involved in the *classical decomposition* of time series.
9. Explain the two popular measures of forecast accuracy.
10. How are quantitative and judgmental forecasts used together in practice?
1. What is a tracking signal and how it is used?

PROBLEMS
1. The AZ Ice Cream Shoppe has recorded the demand for a particular flavor during the first seven days of August.

Date	Actual Sales (Y_t)
Aug. 1	56
2	64
3	63
4	56
5	68
6	59
7	64

Predict the sales for the eighth day of August, using (a) a five-day moving average, (b) a three-day average, and (c) a weighted three-day moving average with weights of .5, .4, and .1.

2. Develop a forecast for period 6 using an alpha of .4 and period 1 value as the initial forecast.

Period	Number of customer complaints
1	45
2	34
3	35
4	42
5	48

3. The following are the advertising and sales data of Jupiter Corporation over an eight-month period.

Advertising (000 omitted)	Sales (000 omitted)
320	$2,600
200	1,500
230	2,150
240	2,250
720	4,700
560	3,700
470	3,300
750	4,750

(a) Develop the sales forecasting equation by using the method of least squares.
(b) Compute the coefficient of correlation and the coefficient of determination.
(c) Comment on the choice of advertising in predicting sales.

4. JON Engineering, Inc. has developed the following sales forecasting model:
$Y' = 123.5 + 2.3 X$ where X = advertising
$r = 0.99$
Standard error of the estimate $(S_e) = 31.2$
(a) Make a forecast when advertising is $200.
(b) What will be the range (prediction interval) of this forecast using two standard errors of estimate?
5.
An ice cream parlor experienced the following weekly actual and forecasted data for sales last month:

Week	Actual demand (in gallons)	Forecast demand (in gallons)
1	200	210
2	225	235
3	200	225
4	260	270

Compute MAD.

6. Given the sales data below, prepare a naive forecast, which is actual sales of the previous year,   for each of the 10 years and determine if the forecast is in control. Use 2 sigma control.

Year	Sales
1	220
2	226
3	210
4	217
5	215

ANSWERS

1. Quantitative methods are based on the analysis of historical data while qualitative (judgmental) methods depend on expert opinion. Obviously if historical data is unavailable, quantitative cannot be used. Such would be the case with technology forecasts. For such data as sales and costs, quantitative approaches are useful. Quite frequently a combination of the two is used.

2. Forecasts are needed in order to (a) plan resource requirements such as production facilities, (b) work force levels and planning purchases of materials, and (c) for financial planning and capacity planning.

3. (a) Preliminary data analysis of scatter diagram. (b) determination of forecasts choice of method: quantitative and/or judgmental. (c) evaluation and determination of a final forecast - consideration of accuracy and implications of errors, data collection and processing. (d) control and feedback - comparison of actual observations with forecasts.

4. Expert opinion - new technologies or new products unlike any currently on the market.
  Delphi method - space travel, long range economic conditions.
  Sales polling or consumer surveys - new products, restaurants, fast food, consumer appliances.

5. A time series is a set of observations measured at successive points in time or over successive periods of time.

6. A moving average is an average of the most recent *n* data values for any point in time.

7. Exponential smoothing is a weighting of the current actual value and the previous forecast. As such, it is essentially a weighted average of the previous time series values with more emphasis placed on the most recent observations. It is known to be effective when there is randomness and no seasonal fluctuations in the data.

8. The approach basically involves the following four steps: (a) determine seasonal indices, using a four-quarter moving average, (b) deseasonalize the data, (c) develop the linear least squares equation in order to identify the trend component of the forecast, and (d) forecast the sales for each of the four quarters of the coming year.

9. Forecast errors are measured by mean absolute deviation (MAD) and mean squared error (MSE). These enable one to quantitatively measure forecast errors.

10. Since quantitative methods are slow to adapt to unexpected changes in the environment, qualitative (judgmental) forecasts are often also used. Quantitative forecasts are frequently modified by judgmental forecasts.

11. It is a moving sum of forecast errors divided by MAD. It is computed to measure the adequacy of a forecasting technique.

SOLUTIONS TO PROBLEMS

1.

(a) using a five-day moving average

$$Y'_8 = \frac{63 + 56 + 68 + 59 + 64}{5} = 62$$

where Y' = predicted

(b) Using a three-day average.

$$Y'_8 = \frac{68 + 59 + 64}{3} = 63.7$$

(c) $Y'_8 = .5(64) + .4(59) + .1(68) = 32 + 23.6 + .68 = 56.28$

2.

Period Y'_t	Number of customer complaints	Forecast = Y'_{t+1} = αY_t + (1 - α)
b	45	
2	34	45
3	35	.4(34)+.6(45)=40.6
4	42	.4(35)+.6(40.6)=38.4
5	48	.4(42)+.6(38.4)=39.8

For period 6: .4(48)+.6(39.8) =43.1

3.

(a) Based on the method of least squares, we obtain:

Advertising X	Sales Y	XY	X^2	Y^2
320	$2,600	832,000	102,400	6,760,000
200	1,500	300,000	40,000	2,250,000
230	2,150	494,500	52,900	4,622,500
240	2,250	540,000	57,600	5,062,500
720	4,700	3,384,000	518,400	22,090,000
560	3,700	2,072,000	313,600	13,690,000

56

470	3,300	1,551,000	220,900	10,890,000
750	4,750	3,562,500	562,500	22,562,500
3,490	24,950	12,736,000	1,868,300	87,927,500

From the table:

$$n = 8 \quad \Sigma X = 3{,}490 \quad \Sigma Y = 24{,}950 \quad \Sigma XY = 12{,}736{,}000 \quad \Sigma X^2 = 1{,}868{,}300$$

Substituting these values into the formula for b first:

$$b = \frac{n\Sigma XY - (\Sigma X)(\Sigma Y)}{n\Sigma X^2 - (\Sigma X)^2} = \frac{(8)(12{,}736{,}000) - (3{,}490)(24{,}950)}{(8)(1{,}868{,}300) - (3{,}490)^2} = \$5.35$$

$$a = (\Sigma Y/n) - b(\Sigma X/n) = 24{,}950/8 - (1.22)(3{,}490/8) = 3{,}119 - 2{,}334 = \$785$$

Thus, the cost function formula is $785 + $5.35 X

(b)

$$r = \frac{[\, n\Sigma XY - (\Sigma X)(\Sigma Y)\,]}{\sqrt{[\, n\Sigma X^2 - (\Sigma X)^2\,][\, n\Sigma Y^2 - (\Sigma Y)^2\,]}}$$

$$r = \frac{(8)(12{,}736{,}000) - (3{,}490)(24{,}950)}{\sqrt{[\,(8)(1{,}868{,}300) - (3{,}490)^2\,][(8)(87{,}927{,}500) - (24{,}950)^2]}}$$

$$= 14{,}812{,}500/14{,}961{,}453 = 0.99$$

Then, $r^2 = (0.99)^2 = 0.9801 = 98.01\%$

(c) Advertising was an excellent choice in explaining the behavior of sales as the high r-squared indicated: 98.01 percent of the total change in sales was explained by advertising alone. Only 1.99 percent was due to chance.

4.
(a) Given $Y' = 123.5 + 2.3(\$200) = 583.5$
(b) The range (prediction interval) of this forecast using two standard errors of estimate will be $583.5 \pm 2(31.2) = 62.4$ or $521.1 to $645.9

5.

Week	Actual(A)	Forecast(F)	e=(A-F)	|e|
1	200	210	-10	10
2	225	235	-10	10
3	200	225	-25	25
4	260	270	-10	10
				55

Using the figures,

MAD $= \Sigma |e| /n = 55/4 = 13.75$

6.

The computation is shown below.

Year	Sales	Forecasts	Error	Error^2
1	220			
2	226	220	6	36
3	210	226	-16	256
4	217	210	7	49
5	215	217	- 2	4
			- 5	345

.

First, compute the standard deviation of forecast errors

$S_f = \sqrt{e^2 / (n - 1)} = \sqrt{345/(5 - 1)} = 9.29$

Two sigma limits are then plus or minus $2(9.29) = -18.58$ to $+18.58$

The forecast errors appear to be within the limits, so the forecast is in control, although more observations are desired.

CHAPTER 4
PROCESS SELECTION AND CAPACITY PLANNING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Discuss the concept of production design.
2. Prescribe a method for process planning.
3. Illustrate a modular design.
4. Describe the process to develop automation.
5. Develop a system of standardization.
6. Explain the role of Flexible Manufacturing System (FMS).
7. Explain Computer-Integrated Manufacturing (CIM).
8. Demonstrate Computer-Aided Design (CAD).
9. Demonstrate Computer-Aided Manufacturing (CAM).
10. Explain how to conduct product analysis.
11. Describe a method of process selection.
12. Define *reliability.*
13. Compute the failure rate.
14. Calculate the mean time between failures (MTBF).
15. Explain the concept to utilize and maximize the capacity.
16. Evaluate capacity alternatives.

The task of planning any system must be undertaken with considerable care. Planning is a function of management at all levels. The planning activities of the operations manager differ from planning by other functional area managers. Planning the operations system involves product design, the determination of processes required, the decision establishing the capacity of the system and the design and measurement of the work system. Establishing a sequence for planning is difficult, as a great deal of the planning function is correlated and executed simultaneously. The order in which operations planning activities are discussed does not necessarily represent the actual sequence in which it will occur. The planning function of the operations manager will be examined in this and succeeding chapters.

PRODUCT DESIGN

The basic limiting characteristics of the production system design are set during the product design phase. In designing the product, or the item to be processed in non-manufacturing systems, the product designer specifies materials, tolerances, basic configurations, methods of joining parts, etc., and through these specifications sets the minimum possible production cost. The conscious effort to design for low manufacturing cost is often referred to as *production design.* Given the product design, *process planning* for manufacture must be carried out to specify the process required and the sequence of the processes. We will cover the general topics of processes and process planning at a later point; now we wish to focus our attention on the product design and its implications for the productive system which must be designed.

The two basic steps in designing a product are functional design and production design.

FUNCTIONAL DESIGN

In this step the product is designed to be functional. Decisions are made on dimensions, materials to be used, type of final finish required for appearance, etc. At this stage the designer is more concerned with the product itself than the methods of production. The main concerns are: (a) functional consideration, (b) customer appeal, (c) cost, and (d) ease of operation and maintenance.

PRODUCTION DESIGN

In this stage, the designer considers introduction of modifications and new concepts into the product to make it more suitable for production. Some of the concepts employed at this stage are:

Standardization. The designer can facilitate the production of the part by standardization of a part or the whole product. Standardization can also cut production costs by eliminating the need for planning for several different product varieties. It allows firms to work larger and often economical quantities of fewer items. However, standardization has limitations. It can forestall improvements and limits the options available to consumers.

Modular designs. Modular designs facilitate production and maintenance. This type of design is used extensively in computers. Products are made of easily detachable subassemblies or sections. *Simplification*. Sometimes the designer may include some features in the design that, although not very critical to the function of the product, create severe problems in the production stage. To correct these situations, sometimes some part of the design must be simplified.

Once developed, many products also undergo *value analysis* (or *value engineering*). This is an attempt to see if any materials or parts can be substituted or redesigned in such a way as to continue to perform the desired or intended function, but at a lower cost.

INTERACTION BETWEEN PRODUCT DESIGN AND PRODUCTION COSTS

The nature of the product design can affect costs in a wide variety of cost categories, going far beyond the direct labor and material costs involved. Based on studies in the aerospace industry, the following is a list of cost categories affected by product design:

1. Raw material.
2. Equipment.
3. Direct labor.
4. Indirect labor.
5. Tooling.
6. Engineering.
7. Sales and administration.

Many of the indirect costs tend to be hidden. For example, the number of individual parts in a design can drastically affect the indirect costs due to greater paperwork and the greater cost

of ordering, storing, and controlling the larger number of parts. Thus, the selection of product design details must reflect consideration of all the foregoing factors.

BASIC PRODUCT DESIGN ALTERNATIVES

A great deal of the flexibility open to the product designer lies in the selection of materials, which in turn often specify basic kinds of processes. For example, if the designer selects a molded plastic material, then the entire mode of production and the basic sequence of activities are also set. Yet, there are usually alternatives which may extend through the entire range of die castings, forgings, stamped and formed parts, sand castings, and parts machined from solid metal. Each is appropriate under a certain combination of conditions of functional requirements and manufacturing costs. The volume to be produced should be an extremely important factor since for a given functional requirement some processes are well adapted to smaller volumes, while others are appropriate for larger volumes. The breakeven volume between any two processes depends on the particular situation. Some of the ways in which contrasting designs can affect costs follows.

PROCESSES AND MATERIALS

As already noted, the particular material and related process often go together. There are wide variations in the associated costs. For example, the material cost for molded plastics is medium to high, as is the tool and die cost. However, direct labor costs, finishing costs, etc. are likely to be low, making the material and process appropriate for many applications of large volume.

Joining of Parts

Designs can specify many different methods for joining parts, including welding, spot welding, bolting, riveting, staking, and sometimes stapling. Not all of these alternatives are always open to designers. Usually more than one alternative is available and costs of production can be significantly different.

Tolerances

If tolerances are specified more tightly than is necessary for functional requirements, a more costly process may be required. On the other hand, in some situations a closer tolerance specification can minimize assembly and adjustment costs. The overall implications need to be considered.

Simplified Designs

As noted previously, the fewer the parts involved, the smaller certain indirect costs will be. When two or more parts are finally assembled rigidly together, the question of whether a one-piece design is appropriate should be raised. If a single material can meet service requirements, then not only will assembly costs be reduced, but the indirect costs of control will also be reduced.

Reduced Processing

The selection of the initial state of the raw material can often reduce processing. A wide variety of intermediate shapes and cross sections of plastic and metal materials are produced, and

designers can often select one of these materials to be the initial raw material, thereby reducing the amount of further processing.

QUALITY FUNCTION DEPLOYMENT

Quality function deployment (QFD) is a structured way to integrate product/service design and process design. It attempts to transform customer requirements and competitive capabilities into provider targets, extending from product and process research to operations, marketing, and distribution. The structure begins with developing a "house of quality," a matrix consisting of (1), customer needs (the "whats")--the "voice of the customer," (2) the company's and key competitors' abilities to satisfy those needs (the "hows"), and (3) the "roof" of the house showing any correlation between the operating requirements. This analysis allows a firm to (a) compare the firm to its competitors, and (b) set target values on each of the operating requirements.

The design team uses the basic house of quality in the product-planning stage. More detailed matrices may be devised for three remaining stages of design, i.e., product design, process planning, and process control, as shown in Figure 1.

PROCESSES AND PROCESS PLANNING

Some aspects of process planning take place jointly with the product design phase. Nevertheless, given the product design, someone must consider the processes required in order to design the production system to be used. We will first consider processes in the general sense and then the nature of process planning.

Processes

Processes involve transformations of some kind. The transformation process may be chemical, changes in shape or form, assembly, transportation, inspection, or clerical. Taking another dimension, transformation processes may also cover a spectrum extending from completing manual tasks through man-machine systems to automated processes. The special aspects of manual tasks and the man-machine relationship are covered separately in Chapter 6 on job design and man-machine systems.

Chemical Processes

Chemical process are particularly important in the petroleum, plastics, and metal industries. Chemical processes are often of the batch type; however, continuous flow chemical processes are important in petroleum, soaps and detergents, etc.

FIGURE 1
AN OVERVIEW OF QUALITY FUNCTION DEPLOYMENT

```
┌─────────────┐          ⎧  Customer requirements
│   Product   │ ═══════▷ ⎨
│   planning  │          ⎩           ⇓
└─────────────┘

                         ⎧  Design requirements
┌─────────────┐          ⎨
│   Product   │ ═══════▷ ⎪           ⇓
│   design    │          ⎩
└─────────────┘

                         ⎧  Component/item features
┌─────────────┐          ⎨
│   Process   │ ═══════▷ ⎪           ⇓
│   planning  │          ⎩
└─────────────┘
                         ⎧  Process operations
┌─────────────┐          ⎨           ⇓
│   Process   │ ═══════▷ ⎪
│   control   │          ⎩  Operating requirements
└─────────────┘
```
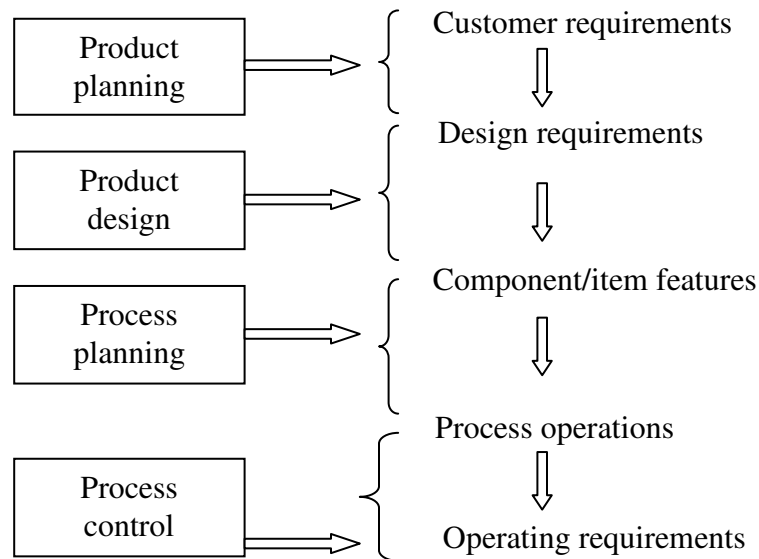
Processes to Change Shape or Form

The mechanical industries best illustrate processes to change shape or form, the best-known example being the metals machine shop. Other examples are in woodworking and plastics molding. As noted previously, the metals industry commonly produces intermediate shapes such as bars, sheets, billets, and beams which can be used as raw materials for further processing.

Assembly Processes

The modern assembly line and the kinds of activities associated with it are typical. These activities include welding, soldering, riveting, screw-fastening, stapling, and adhesive joining. Assembly processes are dominantly manual in character, with mechanical aids to reduce fatigue and increase productivity. Much of the analysis of these kinds of tasks depends on motion study and study of the relationship between the worker and his workplace and tools.

Transport Processes

Internal material handling represents one of the costly kinds of operations within a manufacturing system. The transformation involved is the transformation of place. Some of the basic layout types in manufacturing are designed to minimize transport processes and/or to take advantage of a particularly effective transport process.

Clerical and Information Processes

Clerical activities focus on the transformation of information and are characterized both by manual activity and by the most sophisticated integrated information systems. Information

systems processes are currently receiving a great deal of attention, partly because of the tremendous growth of clerical and information system costs.

NOTE:
Major factors affecting choice of process designs include:
1. Degree of automation
2. Production flexibility: product and volume flexibility
3. Nature of product/service demand
4. Level of quality

GENERAL AND SPECIAL PURPOSE EQUIPMENT

General purpose equipment finds its field of application in operations characterized by relatively low volume and/or changing part of product design. General purpose equipment meets the needs of flexibility. In a machine shop, the general purpose machines are the lathes, drill presses, grinders, etc. The large batch-type computing machines are general purpose in nature.

Special purpose equipment has ordinarily been designed for, or adapted to, a specialized highly repetitive job. For example, in a machine shop, a special drill press might be designed to drill a series of holes to a specified depth in a specified material. Such machines have ordinarily evolved from the general purpose counterparts, but have been redesigned for specialized needs because of high-volume use. Special purpose machines are likely to be expensive in cost and inflexible, resulting in low or no salvage value. On the other hand, they are ordinarily very productive for their special purpose.

AUTOMATION

Automation is a further step in the substitution of machine power for manpower. With automation, machines now perform many of the *control* functions formerly performed by human operators. The ultimate development of automation is a completely integrated automatic sequence of operations commonly termed the automated factory.

There are two main branches of automation, one requiring information feedback. The branch which does not involve information feedback is essentially the automatic handling of parts between operations in such a way that the part or product is indexed and laced in position for the subsequent operation. The entire sequence of operations is carefully coordinated, resulting in essentially a single giant machine. Automation not involving information feedback may be characterized as progressive mechanization and is often called *open loop* automation. It is common in very high volume mechanical industries such as the fabrication of automobile parts. There are basically three levels of automation: the stand-alone piece of equipment, the cell, and the completely integrated factory.

Numerical Control

One very important branch of automation is the field of computer-numerically controlled processes. It is stand-alone machines controlled by a computer. In the mechanical industries, for example, numerically controlled machine tools are under the operation control of a digital computer which specifies the positions and paths of the cutter tools. In these systems the

information feedback loops continually compare actual tool position with programmed tool position, calling for correction when necessary.

For numerically controlled machine tools there are two kinds of control. *Position control* can control the tool in two dimensions and is ideally suited for machine tools such as the drill press. Current systems use a punched tape for instructions, which are coded to indicate the beginning of a new block of data concerning the position reading for the x dimension and the y dimension. Drive motors respond to the instructions and position the tool in exactly the programmed location through the feedback control loops. The system then calls for the drill head to drill the holes and retract, finally signaling the tape unit to read in the next position. *Contour control* adds the third dimension, specifying not only position but the actual path that the cutter must take. While the programming problem is more complex with contour control, complex curves and surfaces can be specified.

Such systems have great inherent flexibility in terms of the operations and shapes which can be produced as well as in changeover from one order to the next. A major advantage is that the machine tool is not tied up during setup, since almost all of the preparation time is in programming which can be done externally to the production process itself.

Robotry

It is usually possible to develop mechanical robots to do most highly repetitive manual jobs. Only their costs stands in the way of more of them.

The Cell

The cell goes one step further, and integrates computer-controlled machines and automated material handling equipment. A particular example of a cell is the *flexible manufacturing system* (FMS). The FMS is a system that produces a family of products from start to finish using robots and other automated equipment under the control of a computer system. This ability to produce a variety of products with the same set of equipment is clearly advantageous. There may be several cells within a factory. Figure 2 illustrates such a system.

FIGURE 2

A FLEXIBLE MANUFACTURING SYSTEM
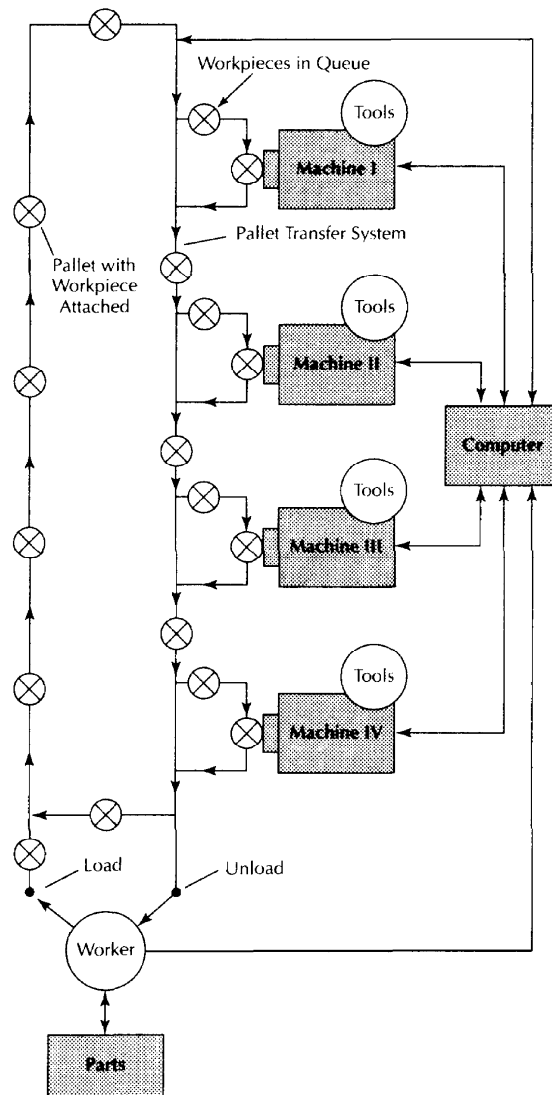
Although the initial cost of these systems is high, per unit production costs are low, quality of products is high, and product flexibility is high.

Computer-Integrated Manufacturing (CIM)

If automation is justified, it may mean installation of computer-integrated manufacturing (CIM). CIM implies the following capabilities: (1) the products are designed through the use of a *computer-assisted design system* (CAD); (2) a *computer-assisted engineering system* (CAE) is used to test the design; (3) the product is manufactured using a *computer-assisted manufacturing system* (CAM) (CAMs use computer-controlled machines and robots); and (4) an information system connects the various automated components. In a CIM system, all automated components

66

are linked by a centrally controlled information system. A major justification for investments in computer-integrated manufacturing (CIM) projects is reduction in the costs of spoilage, reworked units, scrap, and reduction in manufacturing cycle time.

Flexible Manufacturing System (FMS)

Flexible manufacturing systems (FMS) is an approach that allows manufacturing facilities to rapidly and efficiently change from making one product to another. For example, A VCR factory can use FMS to produce different models using similar facility which can be rescheduled and rearranged to fit into different manufacturing pattern. For some firms, FMS is an extension of CIM. With older systems, an assembly line was set up to make one type of product and it could take days or months to change the equipment to manufacture another model or other products. The changeover process was also costly. Today, facilities are designed to be flexible and adaptive. One major advantage of an FMS is the ability to react to market needs or competition. FMS is implemented using computer systems, robotics, and other manufacturing techniques. The trend is to let the computer make the necessary changes to the equipment, assembly lines, and other processes. Flexible Manufacturing System (FMS) is most suited for batch operations.

PROCESS PLANNING

While in the functional sense process planning begins during the engineering design of the product, in the organizational sense the term *process planning* assumes that, given the product, we must design a system for processing. This involves a total analysis of the product and its processing requirements, decisions concerning the purchase of items outside versus their internal manufacture, and techniques for selecting among competing processes.

PRODUCT ANALYSIS

Given the product design, usually summarized on engineering drawings, the various parts are subjected to an analysis to determine the necessary manufacturing steps. Product analysis is most complex for assembled products that are made up of a large number of parts. Thus, the early phases of product analysis may produce diagrams which "explode" the product into its various subassemblies and parts. These diagrams may be pictorial or schematic.

Assembly Charts

Assembly charts, often called *gozinto* charts (from the words *goes into*), are used to provide an overall *microview* of how materials and subassemblies are united to form finished products. Figure 3 shows an assembly chart constructed for the manufacture of a wood telephone stand. In the assembly chart, the assembly and inspection operations are shown with symbols on the right, and the parts and materials which flow into each assembly operation are shown on the left. Thus, we have a schematic explosion of the product showing how the various parts and materials flow together to produce the assembled unit. Basic decisions concerning the advisability of subassembly units can be made at this time. Also, consideration can be given to the advisability of purchasing various items outside versus manufacturing them internally. For example, in the telephone stand, the shellac, lacquer, and wood screws are fairly obvious candidates for outside purchase. The economic analysis of make-buy policies will be considered below.

Operation Process Charts

Given the assembly diagram, the next step is to detail the operations and inspections required to fabricate each of the parts which will be manufactured internally. This is done by extending the detail for each part. Figure 3, discussed earlier, is an operation process chart for the telephone stand. Reference to Figure 3 shows the operations and inspections required for the top, sills and legs of the telephone stand. The summary shows that 20 fabrication and assembly operations and 5 inspections are required. The time requirements in minutes per unit are shown for each of the operations, the inspections being set up for daywork operations.

FIGURE 3

ASSEMBLY CHART FOR TELEPHONE STAND
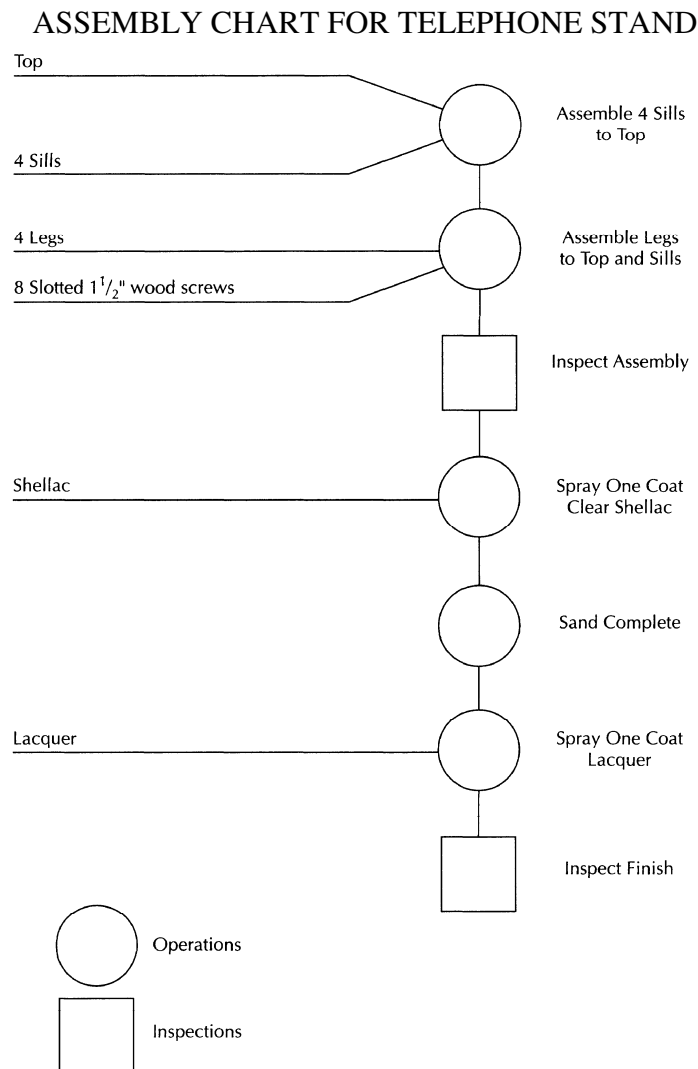
Flow Process Charts

While the operation process chart details the skeleton of activities which must be performed, it purposely leaves out the required nonproductive activities such as transport and storage. Figure 4 shows the individual steps required to process a given operation. This planning tool breaks down the operations into five classes—operation, transport, inspect, delay, and store. The frequency of occurrence of each class, distance traveled, and description and time for each step are recorded. A final step would be to draw the flow process chart on the physical layout in order to be able to visualize the physical flow of relationships and the distances traveled.

FIGURE 4

FLOW PROCESS CHART

$*$ = Points critical to the success of the service
t = Points at which failure is most often experienced
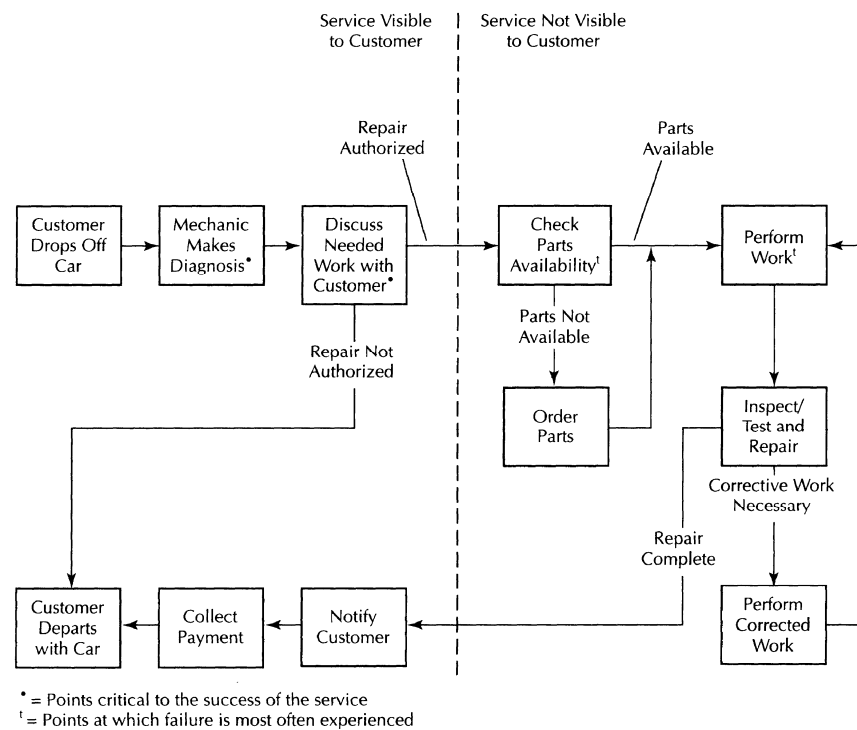
Analysis of Flowcharts

Flowcharts can be used as planning aids both for new products and for the analysis and improvement of existing products. The analytical process may be summarized by the following questions:

1. *Why* is the activity being done? This should establish the objective of the activity. If a valid objective cannot be established, perhaps the activity should be eliminated.
2. *What* is being done? Establish the value of work being done in relation to the basic objective.

3. *Where* is the activity being done? Establish that the location is the most efficient for the activity.
4. *When* is the work being done? Is this the most efficient sequence of activities?
5. *Who* does the work?
6. *How* is the work being performed? Can the activity be made simpler and easier for men and equipment?

MAKE-BUY ANALYSIS

In deciding whether a given item should be manufactured internally or purchased outside, important economic factors and some intangible and noneconomic factors influence the organization's make versus buy policies.

Economic Analysis

In general, make-buy policies will reflect the economic analysis. If internal manufacture is less expensive, that course of action will be taken. If the reverse is true, the item will be purchased outside. As noted in the materials on cost analysis, every situation must be analyzed in terms of the *incremental costs*. It can also be handled by using a simple break-even problem: Where (at what quantity) does the cost of "make" breakeven with the cost of "buy"? There are often advantages to the internal manufacture because of existing capacity. In such situations, the internal costs of manufacture may be mainly the direct costs of labor and material, equipment and overhead items being already available. On the other hand, the reverse conditions might be true, favoring outside purchase, if it were necessary to acquire special equipment in order to manufacture an item internally.

EXAMPLE 1

David Davidson, purchasing agent for Donald Corp. buys a part for $9.00 per unit. Engineers at the company estimate that they could make the part for $6 per unit, but would incur additional fixed costs of $210,000 per year. Should they make the part?

David sets the cost of "buy" equal to the cost of "make" and solves for the breakeven quantity. That is.

$$\$9x = \$6x + \$210,000$$
$$\$3x = \$210,000$$
$$x = 70,000 \text{ units}$$

So, if annual quantity is less than 70,000 units, buy the part. Otherwise, make it in-house.

Intangible Factors

Quality, reliability, availability of supply, control for trade secrets, existing patents, flexibility, and alternative sources of supply are all factors which may bear on a particular make-buy decision.


Make-Buy Policies

The policies followed by a given organization are usually based largely on the economic criterion, modified by the intangible factors. Many times, intangible factors will dominate, such as when reciprocal agreements are made with important customers or when customer goodwill is a dominating factor in the decision.

PROCESS SELECTION

When operations can be performed by more than one process, an economic analysis should normally be made to determine which process should be chosen. The analysis follows the general concepts of the breakeven charts, which we discussed earlier. For each process, we must estimate costs of setup and tooling, representing the fixed costs, and the variable costs of labor and material. These may be related graphically, as we have shown in Figure 5, which indicates the breakeven points for three lathe processes. For the particular operation in Figure 5, the engine lathe would be appropriate for quantities up to approximately 10 units, the turret lathe would be economical for quantities between 10 and 63, and the automatic screw machine would be economical for quantities above 63 units.

Other factors often dominate in process selection, such as expediency, quality control, availability, and simply preference for a particular process. Also, there are often deviations from plans at the time of production, as when the desired machine is down because of maintenance.

FIGURE 5
BREAKEVEN CHART FOR THREE LATHE PROCESSES
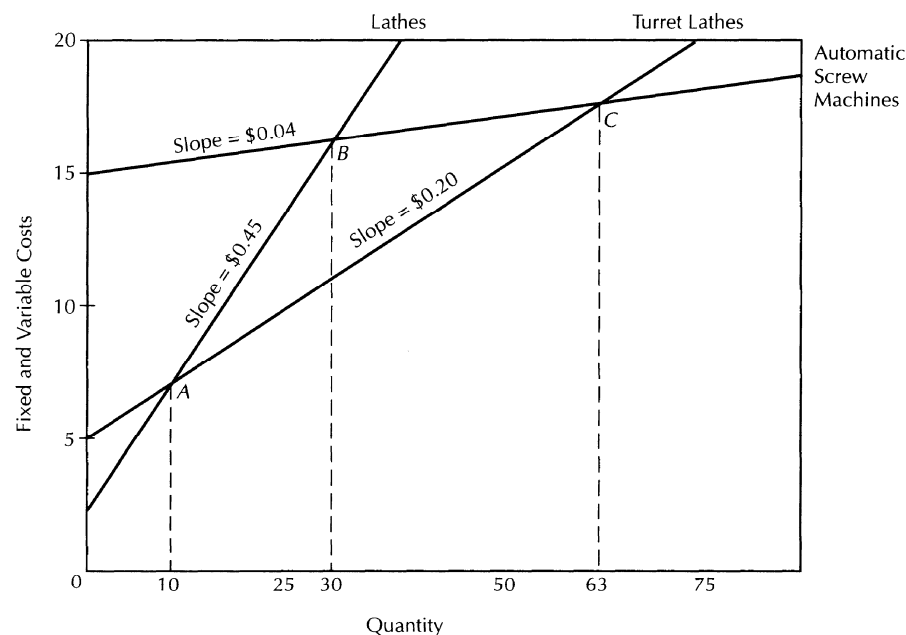
Reliability and Maintenance

Good quality in design, materials, and processes can eliminate many manufacturing problems and thus reduce cost and increase productivity. A good design should seek out possible causes of product failure and minimize their chances of occurrence. This is critical to the success of the product in the marketplace and prevention of product liability claims and excessive warranty costs.

Reliability is a term that is often confused with quality. Quality, as we defined it in Chapter 1, is conformance to specification. Reliability, on the other hand, includes the dimension of time. Specifically, *reliability* is defined as the *probability* that a product or process will perform satisfactorily over a period of time under specified operating conditions. For example, an autopart maker might state that the reliability of a 48-month auto battery is .94. This means that 94 out of 100 batteries should last 48 months under normal operating conditions (12,000 miles per year, for example).

High quality does not necessarily mean high reliability. A product may meet all the specifications, but may not last over a long period of time. However, reliability must be designed into products. This often presents a dilemma for product designers since increased reliability often means higher costs, more weight, and larger sizes of products. Thus, trade-offs are typically made between these characteristics and reliability.

Measures of Reliability

There are several important measures of reliability. They are important for product design and for establishing maintenance policies. They include:

(a) *Mean time between failures* (MTBF). Denoted by the Greek letter μ, it is a measure of reliability for products that fail and can be repaired. For example, the MTBF for a particular type of automatic nozzles on gasoline pumps might be 18 months. This means that, on the average, a failure will occur every 18 months. The MTBF is useful in developing preventive maintenance policies.

(b) *Mean time to repair* (MTTR). It is the average required to replace (or repair).

(c) *Availability* (A). It is the proportion of time the item is ready for use. The formula is

$$A = \frac{MTBF}{MTBF + MTTR}$$

(d) *Failure rate* (λ). It is the average number of failures per time period, which is measured as the number of failures per unit per time. The failure rate is defined as

$$\frac{Number \cdot of \cdot failures}{Number \cdot of \cdot units \cdot tested \cdot x \cdot total \cdot length \cdot of \cdot time}$$

For example, if 5,000 light bulbs are tested for 100 hours and 120 fail during this time period, the failure rate is

$$\frac{120 \cdot failures}{(5,000 \cdot units \cdot tested)(100 \cdot hours)} = .00024 \text{ failures per unit per hour}$$

The failure rate can also be computed as:

$$\frac{1}{\text{MTBF}} \text{ or } 1/\mu$$

(e) *Reliability* (R), which is the probability an item will work for a given time period (t) is

$$R = e^{-\lambda t}$$

where e = the base of natural logarithm = 2.718
  λ = constant failure rate
  t = length of time period

EXAMPLE 2

Mike Constas, a newly appointed director of maintenance at Hoch Eclectic, is concerned with downtime of the 48 winding machines. Maintenance records show that the mean time between failures (MTBF) is about 80 days on each machine, and that the mean time to repair (MTTR) is one day.

Availability: A = 80/(80 + 1) = 0.988 or 98.8 percent of the time.
Failure rate: λ = 1/80 = 0.0125 failures per day for each machine
Reliability: R = $e_{-0.0125(80)} = e^{-1.0} = 0.368$

In general, the failure rate of a product is not constant, but follows a pattern as shown in Figure 6.

FIGURE 6
FAILURE RATE CURVE
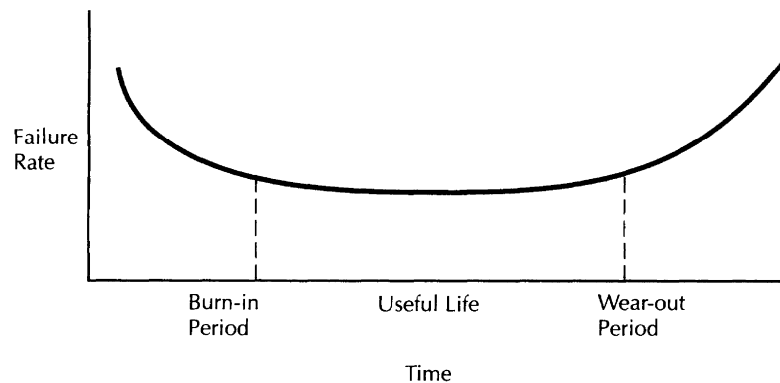
During the early period of operation, called the *burn-in, debugging*, or *infant mortality* period, the failure rate is high. This is often caused by poor materials or lack of quality. In the next phase, the failure rate is lower and somewhat stable. At the last stage, the product begins to wear out and the failure rate rises.

When the product enters the wear-out phase, the probability distribution of remaining life is sometimes depicted by the bell-shaped, normal distribution. If the mean and variance of product life are known, we are able to compute the probability that the remaining life will exceed a given life.

EXAMPLE 3

From actual road tests, a new steel-belted tire was estimated to have the mean tire mileage μ = 36,500 miles and the standard deviation, σ = 5,000 miles. Suppose that a 36,000-mile warranty mile is contemplated. What percentage of tires can be expected to last more than 42,000 miles? The situation can be seen as trying to find the area of the shaded region in Figure 7.

FIGURE 7
TIRE MILEAGE

Probability that
x exceeds 42,000
= 0.1357 = 13.57%

μ = 36,500   42,000

Mileage x
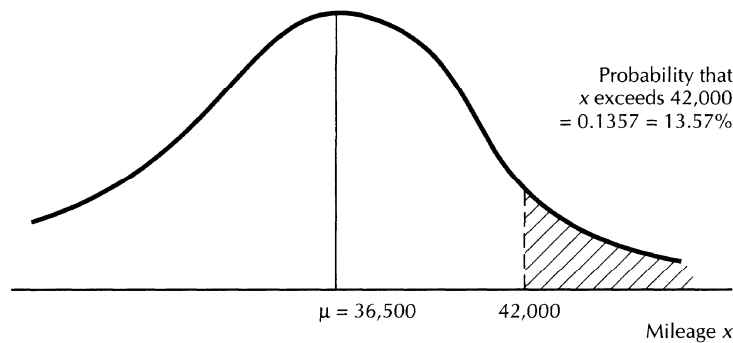
At x = 42,000 miles, we have

$$z = \frac{x - \mu}{\sigma} = (42,000 - 36,500)/5,000 = 1.1$$

From Table 1 (Normal Distribution Table) in the Appendix, we find that this area is .5000 - .3643= .1357, which means that about 13.57% of the tires will exceed 42,000 miles. In other words, if the warranty is set 42,000 miles, for example, then 86.43 percent of the tires will wear out before 42,000 miles.

PROCESS RELIABILITY

Many production systems are comprised of several machines or operations in series. For example, individual parts are transferred from one operation to the next by a robot; thus if one machine or robot fails, the entire production process must stop. If we know the individual reliability of each machine, we can compute the total reliability of an *n*-machine series system, R, by taking the product of the individual reliabilities;

$$R = R_1 R_2 \ldots R_n$$

| Robot | → | Turing | → | Milling | → | Grinder |
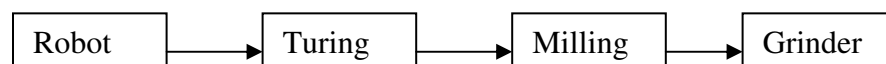
If we assume that the reliability of the robot, turning center, milling machine, and grinder are .99, .98, .99, and .96, then the total reliability is

$$R=(.99)(.98)(.99)(.96) = .92$$

Thus there is 92% chance that the system will be working over a specified period of time. This calculation assumes that each operation is independent of the others.

Suppose that the system is redesigned with two grinders. We say that the grinders are in *parallel,* as shown below, because even if one fails, the system can still operate.
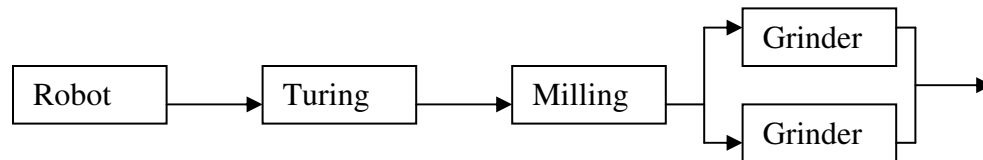
We compute the reliability of the parallel grinders by using the following formula:
$$R = 1 – (1 – p_1)(1 – p_2)…(1 – p_n)$$
p_j is the reliability of the *j*th component in parallel. Thus if each grinder has a reliability of .96, the reliability of both grinders is
$$R_{grinders} = 1 – (1 - .96)(1 - .96) = 1 - .0016 = .9984$$
Notice that total grinder reliability has increased considerable by adding the extra machine.

To compute the total system reliability, use .9984 as the reliability of the grinders. Basically, we replace the parallel grinders with one grinder having a reliability of .9984, as follows:
$$R= (.99)(.98)(.99)(.9984) = .96$$

NOTE:

If a series system has parallel components, we first compute the reliability of the parallel components using the formula, $R_{grinders}$ and then apply the original formula to compute total system reliability. Adding extra machine helps increase reliability. But good quality control and testing, improved production methods, better materials, and preventive maintenance are other ways.

MAINTENANCE

When production machines break down, we must absorb the costs of downtime and possible lost sales, idle direct and indirect labor, delays in dependent processes and increased scrap, as well as the costs of maintenance and repair. In designing maintenance programs, our objective is to balance the costs of maintenance and repair against the costs which result from breakdown. The policies under managerial control which can be used to optimize the maintenance system are:
1. Determining the appropriate level of preventive maintenance.
2. Determining the size of repair facilities and crews.
3. Determining the appropriate level of slack in the system at critical stages.

A fundamental point to keep in mind about the reliability of systems in general and of machines in particular relates to series and parallel components. When a large number of

components must function in series, if any one of the components fails, the system fails. For example, a machine made up of 50 components in series, each with an average reliability of 99.5 percent, has a system as a whole reliability of only 80 percent. Thus, while the probability of component breakdown is very small, system reliability may not be very good. This is the basic reason why complex machines are likely to be prone to breakdown.

PREVENTIVE MAINTENANCE
The concept behind a preventive maintenance program is to find a cycle for preventive maintenance which anticipates some substantial fraction of breakdowns before they occur. Thus, while preventive maintenance would have to occur more often than the average breakdown, in some cases such servicing may prevent the occurrence of certain kinds of costs associated with machine downtime.

ECONOMIC TRADE-OFFS IN MAINTENANCE
The principal objective of maintenance is to maintain equipment in good condition. This results in improved efficiency of labor, reduction of downtime due to unexpected breakdowns, and a general increase in productivity. An efficient maintenance program also keeps costs down in relation to the level of production. There are two types of maintenance activities: repair due to machine failure and preventive maintenance. Determining an appropriate maintenance policy for a piece of equipment should take into account the economic and operational trade-offs involved. Figure 8 illustrates these economic trade-offs that are typical of preventive maintenance problems.

FIGURE 8
ECONOMIC TRADE-OFFS IN MAINTENANCE
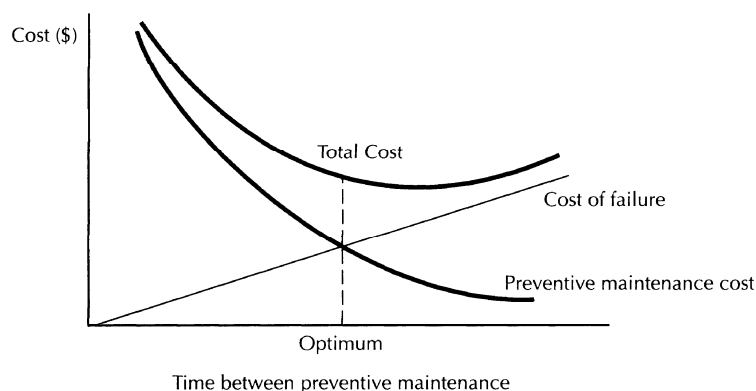
The following example illustrates how reliability data can be used to determine an appropriate maintenance policy.

EXAMPLE 4
A part of a bath-room-tissue production system is a saw/wrapper machine, which cuts long rolls into smaller pieces and wraps them into packages prior to placing them into cartons. The mean time between failures (MTBF) is currently 34 hours. At present, the machine is repaired only when it fails, at an average cost of $50. The company is considering a preventive

maintenance program that will cost $30 for each inspection and adjustment. The question is: should this be done, and if so, how often should preventive maintenance occur?

To find the best policy, we compute and compare average annual cost.
Consider, for instance, the current policy. Assuming 260 working days per year and 1 shift per day, there are 2,080 hours of available time. If the mean time between failures is 34 hours, then we expect 2,080/34 = 61.2 breakdowns per year. Hence the annual cost will be (61.2)($50) = $3,060. Now suppose that the machine is inspected every 25 hours and adjusted. If we assume that the time until the next failure after adjustment follows the distribution in Figure 8, then the probability of a failure under this policy is zero. However, inspection every 25 hours will occur 2,080/25 =83.2 times per year, resulting in a cost of (83.2)($30) =$2496. Next suppose we inspect every 30 hours.

From Figure 7, the probability of a failure occurring before the next inspection is .20. Thus the total expected annual cost will be the cost of inspection, ($30)(2,080/30) =$2080, plus the expected cost of emergency repair ($50)(2,080/30)(.2) =$693. The total is $2,773. We may perform similar calculations for other maintenance intervals. The results are shown in Figure 10. Thus we see that a maintenance interval of 25 hours results in a minimal cost policy.

FIGURE 9
PROBABILTIY DISTRIBUTION OF TIME BETWEEN FAILURES

Time between failures	Probability
27.5	.2
32.5	.4
37.5	.3
42.5	.1

FIGURE 10
COST COMPUTATION FOR PREVENTIVE MAINTENANCE

(1) Time between inspections	(2) Number of inspections per year	(3) Probability of failure before next inspection	(4) Inspection costs	(5) Failure costs	Total costs
25	83.2	0	$2,496	$0	$2,496
30	69.3	.2	$2,080	$693	$2,773
35	59.4	.6	$1,782	$1,782	$3,564
40	52	.9	$1,560	$2,340	$3,900

NOTE:
In this example, note that as the time between inspections increases, the inspection cost decreases, but the failure cost increases. These economic trade-offs are typical of preventive maintenance problems and will generally follow a graph similar to that of Figure 8.

Capacity Planning

Capacity is the rate at which work is normally produced or the amount of output actually achieved. No single measure of capacity will be appropriate in every situation. Table 1 provides some examples of commonly used measures of capacity. Three definitions of capacity are useful:

(a) Design capacity: the maximum output that can possibly be achieved.
(b) Effective capacity: the maximum possible output given quality factors, product mix, machine maintenance, scheduling difficulties, etc.
(c) Actual output: the rate of output actually attained. It is typically less than the effective output due to machine breakdowns.

Production typically is planned sales (forecasted sales) plus desired ending inventory minus beginning inventory. It can be constrained , however, by:
1. Machine breakdowns
2. Shortage of materials
3. Lack of skilled labor
4. Other related problems

These different measures of capacity are useful in defining two measures of system effectiveness: efficiency and utilization. *Efficiency* is the ratio of actual output to effective capacity, while *utilization* is the ratio of actual output to design capacity.

$$\text{Efficiency} = \frac{\text{Actual} \cdot \text{output}}{\text{Effective} \cdot \text{capacity}}$$

$$\text{Utilization} = \frac{\text{Actual} \cdot \text{output}}{\text{Design} \cdot \text{output}}$$

Efficiency may be misleading when effective capacity is low compared with design capacity. In this situation, high efficiency appears to indicate effective use of capacity when, in reality, this is not the case.

EXAMPLE 5

Given the data on relevant capacity definitions:

Design capacity = 100 cars per week
Effective capacity = 80 cars per week
Actual output = 72 cars per week

$$\text{Efficiency} = \frac{\text{Actual} \cdot \text{output}}{\text{Effective} \cdot \text{capacity}} = 72/80 = 90\%$$

$$\text{Utilization} = \frac{\text{Actual} \cdot \text{output}}{\text{Design} \cdot \text{output}} = 72/100 = 72\%$$

Note here that 90% use of effective capacity is quite satisfactory, but compared with the design capacity of 100 units per week, 72% is mush less impressive.

Decisions as to whether to expand capacity can be strategic or tactical. Strategic decisions involve the size of facilities, the amount of equipment available and/or the amount of labor and materials available. Tactically, capacity can be increased by way of (a) adding one more shift, (b) going into overtime, and/or (c) outsourcing. Strategic requires long-term capital expenditures.

TABLE 1
MEASURES OF CAPACITY

Types of business	*Input measures*	*Output measures*
Oil refinery	Size of refinery	Barrels of fuel oil per day
Retail sales	Number of square feet	Units sold per day
Theater	Number of seats	Number of performances per week
Steel mill	Size of furnace	Tons of steel per week
Airline	Number of seats	Number of flights
Auto manufacturing	Machine hours/labor hours per month	Number of cars per shift

EVALUATING ALTERNATIVE CAPACITIES
There are several ways to evaluate alternative capacities, including
1. Cost-Volume-Profit (CVP) analysis
2. Capital budgeting
3. Decision tree approach to capacity decisions

COST-VOLUME-PROFIT AND BREAK-EVEN ANALYSIS
Cost-volume-profit (CVP) analysis allows operations managers to perform many useful analyses. CVP analysis deals with how profit and costs change with a change in volume. More specifically, it looks at the effects on profits of changes in such factors as variable costs, fixed costs, selling prices, volume, and mix of products sold. By studying the relationship of costs, sales, and net income, management is better able to evaluate capacity alternatives. *Break-even analysis*, a branch of CVP analysis, determines the break-even sales. The break-even point represents the level of sales revenue that equals the total of the variable and fixed costs for a given volume of output at a particular capacity use rate. For example, you might want to ask the break-even occupancy rate (or vacancy rate) for a hotel or the break-even load rate for an airliner.

The *equation approach* is based on the cost-volume-profit equation which shows the relationships among sales, variable and fixed costs, and net income.

$$TR = TVC + TFC + \text{Net Income}$$

At the break-even volume, TR = TVC + TFC + 0. Defining Q = volume in *units*, the above relationship can be written in terms of x:

$$PQ = AVC \, Q + TFC$$
$$(P - AVC)Q = TFC$$

Solving for Q yields the following formula for break-even sales volume:

$$Q = \frac{TFC}{(P - AVC)} = \frac{\text{Total Fixed costs}}{\text{Unit CM}}$$

The term (P - AVC) is called the *unit contribution margin* (CM), because it is the profit contribution that each unit sold will make toward covering fixed cost and generating profit.

EXAMPLE 6
     A firm is considering three capacity alternatives: A, B, and C. Alternative A would have an annual fixed cost of $100,000 and variable costs of $22 per unit. Alternative B would have an annual fixed cost of $120,000 and variable costs of $20 per unit. Alternative C would have an annual fixed cost of $80,000 and variable costs of $30 per unit. Revenue is expected to be $50 per unit.
Using the formula:

$$Q = \frac{TFC}{(P - AVC)} = \frac{\text{Total Fixed costs}}{\text{Unit CM}}$$

Break-even quantities for A, B, and C are:

$Q_A = \$100,000/(\$50 - 22) = 3,571$
$Q_B = \$120,000/(\$50 - 20) = 4,000$
$Q_C = \$80,000/(\$50 - 30) = 4,000.$
A has the lowest break-even quantity.

DECISION TREE APPROACH TO CAPACITY DECISIONS
     Based on the industry supply and demand analysis, Madden Corporation wishes to build a full-scale manufacturing facility. It is considering:
     A. Build a large plant, costing $6 million.
     B. Build a small plant, costing $2 million.

The probabilities of various demands and present values of projected cash inflows for these demand situations are given below.

Action	Demand Conditions	PV of Cash Inflows ($)	Probabilities
A	High	$8 million	0.5
	Medium	4 million	0.3
	Low	1.5 million	0.2
B	High	$2.5 million	0.5

		PV of		
	Medium	2 million	0.3	
	Low	1.5 million	0.2	

We can construct a decision tree to analyze the two options.

Expected NPVs for A and B are as follows:

Action	Demand Conditions	PV of Cash Inflows ($) (1)	Probabilities (2)	(1)x (2)
A	High	$8 million	0.5	$4 million
	Medium	4 million	0.3	1.2 million
	Low	1.5 million	0.2	.3 million
			PV	$5.5 million
			I	6 million
			Expected NPV =	-0.5 million
B	High	$2.5 million	0.5	$1.25 million
	Medium	2 million	0.3	.6 million
	Low	1.5 million	0.2	.3 million
			PV	$2.15 million
			I	2 million
			Expected NPV =	0.15 million

You may choose option B since its expected NPV is greater than option A's. In fact, option A has a negative NPV. This approach does not tell us how risky each option is.

QUESTIONS
1. What role do assembly drawings, parts lists, and assembly charts play in process design?
2. Discuss the principal differences between general-purpose and special-purpose equipment and the selection decision.
3. List some of the major types of material-handling equipment and their applications in manufacturing.
4. What are the essential differences between continuous-flow, mass production, batch processing, job shop, and project systems?
5. What are the limitations of *quality function deployment (QFD)* for designing a product/service?
6. Discuss the importance of reliability in production systems.
7. What types of maintenance activities are commonly performed? How does a manager determine preventive maintenance policies?
8. Define *capacity*.
9. What does capacity planning involve?
10. List three popular approaches to evaluation capacity alternatives.

PROBLEMS
1. The maintenance records show the following historical time between failure and repair time for a certain punch press. The first breakdown happened on May 5.

Date	May 5	June 6	July 19	Sep. 7	Oct. 30
Number of hours of use before breakdown	221	335	190	250	284
Number of hours spent on repair	12	18	16	10	14

(1) Calculate the following:
   (a) The mean time between failures
   (b) The mean time to repair
   (c) The availability of the machine
   (d) The average number of failures per time period.
   (e) The reliability of the machine in 256 hours of use.
(2) The machine is used 8 hours a day, 20 days per month, on the average. A contract requires 160 hours of the machine time and is due within one month. Calculate the probability that the machine will not break down during this period and will not cause a delay.

2. Given the following system (the probability of failure of each component is shown below each box), what is the overall reliability of the system?


```
┌─────────┐      ┌─────────┐      ┌─────────┐
│    A    │─────▶│    B    │─────▶│    C    │
└─────────┘      └─────────┘      └─────────┘
    0.05             0.12             0.09
```
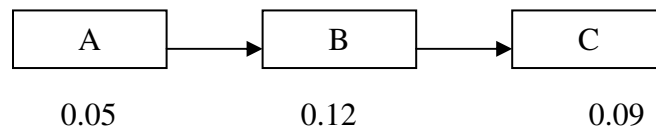
If the component B is backed up with another component with a probability of failure = 0.05, what is the overall reliability?

3. The lifetime of a new stereo is estimated to be 8 years with a standard deviation of 1.5 years.
   (a) Determine the probability of the stereo failing after 4 years.
   (b) If there is a full replacement guarantee of 3 years, what is the expected proportion of replacement?
   (c) If the company is willing to replace up to 5%, what guarantee period should it specify?

4. The probability of breakdown of Machine A versus the number of hours elapsed after previous maintenance is given below.

Number of hours after previous maintenance	Probability
10	0.01
20	0.05
30	0.15
40	0.15
50	0.15
60	0.15
70	0.20

| 80 | 0.14 |

The number of working days in a year is 250 on a 2-shift basis. A breakdown costs $350 to repair, and a preventive maintenance costs $150. Determine:
  (a) The mean time between failures (MTBF)
  (b) The maintenance cost if no preventive maintenance is followed.
  (c) The cost of a preventive maintenance policy carried out once every 10 hours.
  (d) The best maintenance policy. Decrease the frequency of preventive maintenance in increments of 10 hours and evaluate total costs.

5. A firm buys a stock item at a cost of $5 each. The company can make the item by incurring a one time fixed cost of $10,000, and variable cost of $3 per unit. What is the breakeven quantity? What does this quantity mean?

6. A solar panel maker is making a decision about whether to make or buy a part. If the firm invests $3,500 in a new die, it will be able to make this part in-house for an added cost of $1 per unit in variable costs. If, however, it buys the part, the vendor has quoted two prices, $1.55 each for quantities up to 10,000 units and $1.30 each for all orders of over 10,000. Calculate the two break-even crossover points.?

7. Title Insurance Co. processes all titles sequentially through four centers. The capacity and actual average output of each individual work station is given below.

Work station	A	B	C	D	Actual average output
Number of titles	25	30	23	39	19 titles per day

Calculate (a) the effective capacity of the system, (b) efficiency, and (c) utilization, assuming design capacity of 39 titles.

ANSWERS

1. In order to select appropriate processes and equipment, one must first understand what is being produced. Assembly drawings, parts lists, and assembly charts provide information about the individual components that must be made and assembled.
2. Special-purpose equipment may only be limited to a few uses whereas general-purpose equipment can handle a large variety of jobs. One should consider the variety of work available, output rate desired, and cost when selecting between these two types of equipment.
3. Industrial trucks- used to move large items between many locations; good for warehouse operations. Conveyors- used for uniform loads over fixed paths; good for production lines or in-process storage and inspection. Cranes- used when floor space utilization makes forklifts undesirable or when products are bulky and heavy and require frequent movement. Automated storage and retrieval systems- used primarily in warehouses for fast turnover of uniform loads. Tractor-trailer systems- used for large volumes or bulky of heavy material over long distances.
4. The differences can be classified by product volume, variety, degree of automation and frequency of setup or change.

5. The QFD approach can be very time consuming, it is based on customer perceptions, and the results reflect a compromise on consumer wants. Nevertheless, meaningful results can be achieved if the approach is effectively applied to important dimensions of the product.
6. A process with low reliability will usually incur high costs, lower productivity, and lower quality of the product being made. It also will cause scheduling problems within the plant and lead to customer dissatisfaction.
7. Repair due to failure, preventive maintenance. A preventive maintenance policy is determined by analyzing the expected cost for various time intervals between inspections based on failure probabilities. In general as the time interval increases, failure costs increase while inspection costs decrease. The minimum cost time interval is sought.
8. Capacity refers to a system's potential for producing goods or delivering services over a specified time interval.
9. Capacity planning involves both long-term and short-terms considerations. Long-term consideration relates to the overall level of capacity, while short-term concern relates to variations in capacity requirements due to seasonal, random, irregular fluctuations in demand.
10. Three popular approaches to evaluation capacity alternatives are (a) cost-volume-profit (CVP) analysis, (b) capital budgeting, and (c) decision tree approach to capacity decisions.

SOLUTIONS TO PROBLEMS

1.
(1)

    (a) MTBF = μ = (221 + 335 + 190 + 250 + 284)/5 = 256 hours

    (b) MTTR = (12 + 18 + 16 + 10 + 14)/5 = 14 hours

    (c) A = 256/(256 + 14) = 0.948

    (d) λ = 1/μ = 1/256 = 0.0039 failure per hour

    (e) R = $e^{-\lambda t}$ = $2.7183^{(-0.0039 \times 256)}$ = 0.368

(2) R = $e^{-\lambda t}$ = $2.7183^{(-0.0039 \times 160)}$ = 0.535

2.
Reliability of the first system = (0.95)(0.88)(0.91) = 0.7608.
For the system shown below:
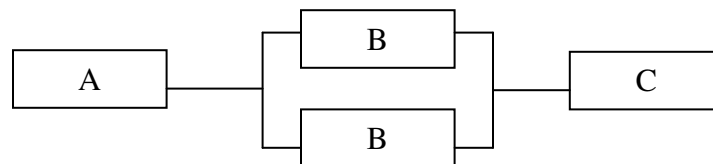
Reliability = R_A x R_B x R_C = 0.95 x [1 – (0.12)(0.15)] x 0.91 = .95 x 0.982 x 0.91 = 0.85
Thus, the reliability in the second system is improved from 0.76 to 0.85.

3.
(a) For a useful life of 4 years,

$z = \dfrac{x - \mu}{\sigma}$ = (4 – 8)/1.5 = -2.67 . The probability that the product fails within 4 years is 0.0038 (1 – 0.9962).

(b) z = (3 – 8)/1.5 = -.33. The probability is 0.0004 (1 – 0.9996).

(c) For replacement probability of 0.05 which corresponds to z = 1.65

$z = \dfrac{x - \mu}{\sigma}$; 1.65 = (x – 8)/1.5; solving for x yields 5.525 years. Thus the firm can afford to

specify a guarantee period of as high as 5 years.

4.

(a) MTBF = (10)(0.01) + …. + (80)(0.14) = 54.2 hours.

(b) Cost of breakdown repair = number of breakdowns expected x repair costs = (4,000/54.2) x $350 = $25,830

(c) The cost of preventive maintenance policy of every 10 hours:

Preventive maintenance cost = (4,000 hours/10 hours) x $150 =   60,000

Breakdown cost = (4,000/10)(0.01)($350) =   1,400

    Total $61,400

(d)

Cost Computation for Preventive Maintenance

(1) Time between inspections	*(2)* Number of inspections per year	*(3)* Probability of failure before next inspection	*(4)* Inspection costs	*(5)* Failure costs	Total costs
10	400	0.01	60,000	1,400	61,400
20	200	0.06	30,000	4,200	34,200
30	133	0.21	19,950	9,776	29,726
40	100	0.36	15,000	12,600	27,600
50	80	0.51	12,000	14,280	26,280
60	67	0.66	10,000	15,477	25,477
70	57	0.86	8,571	17,157	25,728

Preventive maintenance policy every 60 hours gives the lowest total costs.

5.

David sets the cost of "buy" equal to the cost of "make" and solves for the breakeven quantity. That is.

$$\$5x = \$3x + \$10,000$$
$$\$2x = \$10,000$$
$$x = 5,000 \text{ units}$$

The break-even quantity is 5,000 units. At this quantity, buying or making costs the same. If annual quantity is less than 5,000 units, it is less costly to buy the part. Otherwise, make it in-house.

6.

Because of the price discount, we buy over 10,000 units. We need to compute two break-even crossover points, one comparing each purchase price with in-house manufacturing costs:

$$\$1.55x = \$3,500 + \$1x$$

$$\$.55x = \$3,500$$
$$x = 6,364 \text{ units}$$
$$\$1.30x = \$3,500 + \$1x$$
$$\$.30x = \$3,500$$
$$x = 11,667 \text{ units}$$

Because there is no start-up cost involved and no machine to buy, buying the part would always be less costly for all small quantities. The figure below indicates that although buying would be less costly up to 6,364 units, making is less costly thereafter. The volume-price discount at the 10,000 unit mark complicates matters. For quantities just over 10,000, again it pays to buy but only up to 11,667 units, after which it again is profitable to make.

7.
   (a) Effective capacity = capacity of most limited component in the line = 23 titles per day
   (b) Efficiency = 19 titles per day/23 titles per day = 82.6%
   (c) Utilization = 19/39 = 48.7%

CHAPTER 5
FACILITY LOCATION PLANNING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Explain a locational break-even analysis.
2. Demonstrate factor ratings.
3. Illustrate the center-of-gravity method.
4. Outline and discuss the transportation LP problem.
5. Explain how the northwest corner rule works.
6. Describe Vogel's approximation method (VAM).
7. Illustrate the MODI (modified distribution) method.
8. Demonstrate the stepping-stone method.

In its strategy formulation, a company determines what types of goods or services it will offer and in what markets it will compete. It makes demand forecasts to estimate the demand that can be found in various markets. Part of the company's strategy consists of selecting the location from which potential markets will be served. The location of a service operation helps determine how conveniently customers can conduct business with the company.

Location of production and service operations can have a great impact on investment and operating costs, thereby affecting profits and perhaps the price at which goods or services can be offered, as well as some aspects of the productive system design. While location is a factor of importance, ordinarily many alternative locations can be equally good. While normally plant location is considered or reconsidered consciously only periodically, in some sense broad alternatives are considered whenever an expansion or contraction is necessary.

FACTORS IN LOCATION
Rational decisions concerning plant location are intended to minimize relevant costs. Normally, however, we are thinking of not only operating costs but also costs in the longer term. Thus, differences in operating costs might be compensated for in the longer term by differences in capital investment.

A wide variety of subjective factors can influence location decisions. Therefore, it is common to rate alternative locations on such subjective factors as the following.

1. Labor supply.
2. Type of labor.
3. Labor union activity.
4. Community attitude.
5. Appearance.

6. Transportation.
7. Availability of utilities.
8. Recreational facilities.

While these factors are subjective, we are really thinking of long term costs in attempting to rate alternative locations on the basis of these dimensions. Thus, a tight labor supply or heightened union activity could mean higher labor costs in the future. A community attitude oriented against industry could mean a future tax loading on intruding business.

One of the most important subjective factors in location analysis is the personal preference of the owners and managers. In fact, personal preference may well dominate as a factor in the location of single-plant enterprises. Multiplant enterprises are much more likely to be influenced primarily by objective and subjective economic factors.

SITE SELECTION

Given a general area for location, a site within the area must then be chosen. The following requirements must be met.

1. A site zoned for the activity contemplated.
2. A site large enough to accommodate present floor plan needs and room for expansion, parking, transportation facilities, etc. Normally a site size five times the actual plant area is regarded as the minimum.
3. Provision for necessary transportation facilities, utilities, and waste disposal.
4. A soil structure that can carry the required bearing loads of foundations.

Alternative sites also need to be studied from the point of view of the relation of investment versus operating cost effects. The concept of breakeven analysis can be used to compare various sites on the basis of total costs relative to volume of operation. Thus, a site which may require large capital expenditure but which makes possible low operating costs may be a more economical site than one that has the reverse cost characteristics.

MULTIPLANT LOCATION

When the addition of a proposed plant produces a multiplant situation, then each alternative plant location must be considered in the framework of a production-distribution system. In such a situation, the linear programming models (discussed in Chapter 2) and transportation linear programming (to be discussed later in the chapter) represent a valid conceptual framework. Each alternative location would produce a different allocation of shipments to distribution points, depending on the relative costs of production and distribution in the network. Thus, the location which produces the minimum cost for the system would be the one favored in objective terms.

For the Multiplant situation, locational dynamics affect the operation of plants from period to period as markets change. For example, if overall demand were to decline, it might be more economical to close one plant and operate the other plants at higher capacities, even using

more costly capacity units, such as overtime. Again, linear programming distribution methods are a value in appraising the various alternatives.

SPECIAL CONSIDERATIONS IN LOCATION DECISIONS

Over the last decade many factors have shifted in relative importance to the location decision process. New emphasis is being placed on energy availability, energy costs, and pollution problems. Often companies that have a history of pollution, or that manufacture products which by known production processes generate pollutants have met with community resistance when they sought to locate plants in a given geographical area. Consequently, the added costs of pollution control equipment, state environmental compliance, disposal of toxic by-products, and monitoring efforts must be considered part of the overall cost determination.

The rapid growth of energy costs and national efforts to reduce dependence on foreign energy sources, impacts the location decision: A company must determine whether the available public utilities are capable of supplying its energy needs on an uninterrupted basis and must consider the possibility of alternative approaches to generating power, such as solar energy and energy recycling. Coupled with energy considerations are the attitudes of personnel working in Sunbelt versus non-Sunbelt locations. Extreme climatic conditions which cause excessive energy use and delays in the distribution and receipt of materials are being avoided.

Another factor which must be considered are the taxes of the community and state in which the plant could be located. These taxes include not only normal taxes on business profits but also requirements for contribution to unemployment compensation, taxes on inventories, and local taxes.

Many communities offer a wide variety of help to companies which plan to locate in them. This help ranges from supplying detailed information on site locations, land costs, etc., to direct subsidies, financed by industrial revenue bond issues, to defray the cost of plant production. Since many of these bond issues are tax-free municipal bonds, their use lowers the cost of capital for plant construction. In some cases, communities build plants to specifications and lease them to companies over an extended period, thereby allowing the companies to avoid the high expenditures associated with plant construction.

Location Decisions

There are several methods that help management decide on a location for facilities. They include:

(a) Locational break-even analysis
(b) Factor ratings
(c) The center-of-gravity method
(d) Transportation linear programming

LOCATIONAL BREAK-EVEN ANALYSIS

Potential locations can be compared on an economic basis by estimating the variable and fixed costs and then graphing them for a representative sales or production volume at each location. Assuming equal revenues from all locations considered, you would select the location

with lowest total cost. Otherwise, revenue figures must be also included in your analysis, and comparisons should be made on the basis of profit (total revenue minus total cost) at each location.

EXAMPLE 1
　　Management is considering three potential sites for plant facilities, which have the following cost structure for a product expected to sell for $200. Find the most economical location for an expected sales volume of 4,000 units per year.

Potential location	Variable cost per unit	Fixed cost per year
Cambridge (X)	$75	$150,000
Austin (Y)	50	200,000
San Jose (Z)	25	400,000

For each location, compute the fixed cost (costs at zero volume) and total costs (TC) at the expected volume, Q.

$$TC = FC + VC(Q)$$

X: TC = $150,000 + $75 (4,000) = $450,000
Y: TC = $200,000 + $50 (4,000) = $400,000
Z: TC = $400,000 + $25 (4,000) = $500,000
The most economical site is Y since it is the least expensive.

Factor Ratings
　　Factor ratings is a procedure in which each alternative site is rated according to each factor relevant to the decision, and each factor is rated according to importance. Weights may total 1.00. We score each location and multiply the scores by the weights. Total the points for each location and choose the location with the maximum points. The technique is popular since (1) it enables managers to bring diverse locational considerations into the evaluation process and (2) it fosters consistency of judgment about location alternatives.

EXAMPLE 2
　　A firm is considering two sites, A and B, for its research laboratory. The following is the list of factors to be considered and their associated weights and ratings.

Factors	Weights	A		B	
		Score	Weighted score	Score	Weighted score
Labor supply	.33	40	13.20	30	9.90
Markets	.25	80	20.00	80	20.00
Environment	.20	70	14.00	45	9.00
Material supply	.05	70	3.50	50	2.50
Site and construction cost	.02	60	1.20	90	1.80
Operating cost	.15	90	13.50	50	7.50
Total score			65.40		50.70

Based on the total weighted score, A should be chosen.

The Center-of-Gravity Method

The *center-of-gravity method* is a method used to determine the location of a distribution center that will minimize transportation costs. The method treats shipping cost as a linear function of the distance and the quantity shipped. We assume, however, that the quantity to be shipped to each destination is fixed. The coordinates of the center of gravity (i.e., the location of the distribution center) can be obtained by finding the *weighted* average of the *x* coordinate and the *weighted* average of the *y* coordinate, with weights being the quantities to be shipped, i.e.,

$$\bar{x} = \sum x_i Q_i / \sum Q_i$$
$$\bar{y} = \sum y_i Q_i / \sum Q_i$$

where Q_i = Quantity to be shipped to location i.
    x_i = x coordinate of destination i
    y_i = y coordinate of destination I
Note: if the quantities shipped are equal, simple averages will do with Q_i terms.

EXAMPLE 3
    Given the following data:

Destination	(x,y)	Quantity
A	3,5	800
B	5,1	900
C	6,7	200
D	8,4	100

The center of gravity can be determined as follows:

$$\bar{x} = \sum x_i Q_i / \sum Q_i = \frac{3(800) + 5(900) + 6(200) + 8(100)}{800 + 900 + 200 + 100} = \frac{8900}{2000} = 4.45$$

$$\bar{y} = \sum y_i Q_i / \sum Q_i = \frac{5(800) + 1(900) + 7(200) + 4(100)}{800 + 900 + 200 + 100} = \frac{6700}{2000} = 3.35$$

The idea behind this method is to pick the site close to the center of gravity.

Transportation Linear Programming

Transportation linear programming is useful in location planning. This method may be helpful especially after the initial screening phase has narrowed the feasible alternative sites. The remaining candidates can then be evaluated on the basis of the criterion, which is typically minimum overall transportation cost. The transportation method of linear programming is most suitable for multiple supply, multiple warehouses.

The *transportation method* is a special form of linear programming whose objective is to assign sources to destinations so as to minimize total shipping costs. It involves the following steps:

Step 1: Set up the transportation table so that the total number of shipments available equals to the number of shipments needed.
Step 2: Develop an initial feasible solution by using
- Northwest Corner Rule or
- Vogel's Approximation Method (VAM)
Step 3: Test the solution for improvement using
- MODI (Modified Distribution) Method or
- Stepping-Stone Method
Step 4: Repeat steps 3 and 4 until no further improvement is possible.

NOTE:

Initial solutions	Optimal solutions
▪ Northwest corner	▪ Stepping-stone
▪ Vogel's approximation (VAM)	▪ Modified distribution (MODI)

We only cover the northwest corner rule here.

Northwest Corner Rule
1. Starting with the far left-hand side corner, set the level of this route at either the requirements or the availability, whichever is smaller.
2. Proceed across the table in a general northwest-to-southeast direction, exhausting the availabilities of one row before moving down to the next and exhausting the requirements of one column before moving on to the next.

EXAMPLE 4

	A	B	C	D	Supply

1	2	4	1	3	300
2	8	2	6	5	300
3	6	1	4	2	200
Demand	200	200	300	100	800

Using the *northwest corner rule yields* the following initial feasible solution:

	A	B	C	D	Supply
1	2 200	4 100	1	3	300
2	8	2 100	6 200	5	300
3	6	1	4 100	2 100	200
Demand	200	200	300	100	800

For this solution, the cost is 200(2) + 100(4) + 100(2) + 200(6) + 100(4) + 100(2) = $2,800.

Special Problems
    There are two cases associated with the transportation problem that need special attention.
1. The unbalanced problem
    (a)   Demand less than supply: Create a fictitious destination (or dummy destination)
    (b)   Demand greater than supply: create a dummy plant having a capacity exactly equal to the additional demand.
2. Degeneracy

    This is a situation in which (a) there may be an excessive number of used cells in a solution or (b) there may be an insufficient number of unused cells in a solution. When degeneracy exists, a very simple "patch-up" will solve the problem. We simply place ε (epsilon), an exceedingly small number in some cells. The cell with this in them can be used as stepping stones but have no effect on the cost of a solution, so if epsilon is still in the final solution, it can be ignored.

Note: Location decisions need to be reviewed occasionally. They are not one-time decisions.

QUESTIONS
1. In what ways can the location decision have an impact on the productive system?
2. How do manufacturing and service location decisions differ?
3. List basic approaches to location decisions.
4. What is a location factor rating and how does it work?
5. List the assumptions behind the center-of-gravity method. How does it work?
6. How do location problems for service, retail, and emergency facilities differ from those in manufacturing?
7. What information is needed to use the transportation method?
8. Why does a dummy row or a dummy column become necessary? Explain briefly.
9. How is the transportation method useful in location decisions?
10. Briefly explain the Northwest Corner rule.

PROBLEMS
1. Dry Seal, Inc. is trying to decide between two location sites, A and B. The following data applies to A and B.

Potential location	Revenue per unit	Variable cost per unit	Fixed cost per year
A	$50	$32	$60,000
B	48	29	80,000

Variable cost includes direct material, direct labor, and transportation cost.
(a) Which site would yield the higher profit at an annual volume of 9,000 units?
(b) At what volume would the company be indifferent between the two alternative sites in terms of annual profits?

2. Angela is considering two location alternatives, A and B. The relevant data are given as follows:

Potential location	Variable cost per unit	Fixed cost per year
A	$63	$300,000
B	32	800,000

Sales volume is estimated to be 25,000 units per year. Which location is most attractive?

3. Given the data on scores of three location sites:

			Location	
Factor	*Weight*	*X*	*Y*	*Z*
Raw materials	.4	80	70	80
Market	.2	40	60	80
Transportation cost	.1	90	70	50
Labor cost	.2	70	70	60
Construction cost	.1	90	80	60

Which site would you choose? Why?

4. Determine the optimum location for a distribution center to serve the following locations. Shipments to each location will be about equal.

Destination	*(x,y)*
A	2,2
B	5,6
C	6,3
D	7,5

5. For the destinations and shipping quantities shown below, determine the center-of-gravity location:

Destination	*(x,y)*	*Quantity*
A	3,5	600
B	5,1	400
C	6,7	300
D	8,4	500

ANSWERS

1. Location decisions can have an impact on access to markets, costs on materials, labor, rent, and transportation, quality of work life, and growth potential.
2. Manufacturing firms are more concerned with location of raw materials, transportation costs, availability of infrastructure, and the like, while service operations focus more on convenience, access to markets, traffic flow, and customer service.
3. Four popular methods used in location decisions are: locational break-even analysis; factor ratings; center-of-gravity method; and transportation LP problem
4. Factor rating is a qualitative technique used to develop an overall composite index for relative attractiveness. It involves identifying relevant factors, assigning relative weights to these factors, and rating each alternative site with respect to the factors.
5. The assumptions are: shipping costs between locations constant; demands are constant. The method aims at minimizing the weighted distance between the warehouse and its supply/distribution points.

6. Goods are not moved to or from the facility; customers are. In manufacturing, distribution costs and service times are the important factors whereas for nonmanufacturing, the location with respect to demand and competition, and response time are the crucial ones.
7. The information needed is: (a) supply available from each origin (plant), (b) demand at each destination (market), and transportation cost per unit for each origin/destination combination.
8. A dummy is added to supply or demand, whichever is lower.
9. The transportation LP method can be used to compare the total cost of alternative locations in terms of their shipping costs.
10. The northwest corner rule works as follows: (a) starting with the far left-hand side corner, set the level of this route at either the requirements or the availability, which is smaller, and (b) proceed across the table in a general northwest-to-southeast direction, exhausting the availabilities of one row before moving down to the next and exhausting the requirements of one column before moving on to the next.

SOLUTIONS TO PROBLEMS

1.
(a) Total profit = total revenue – total cost
For site A: $50(9,000 units) - $32(9,000) - $60,000 = $102,000
For site B: $48(9,000 units) - $29(9,000) - $80,000 = $91,000.
The answer is site A.
(b) $50Q - $32Q - $60,000 = $48Q - $29Q - $80,000, or
$18Q - $60,000 = $19Q - $80,000. Solving for Q we obtain Q = 20,000 units.

2.
     At the expected demand of 25,000 units, total costs for the alternatives are:
For site A: $63(25,000) + $300,000 = $1,875,000
For site B: $32(25,000) + $800,000 = $1,600,000.
Location B is more attractive, although annual fixed costs are much higher than for A.

3.
Composite scores are: X = 72, Y = 69, and Z = 71, as shown below. Choose X since it gives the highest composite.

Factor	Weight	X			Y		Z	
		Score	Weighted scores		Weighted scores		Weighted scores	
Raw materials	.4	80	32	70	28	80	32	
Market	.2	40	8	60	12	80	16	
Transportation cost	.1	90	9	70	7	50	5	
Labor cost	.2	70	14	70	14	60	12	
Construction cost	.1	90	9	80	8	60	6	
			72		69		71	

4.
$\bar{x} = (2 + 5 + 6 + 7)/4 = 20/4 = 5$

$\overline{y} = (2 + 6 + 3 + 5)/4 = 16/4 = 4$

The optimum location is at (5, 4) of x and y coordinates.

5.

$$\overline{x} = \frac{3(600) + 5(400) + 6(300) + 8(500)}{600 + 400 + 300 + 500} = \frac{9600}{1800} = 5.33$$

$$\overline{y} = \frac{5(600) + 1(400) + 7(300) + 4(500)}{600 + 400 + 300 + 500} = \frac{7500}{1800} = 4.17$$

The center of gravity is at 5.33, 4.17.

CHAPTER 6
DESIGN OF WORK SYSTEMS

LEARNING OBJECTIVES:

After Studying this chapter you will be able to:

1. Detail a job design.
2. Develop an operation chart.
3. Illustrate a flow process chart.
4. Design a multiple-activity chart.
5. Discuss a motion study and a time study.
6. Outline the procedure to develop time standards.
7. Explain MTM (methods-time measurement).
8. Conduct a process for work sampling.
9. Explain the learning curve effect.

One of the greatest assets a company has is its human resources. Since the largest portion of a company's employees often are found in the operation function, it is important to consider the jobs or work people perform within operations. The changing nature of work has been influenced most significantly by the advancement of technology. The majority of work now consists of some form of interface between people and machines. This relationship has significantly changed the nature of workers' tasks. Therefore, a large part of the operations manager's concern with the design of a work system will center around people, machines, and their relationship. Work design is primarily concerned with examination and evaluation of existing or proposed methods of performing work. Job design consists of developing the best way the individual tasks or jobs within the work system can be performed.

In this chapter we examine some aspects of job and work design. In the latter part of the chapter we address the related subjects such as how to measure work and how to determine performance standards. Learning curve phenomena can be incorporated into determining production standards.

WORK AND JOB DESIGN

One of the important aspects of the design of the physical system is the design of the jobs. Job design results in part from the preceding phase of facility layout, and the layout configuration results in part from job design. As noted in the chapter on facility layout, the overall organization of work must be considered at the time of layout, and given a particular organization of the activities decided upon, the layout is impacted. Conversely, if the technology is considered dominant, basic layout configurations are decided on, and job design is impacted. Thus, there is an interaction between the design of the technological system and the design of the social or man system to produce a unified sociotechnical system design. That dimension is the degree to which division of labor will be used. Job enlargement represents an opposing view of

work organization, using job satisfaction as its major criterion. It is a method of increasing job variety by horizontally loading jobs.

MAN-MACHINE SYSTEMS
        The entire spectrum of work from the purely manual to the completely automatic can be conceptualized within the framework of man-machine systems. In fact, one of the important tasks of job design is to allocate to humans and machines the activities to which they are each best suited. In performing work, human functions fall into three classifications:

1. Receiving information through the various sense organs.
2. Making decisions based on information received and stored in the human memory.
3. Taking action based on decisions.
Note how human functions neatly fall within the general structure of a closed-loop automated system.

        When humans and machines are viewed outside an economic basis for allocating tasks to them, it appears that the kinds of tasks most appropriate for humans and machines fall within the following general guidelines:

A. Humans appear to surpass existing machines in their ability to:
    1. Detect small amounts of light and sound.
    2. Receive and organize patterns of light and sound.
    3. Improvise and use flexible procedures.
    4. Store large amounts of information for long periods and recall relevant facts at the appropriate time.
    5. Reason inductively.
    6. Exercise judgment.
    7. Develop concepts and create methods.

B. Existing machines appear to surpass humans in their ability to:
    1. Respond quickly to control signals.
    2. Apply great force smoothly and precisely.
    3. Perform repetitive and routine tasks.
    4. Store information briefly and then erase it completely.
    5. Perform rapid computations.
    6. Perform many different functions simultaneously.

CONCEPTS
        People and machines perform similar functions in doing work, though they each have comparative advantages. The functions they perform are divided into the four basic classes: sensing, information storage, information processing, and action. In completely manual systems, all of the functions are performed by humans. At the other end of the spectrum, in completely automatic systems, all of the functions are performed by machines. In the common situation between the two extremes, involving teamwork between humans and machines, the functions are allocated and/or shared between men and machines, and such systems may be semiautomatic.

Thus, in conceptualizing man-machine systems, it is useful to establish the classifications manual, semiautomatic, and automatic systems, noting that in all three classifications the basic closed-loop feedback structure is operating.

Manual systems involve humans, commonly with mechanical aids or hand tools. Humans are the power source, and they act as controllers of the process, using the tools to help multiply their efforts.

Semiautomatic systems involve men mainly as controllers of processes where they interact with the machine by sensing information about the processes, interpreting it, and manipulating controls. The power source is usually supplied by the machine or is shared in some combination between humans and machine.

Automatic systems combine all of the functions of sensing, information storage and processing, and action within the machine system. If the machine is truly automatic, then it must be fully programmed to sense and take required action in all possible situations, and this is not usually economically justified. Man, therefore, normally functions as a monitor to assist with process control.

All three types of man-machine systems operate in some kind of working environment, which is a combination of temperature, humidity, noxious gases, noise, vibration, and other factors.

In a sense, the semiautomatic kind of operation is fully representative of the general range of activities found in man-machine systems. In such a situation, man is receiving and interpreting information about the process from information displays, manipulating mechanisms for control, and maintaining a general surveillance. The machine responds to these control actions to convert input to output. Thus, manipulative activity is representative of the dominant features of manual systems; information input, sensing, and controlling activities are representative of both semiautomatic and automatic systems; and information input and general monitoring activities are representative of automatic systems. The environmental and physical relationships of man to the work flow and workplace arrangement are applicable to all man-machine systems. Therefore, it is useful to divide the material dealing with man-machine systems into the following main headings: information input, human manipulative and control activities, and the work environment.

INFORMATION INPUT

In man-machine systems, human sensing can be direct, but it is becoming increasingly indirect, placing emphasis on encoding and information display systems. The design of these display systems for information input to humans is important if operations are to be effective. While input to the human eyes is most common, auditory and tactual input is also used.

Visual Displays

The following are guides to the design of visual displays:
1. Dials should be about 2.75 to 3 inches in diameter for a reading distance of up to 30 inches.

2. Dial marks should be located at the 0, 5, 10, 15, etc., positions. The marks at the 0, 10, 20, etc., positions should be longer than the others and should be the only ones numbered.
3. The distance between numbered markers on dials should be about one-half inch.
4. The separation between scale markers should be uniform around the dial.
5. There should be a gap between the beginning and the end of the scale.
6. Values on the scale should increase in a clockwise direction.
1. Banks of dials should be oriented in a pattern so that normal readings are in the 9 or 12 o'clock positions.

Auditory and Tactual Displays

Auditory displays have particular value as warning devices or as devices to attract attention. They are also used when vision is impaired. Tactual displays are sometimes used to code control knobs by shape so that they can be identified by touch.

HUMAN MANIPULATIVE AND CONTROL ACTIVITIES

Given information input by direct or indirect means, the human operator of man-machine systems responds by performing work in the physical sense. He may be assembling objects, manipulating controls, and in general using his body to accomplish the required tasks within the objectives of the system.

Analysis of Manual Activity

The analytical methods commonly used for manual activity are charts and graphs which display how the activity is carried out. Flowcharts have been developed for use in various specific situations.

The principles of motion economy are a set of general statements concerning the arrangement of work, the use of the human hands and body, and the design and use of tools. These guides to job design have general applicability, though they are not in fact principles in the strict sense of the word.

Analysis of Control Activity

A great deal of research concerning manual control activity has been performed. It may be summarized under the following headings:

1. A knowledge of the forces that humans can exert in various positions and with different parts of the body.
2. Data on the speed and accuracy of various kinds of positioning movements.
3. Data concerning positioning through settings of dials, cranks, and handwheels.
4. Coding of controls by color, size, shape, or location.
5. Work area limits.
6. Chair and table heights.

THE WORK ENVIRONMENT
Temperature, Humidity, and Airflow

The sensation of warmth is affected by each of these factors and has been combined into a single psychological scale called *effective temperature*. Effective temperature is the

temperature of still, saturated air which gives the same sensation of warmth or cold as various combinations of air temperature, humidity, and air movement would. Elevated effective temperature has a marked effect on both mental and physical work.

Noise

Research data show that hearing loss with age is characteristic of the general population, even of persons not exposed to high-noise environments. However, the severity of hearing loss depends on the intensity of exposure. It appears that the effects of noise on work performance are minimal.

Light

Various lighting criteria have been used in research studies. However, critical illumination levels seem to be preferable for performance types of criteria. The critical level of illumination for a given task is that level beyond which there is practically no increase in performance for increases in illumination intensity. Lighting standards based on critical illumination levels have been set for a wide variety of generalized tasks.

Contaminants and Hazards

A large number of fumes, dusts, gases, liquids, and solids have proved harmful to workers. These, together with the general mechanical hazards from machine moving parts, traffic from material transportation, falling objects, etc., form a part of the work environment.

WORK MEASUREMENT AND PRODUCTION STANDARDS

Standards are highly desirable for almost every kind of organized work. Managers need to have some idea of how long work will take, how many employees will be needed, and what it will cost. Only with this information can they make intelligent decisions about schedules, facilities, people needed, costs, and selling prices. Work measurement is the methodology by which production standards are determined. Production standards, in turn, are the basis for judging what represents a "fair day's work."

PRODUCTION STANDARDS

Uses of Standards

Production standards provide basic data for many decision-making problems as well as for many day-to-day operating problems. They are particularly important where labor cost is a predominant factor. Some of their uses are as follows:

1. Assessing the labor component for decision problems such as make versus buy, equipment replacement, and process selection.
2. Conducting day-to-day operations in the scheduling or loading of machines, giving promised delivery dates, providing bid prices to customers, etc.
3. Establishing the basis for labor cost control and incentive wage payment systems.

The Essence of The Standards Determination Problem

Actually, in order to set production standards, it would be necessary to know the distribution of performance times (or production rates) for the entire working population for each specific job. If we knew the distribution for each job, it would be a simple matter to establish

the standard at some particular point in the distribution, for example, either at the average of the distribution or possibly at a level which would accommodate perhaps 95 percent of the working population. Ordinarily, however, there may be only one or two individuals on the job whose work can be measured. The problem, therefore, is to estimate the nature of the entire distribution based on sample data from only one or two workers on the job. This is done by measuring the time actually taken during work performance while rating that performance. The actual time is then adjusted by the performance rating to produce the so-called normal time. The normal time is then augmented by allowances for personal time, delays, and fatigue to produce the standard time.

Performance Rating

The crucial element in the methodology is, then, the performance rating process, since it enters standards determination as a factor and is based on judgment and experience. The process is as follows: a pace or performance level is selected as standard, and the analyst observes this pace, comparing it with other paces and learning to judge pace level in percent of the standard pace.

EXAMPLE 1

If for a certain job normal pace were associated with a cycle time of 0.48 minutes, a pace of work 25 percent faster would require proportionately less time per cycle, or $0.48/1.25 = 0.384$ minutes. A skilled analyst observing the working pace and measuring the cycle time, 0.384 minutes, would rate the performance at 125 percent of normal. By multiplying his observed time by the performance rating in decimals, he would obtain the normal time for the job ($0.384 \times 1.25 = 0.48$ minutes).

All formal measurement systems require the input of the performance rating in some way.

Rating As a Measurement System

Two things are needed in order to be able to measure anything. They are:
1. An accepted standard for comparison.
2. A scale or unit of measurement.

Performance rating meets these two requirements in the following ways. Standards for comparison have been developed for a large number of different kinds of factory and clerical operations in the form of motion-picture films. In each instance, various working paces are shown. The films have been rated by thousands of experienced analysts, and their judgments concerning the selection of normal working pace have been pooled. The films are then used as a basis for training time study of personnel and for retraining them.

Different scales have been adopted and are in common use. Both are calibrated in percent of normal, although one of them selects normal performance to be at the mean of the distribution, while the other establishes normal performance at a level which can be exceeded by approximately 95 percent of the working population.

Commonly accepted figures for the accuracy of performance rating by experienced analysts are ±5 percent. Controlled studies in which films have been rated indicate a standard

deviation of 7 to 10 percent. Given the strong element of judgment in the process, these limits of accuracy are fairly good.

WORK MEASUREMENT SYSTEMS

There are two major work measurement systems designed to determine normal time by somewhat different methods: nonengineered and engineered standards. Nonengineered standards are less costly and more frequently used. They include historical (statistical) data and technical estimate. Engineered time standards are determined scientifically, with great precision. They are: time study (stopwatch methods), work sampling, predetermined standards, and standard data systems.

TIME STUDY (STOPWATCH METHODS)

Time study methods are the most commonly used and employ a stopwatch coupled with a performance rating to determine normal time. The general procedure is:
1. Standardize methods of operation, and record the resulting standard practice.
2. Select an operator experienced and trained in the standard methods.
3. Compute cycle time (CT)—time each task element over a number of cycles (repetitions). The average time for each task element is its cycle time.
4. Determine a performance rating (PR), a rating of the pace at which the employee performed each task element. For example, if the pace was 10% faster than normal, a performance rating assigned is 1.1 or 110%.
5. Compute normal time (NT).
6. Determine allowances (A) for personal time, delays, and fatigue. If allowances as a percentage of total time come out to be 10%, the A value is 0.10.
7. Compute standard time (ST).

The number of cycles times is a function of three things: (a) the variability of observed times; (b) the desired accuracy; and (c) the desired level of confidence for the estimated job time.

The desired accuracy is often stated as a percentage of the average of the observed time. The sample size needed to achieve a certain level of accuracy can be computed using the formula:

$$n = \left(\frac{zs}{a\,\bar{x}} \right)^2$$

where s = sample standard deviation
     a = desired accuracy
     $\bar{x}$ = sample mean
     z = number of normal standard deviations needed to achieve desired confidence.

Typical values of z used in this computation are:

Desired confidence percent	z-value
90	1.65
95	1.96
99	2.58

Of course, the value of z for any desired confidence can be obtained from the normal distribution table.

An alternative formula used when the desired accuracy is expressed as n amount is:

$$n = \left(\frac{zs}{e}\right)^2$$

where   e= desired accuracy (e.g., within one minute of the true mean)

EXAMPLE 2

A time study analyst wished to estimate the time required to perform a certain job. A preliminary work showed a mean of 6 minutes and a standard deviation of 2 minutes. The desired confidence is 95%. What's the sample size needed if the desired error is (a) $\pm$ 10% and (b) one-half minute of the sample mean?

(a) Note that s = 2, $\bar{x}$ = 6, z = 1.96, and a = 10%

$$n = \left(\frac{zs}{a\ \bar{x}}\right)^2 = \left(\frac{1.96(2)}{.1(6)}\right)^2 = 42.68$$

(b) e = .5

$$n = \left(\frac{zs}{e}\right)^2 = \left(\frac{1.96(2)}{.5}\right)^2 = 61.47$$

Development of a time standard involves computation of three times: the observed time or cycle time (CT), the normal time (NT), and the standard time (ST).

$$CT = \Sigma times/n\ cycles$$

$$NT = CT \ x \ PR$$

$$ST = NT \ x \ A$$

Note: There are two cases for allowances. If allowances are a percentage of the work (job) time: $A = 1 + A_{work}$. If allowances are a percentage of the total (workday) time: $A = 1/(1 - A_{total})$.

EXAMPLE 3

A time study revealed the following observed times for a job:

Observation	1	2	3	4	5
Time, x (in minutes)	1.15	1.16	1.12	1.15	1.12

The analyst gave a performance rating of 1.2 for this job. Determine the appropriate standard time for this operation, assuming allowances for personal needs, delays, and fatigue total 15 percent.

n = 5, PR = 1.2, A = .2

(a) The cycle time = Σtimes/n cycles = 5.7/5 = 1.14
(b) The normal time = CT x PR = 1.14(1.2) = 1.37 minutes
(c) The standard time (ST) = NT x A = NT(1 + A_{work}) = 1.37(1.15) = 1.58 minutes. In an eight-hour day, a worker would produce 8 x 60/1.58, or 304 units. This implies 304 minutes working and 480 – 304 = 176 minutes for allowances. Using the total work period, ST = NT(1/(1 – A_{total}) = 1.37(1/(1 – 0.15) = 1.61 minutes. In the same eight-hour day, 8 x 60/1.61, or 298 units are produced with 298 working minutes and 182 minutes for allowances. Depending on which equations is used, there is a difference of 6 minutes in the daily allowance time.

WORK SAMPLING
Work sampling is a random sampling technique designed originally as a methodology for estimating delay allowances. Later, it was applied to the determination of normal time as well. The technique involves observing the worker at many randomly selected moments, and observing the proportion of time the worker is actively working or idle. When the worker is observed to be idle, the reason for idleness can be recorded in order to identify and eliminate problems. The fundamental principle which allows the conversion of these kinds of observations to percentage delay allowances and normal time is: the *number* of observations is proportional to *the amount of time spent* in the working or idle state.

Determining Sample Size
Table and charts are available for finding the proper size sample for the desired level of accuracy, with a given percentage of occurrences of the activity being studied, at the 95% confidence level. Such tables have been derived from the use of the following formulas:

$$e = z\sqrt{\bar{p}/(1 - \bar{p})/n}$$
where

$$\bar{p} = \frac{x}{n} = \frac{\text{Number observed in classification}}{\text{Total number of observations}}$$
= The percentage of occurrence of any class of observations being studied (i.e., working, delay).

For example, to maintain a precision in the estimate of $\bar{p}$ of ±1.0 percentage point at 95 percent confidence, 10,000 observations are required if $\bar{p}$ is in the neighborhood of 50 percent. By contrast, if $\bar{p}$ is only 10 percent and the tolerance on $\bar{p}$ is 2 percentage points, then the sample size required for 95 percent confidence is only approximately 900. While the sample sizes seem large, the observation required is simply a recognition of whether the employee is working or idle.

The appropriate sample size can be determined solving the formula for n:

$$n = \left(\frac{z}{e}\right)^2 \bar{p}(1 - \bar{p})$$

e

EXAMPLE 4

To illustrate work sampling, assume that a study is made of an operation to determine the percentage of time a worker or group of workers are working. The observations are made at random, and a simple tally is made to indicate whether the operator was working or idle when each observation was made. A sample of the resultant tally of 60 observations made in a given day is given below.

State	Total	Percent
Working	49	81.7
Idle	11	18.3
Total	60	100

Note that the operator was working during 49 observations, or 81.7% of the time, and idle during 11, or 18.3%.

To determine the sample size with an accuracy of + 2%, and a confidence level of 95%, substitute into the formula, with $\bar{p}$ = 18% (rounded), as follows:

$$n = \left(\frac{z}{e}\right)^2 \bar{p}(1-\bar{p}) = \left(\frac{1.96}{.02}\right)^2 (.18)(1-.18) = 1{,}417.55 \text{ observations}$$

Determination of Standards.

If in the preceding procedure we had collected some additional data, we could also compute normal time. The additional data are the number of units produced during the total time of the study and the performance rating for each observation of the work time.

$$CT = \frac{(\text{Total time of study in minutes}) \times (\text{Work time \% from work sampling study})}{\text{Total number of units produced}}$$

Studies indicate that production standards determined by work sampling and stopwatch methods are approximately equivalent.

The normal time (NT) and standard time (ST) would then be computed as follows:

$$NT = CT \times PR$$

$$ST = NT(1 + A)$$

EXAMPLE 5

A work-sampling of customer service representatives in a telephone company office revealed that a receptionist was working 84% of thew time at 1.05 performance rating. This receptionist handles 200 customers during a 8-hour study period. Company policy is to give allowances of 10% of total on-the-job time. The CT, NT, and ST are:

$$CT = \frac{480x.84}{200} = 2.02 \text{ minutes per customer}$$

NT = 2.02 x 1.05 = 2.12 minutes per customer
ST = 2.12(1.1) = 2.33 minutes per customer

PREDETERMINED STANDARDS

Tables of predetermined standards for micro-motions are available from the Methods-Time-Measurement (MTM) Association. These tables include micro-motions such as reach, grasp, turn, release, eye travel and focus, etc. Tedious work is required by the analyst to select all the motions and link them together to describe a specific task.

STANDARD DATA

Standard times for particular tasks have been developed in certain industries. There are two kinds of standard data systems: universal data based on minute elements of motion (microdata) and standard data for job families (macrodata or element standard data).

Universal Standard Data

This data gives time values for motion elements, and cycle times are then synthesized by specifying the motions required to perform a given task. The time values associated with given motion elements were built up by measuring in conjunction with performance ratings the times taken for such elements in a wide variety of tasks. Therefore, the performance rating enters the system in that it is used in originally constructing the data. On the other hand, individual performance ratings are not required in order to estimate normal times for jobs. Universal standard data systems are known by various trade names: Methods-Time-Measurement (MTM), Work Factor, and Basic Motion Time Study.

Standard Data for Job Families

This data gives normal time values for major elements of jobs and are often called macrostandard data. Unlike universal standard data, these time values have been based on actual previous stopwatch studies within the job family. Recall that one of the reasons for the elemental breakdown in stopwatch study is to provide data concerning the job families. A large number of studies find how the normal time for some particular element varies with size, depth of cut, type of material, the way the workplace is held in the machine, etc.

Historical Standards and Technical Estimates

Much work is variable and non-standard. Frequently historical averages of times to do different jobs are used. Sometimes, technical expertise is used to "guesstimate" task times.

LEARNING CURVE

The learning curve is based on the proposition that labor hours decrease in a definite pattern as labor operations are repeated. More specifically, it is based on the statistical findings that as the cumulative production doubles, the cumulative average time required per unit will be reduced by some constant percentage, ranging typically from 10 percent to 20 percent. By convention, learning curves are referred to in terms of the complements of their improvement rates.

For example, an 80 percent learning curve denotes a 20 percent decrease in unit time with each doubling of repetitions. As an illustration, a project is known to have an 80 percent learning curve. It has just taken a laborer 10 hours to produce the first unit. Then each time the cumulative output doubles, the time per unit for that amount should be equal to the previous time multiplied by the learning percentage. An 80 percent learning curve is shown in Figure 1.

Unit	Unit time (hours)
1	10
2	0.8(10) = 8
4	0.8(8) = 6.4
8	0.8(6.4) = 5.12
16	0.8(5.12) = 4.096

The learning curve model is as follows:

$$y_n = a\, n^{-b}$$

where y_n = Time for the nth unit

    a = Time for the first unit (in this example, 10 hours)

    b = The index of the rate of increase in productivity during learning (Log learning rate/log 2)

To be able to utilize linear regression, we need to convert this power (or exponential) function form into a *linear* form by taking a log of both sides, which yields:

$$\text{Log } y_n = \log a - b \log n$$

The learning rate, which is indicated by b, is estimated using a *least-squares regression*, with the sample data on y and n. Note that

$$b = \frac{\text{Log (learning rate)}}{\text{Log 2}}$$

which means:

$$\text{Log (learning rate)} = b \times \log 2$$

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The unit time (i.e., the number of labor hours required) for the nth can be computed using the estimated model:

$$y_n = a\, n^{-b}$$

NOTE:

    This learning phenomenon is observed in the behavior of labor and labor driven overhead. Material costs per unit may also be subject to this effect if less scrap and waste occur as a result of learning.

EXAMPLE 6

    For an 80 percent curve with $a = 10$ hours, the time for the third unit would be computed as:

$$y_3 = 10\,(3^{-\log .8/\log 2}) = 10\,(3^{.3219}) = 7.02$$

Fortunately, it is not necessary to grid through this model each time a learning calculation is made; values (nb) can be found using Table 2 of the Appendix (Learning Curve Coefficients). The time for the nth unit can be quickly determined by multiplying the table value by the time required for the first unit.

FIGURE 1
AN 80% LEARNING CURVE
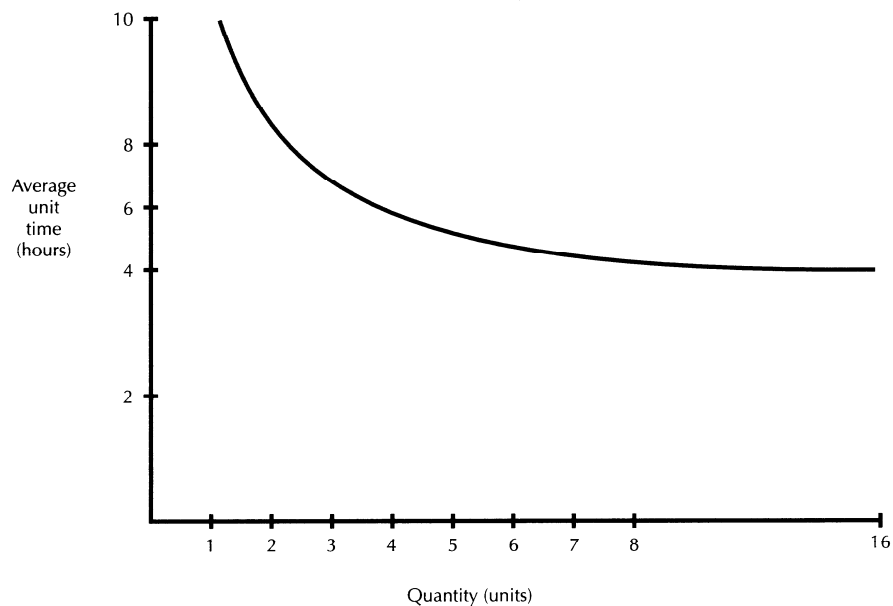
EXAMPLE 7

    NB Contractors, Inc. is negotiating a contract involving production of 20 jets. The initial jet required 200 labor-days of direct labor. Assuming an 80 percent learning curve, we will determine the expected number of labor-days for (1) the 20th jet, and (2) all 20 jets as follows:

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Using Table 2 with n=20 and an 80 percent learning rate, we find: Unit=.381 and Total=10,485. Therefore,

        (1) Expected time for the 20th jet = 200 (.381)= 76.2 labor-days.

        (2) Expected total time for all 20 jets = 200(10.485) =2,097 labor-days.

NOTE:

        The learning curve theory has found useful applications in many areas, including:

        1. Budgeting, purchasing, and inventory planning

        2. Scheduling labor requirements

        3. Setting incentive wage rates

        4. Pricing new products

        5. Negotiated purchasing

        6. Evaluating suppliers' price quotations

Example 8 illustrates the use of the learning curve theory for the pricing of a contract.

EXAMPLE 8

        Big Mac Electronics Products, Inc. finds that new product production is affected by an 80 percent learning effect. The company has just produced 50 units of output at 100 hours. Costs were as follows:

Materials 50 units @$20	$1,000
Labor and labor-related costs:	
Direct labor -- 100 hours @$8	800
Variable overhead -- 100 hours @$2	200
	$2,000

        The company has just received a contract calling for another 50 units of production. It wants to add a 50 percent markup to the cost of materials and labor and labor-related costs. To determine the price for this job, the first step is to build up the learning curve table.

Quantity	Total time (hours)	Average time (per unit)
50	100	2 hours
100	160	1.6 (.8 x 2 hours)

        Thus, for the new 50 unit job, it takes 60 hours in total. The contract price is:

Materials 50 units @$20	$1,000
Labor and labor-related costs:	
Direct labor -- 60 hours @$8	480
Variable overhead -- 60 hours @$2	120
	$1,600
50 percent markup	800
Contract price	$2,400

QUESTIONS

1. Distinguish between job design and work design.
2. Why is job design important? List the important factors that must be addressed in job design.
3. What are some of the reasons that methods analyses are needed?

4. How are devices such as flow process charts and man-machine charts useful?
5. List the various approaches to work measurement.
6. What is a time standard? What factors must be taken into account when developing standards?
7. What are some of the main uses of time study information?
8. What is the procedure for developing a time study?
9. Give some examples of learning curve applications.
10. Why might practicing managers and industrial engineers be skeptical about the job enrichment and sociotechnical approaches to job design?

PROBLEMS

1. An analyst observed 28 week cycles, for which the average cycle time was 5 minutes and the performance rating was 1.05. Allowance for the department is 25% of job time. Determine the appropriate standard time for this job.

2. Given the following time study data conducted by continuous time measurement, compute the standard time. Use an allowance of 15%.

Cycle of observation

Activity	1	2	3	4	5	Performance rating (PR)
Get casting	0.21	0.21	0.21	0.23	0.20	0.95
Fix into fixture	0.27	0.28	0.25	0.26	0.25	0.90
Drilling operation	1.04	1.05	1.00	1.04	1.04	1.00
Unload	0.21	1.19	0.25	0.20	0.22	0.95
Inspect	0.25	0.26	0.24	0.21	0.25	0.80
Replace	0.12	0.12	0.10	0.12	0.13	1.10

3. Comfort Faucet Manufacturing wants to have a 90% probability that the value of the sample mean provides a sampling error of .01 minute or less. The estimated standard deviation from historical experience is .02. Determine the sample size that will provide the required precision.

4. The manager of a small supermarket chain wishes to estimate the proportion of time store clerks spend making price changes on previously marked merchandise. The manager wants a 95 percent confidence the resulting estimate will be within 5 percent of the true value. Based on her previous experience, she believed the proportion would be approximately 30 percent.
   (a) What sample size would the manager need in order to achieve her goal?
   (b) If the manager uses a sample size of 400 observations, what is the maximum possible error that will be associated with the estimate?

5. A work-sampling was made of a cargo-loading operation with the aim toward to developing a standard time. During the total 160 minutes of observation the worker was working 85% of the time and loaded 60 pieces of cargo. The performance was rated at 100%. The company wants to incorporate a 10% allowance factor for fatigue, delays, and personal time. What is the standard time for this operation in minutes per piece?

6. Assembly of a transistor unit has a learning curve of 80 percent. Estimated time to build the second unit is 64 hours. Calculate about how much time will be required for:
   (a) the eighth unit.
   (b) the first ten units.

7. The first P/OM problem Allison did in a set of similar problems took her one hour, and the ninth problem took 24 minutes.
   (a) Determine Allison's learning curve.
   (b) How long did it take Allison to do her set of 10 problems?

ANSWERS

1. Work design is primarily concerned with examination and evaluation of existing or proposed methods of performing work. Job design consists of developing the best way the individual tasks or jobs within the work system can be performed.
2. Job design is important since it has a significant impact on the efficiency and productivity of workers. The factors that need to be addressed in job design are: (a) design of work methods, (b) work measurement, (c) design of physical workplace, and (d) design of the physical, social, and psychological environment.
3. The need for methods analysis can come from changes in tools and equipment, changes in product or service design, the introduction of new products, changes in methods and procedures, and from changes in government regulations or contractual agreements.
4. The approaches to work measurement include: (a) historical data, (b) time study, (c) predetermined data, (d) standard data, and (e) work sampling.
5. Flow process charts and man-machine charts are useful in reviewing and analyzing operations in terms of sequence and workflow. They provide a visual mode of the work.
6. A time standard reflects the length of time a given task should take a qualified worker who works at a sustainable rate, using given methods and equipment, given material inputs, and a given workplace arrangement.
7. The information provided by time study is useful for scheduling, budgeting, manpower planning, cost and time estimation, designing incentive systems, etc.
8. The procedure for developing a time study is: divide the task into smaller work, elements; observe the time to perform each element several times; rate the performance of each work element; determine the normal element time; determine allowance; and determine the standard time.
9. The learning curve theory has found useful applications in many areas, including: (a) Budgeting, purchasing, and inventory planning, (b) scheduling labor requirements, (c) setting incentive wage rates, (d) pricing new products, and (e) evaluating suppliers' price quotations.
10. Job enrichment by definition moves away from specialization which, from a purely mechanical standpoint is the most efficient way of work. Sociotechnical approaches include job enrichment as a design strategy and in addition emphasize worker and work group autonomy. Thus, managers and industrial engineers have legitimate concerns about the implications of these approaches on output, planning and control.

SOLUTIONS TO PROBLEMS

1.
CT = 5 minutes, PR = 1.05, A = 25%.
So, NT = 5 x 1.05 = 5.25 minutes; ST =5.25(1.25) = 6.5625 minutes

2.

Cycle of observation

Activity	1	2	3	4	5	Average	Performance rating (PR)	Normal time
Get casting	0.21	0.21	0.21	0.23	0.20	0.21	0.95	0.201
Fix into fixture	0.27	0.28	0.25	0.26	0.25	0.26	0.90	0.236
Drilling operation	1.04	1.05	1.00	1.04	1.04	1.03	1.00	1.034
Unload	0.21	1.19	0.25	0.20	0.22	0.41	0.95	0.393
Inspect	0.25	0.26	0.24	0.21	0.25	0.24	0.80	0.194
Replace	0.12	0.12	0.10	0.12	0.13	0.12	1.10	0.130
							Normal time=	2.188
							Plus allowance (15%) =	2.516

3.
Note that s =.02, z = 1.645, and e = .01

$$n = \left(\frac{zs}{e}\right)^2 = \left(\frac{1.645(.02)}{.01}\right)^2 = 10.8$$

A sample size of 11 (or more) will provide the required precision.

4.
(a)
$$n = \left(\frac{z}{e}\right)^2 \bar{p}(1 - \bar{p}) = \left(\frac{1.96}{.05}\right)^2 (.3)(.7) = 322.69 \text{ or } 323 \text{ observations}$$

(b)
$$e = z\sqrt{\bar{p}/(1 - \bar{p})/n} = 1.96\sqrt{(.3)(.7)/400} = 1.96(.0327) = .064$$

5.
The NT is:

$$\text{Normal time} = \frac{160 x.85 x1.0}{60} = 2.27 \text{ minutes per piece}$$

ST = 2.27 x 1/(1 - .01) = 2.50 minutes per piece.

6.
The time for the initial unit is 64/.8 = 80 hours. Using Table 2 (Learning Curve Coefficients) in the Appendix we find:

(a) Unit time for eighth unit: 80 x .512 = 40.96 hours.

(b) Total time for ten units: 80 x 6.315 = 505.2 hours.

7.

(a) Before going to Table 2, we determine the factor 24 minutes/60 min. = .4, which corresponds to the 4.02 in the table. Thus, approximately 75% learning percentage.

(b) The total time for 10, using 75% is 60(5.589) = 335.34 minutes, or about 6 hours.

CHAPTER 7
FACILITIES POSITIONING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Develop a layout plan.
2. Outline a method for material handling.
3. Demonstrate a process layout.
4. Describe a product layout.
5. Illustrate a group layout.
6. Demonstrate and describe a fixed-position layout.
7. Diagram a flow process chart.
8. Discuss and defend group technology processes.
9. Perform line balancing.

Selection of a site does not complete all location considerations. After a site has been determined, the focus narrows to the location of various functions inside the work facility. Locating functions within a facility is called layout, plant layout, facility design, or facility management. *Layout* refers to the efforts involved in selecting specific locations for each department, process, machine, support functions, and other activity that will be a part of the operations at a facility. The need for a layout may arise for one or more reasons such as the following:

- A new process or method becomes available.
- The volume of business changes.
- A new product or service is offered.
- A new facility is to be built or an outdated one is to be remodeled.
- The demanded mix of goods or services changes.
- Existing products or services may be redesigned, changing operations at a facility.

LAYOUT OF FACILITIES

In planning any operations system, no matter what type, intermittent, continuous, or batch, the major concern of the manager is to facilitate the flow of inputs. The layout of the processing facilities is a key to the achievement of this goal. This involves determination of the best location of the equipment within the physical facilities to make the flow as close as optimal as possible.

The major goals of a good layout are to:

(a) Minimize materials-handling costs.
(b) Reduce bottlenecks in moving material or people.
(c) Provide flexibility
(d) Provide ease of supervision
(e) Utilize available space effectively and efficiently

(f) Reduce hazards to people.

(g) Facilitate ergonomics, coordination, and communications wherever appropriate.

MATERIAL HANDLING METHODS

Because of the nature of product line layout, some direct means of transportation between operations is required. Thus, quite often, conveyors, industrial trucks, cranes and hoists, or gravity chutes can be used effectively. Where possible, the functions of internal transportation, processing, and storage can be integrated, all being accomplished on conveyor lines, as in many assembly operations.

Like the processing equipment itself, material handling equipment in product layout tends to be special purpose, often designed for the specific situation.

CLASSICAL LAYOUT TYPES

The activities involved in production or service operations may be grouped and arranged in a variety of ways. Several popular types of layout are: product layout, process layout, fixed position layout, or a combination of them. In the product layout, it is the product and its flow that dictate the design. In the process layout, the basic organization of technology is around processes. In the fixed-position layout, the construction of a large product is accomplished in one place.

PRODUCT LAYOUT

Product layout, also called *mass production layout*, *line layout*, and *straight-line layout,* is employed when the product is produced through a continuous process. Here the raw material enters the production line and operations are performed on it in sequence until it goes out as a finished product. The product moves continuously, perhaps down a conveyor line past successive workstations where men and machines perform the necessary operations in sequence. Automobile and home appliance lines are examples of this type of layout. A schematic illustration of the nature of the product layout is shown in Figure 1.

FIGURE 1
SCHEMATIC REPRESENTATION OF A PRODUCT LAYOUT

Product A

| | | | | |
|1| |2| |3| |4| |5|
Planing   Milling   Grinding   Drill Press   Inspection

Receiving

Shipping

Product B

| I | | II | | III | | IV | | V |
Drill Press   Turning   Milling   Painting   Inspection
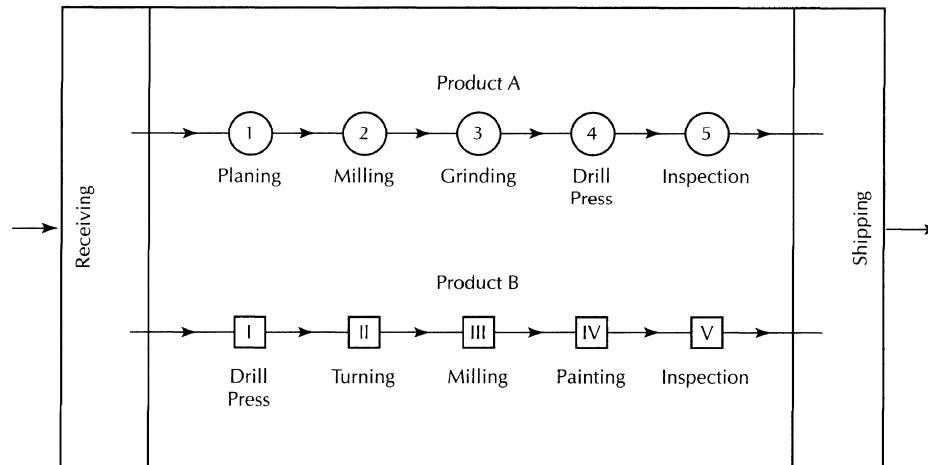
When the conditions for product layout are met, we have a low-cost, highly specialized, very productive system. The requirements are as follows:

1. An adequate volume that makes possible reasonable equipment utilization.
2. Stable product demand.
3. Product standardization.
4. Part interchangeability.
5. Continuous material supply.

The main advantage of product layout is its low production cost per unit. Production control is relatively simple, since product designs are stable and routes through the system are standardized.

The disadvantages of product layout are that the investment in single-purpose equipment is high, and the system is therefore open to obsolescence if product designs change. Also, if there is a breakdown of a machine in the sequence or men are absent, not only is the process immediately affected delayed, but perhaps the entire line is delayed. Thus, seemingly minor stoppages or material shortages could be very costly. Also, the highly repetitive nature of the work has resulted in low job satisfaction and morale in many instances.

Product layout is most commonly used with assembly operations. Fabrication lines are less common because of the difficulty in attaining balance between operations. A common combination is for fabrication operations to be organized on a process basis and assembly on a product or fixed position basis.

PROCESS LAYOUT

In process layout, often called *functional* and *job lot layout*, all machines or processes of the same generic type are grouped together in what are commonly called machine centers or departments. The departments are technologically specialized in such processes as turning, grinding, heat treating, painting, assembly, castings, accounts receivable, and typing pools. This layout is suitable for batch or intermittent production. Workshops producing small quantities of

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products or factories producing batches of made-to-order products are examples of this type of plant layout.

The great advantages of process layout lie in the utilization of highly skilled workmen and/or very expensive equipment and smaller investment. The machines themselves are usually general purpose so that a wide variety of products, parts, sizes, etc. can be accommodated. Also, the items being processed may follow diverse paths through the various departments. Thus, flexibility is the watchword: flexibility of path, flexibility of product design, flexibility of lot size. If one machine breaks down, work can be transferred to a nearby machine which can do similar work, and the delay will rarely interfere with the progress of other orders through the plant. Process layout is particularly adaptable to parts and products made in relatively small batches, since the machines and men are flexible.

The disadvantages of process layout stem from the general-purpose nature of the equipment and the great flexibility of the system. Orders moving through a process layout are likely to take considerable time. Work routing, scheduling, material handling and transportation, and cost accounting are relatively expensive because each order is treated as a unit. A schematic representation of a process layout is shown in Figure 2.

The major economic problem of process layout lies in determining the relative location of the departments. Ordinarily there are many possible combinations of relative arrangements; for example, for 10 departments there would be 36,288 possible arrangements (10 factorial). Therefore, enumeration of each possibility is impossible.

GROUP LAYOUT

Group layout is a hybrid approach combining the features of product layout in a process layout context. It is used in more structured job shops.

FIGURE 2
SCHEMATIC REPRESENTATION OF A PROCESS LAYOUT

Turning   Planing   Grinding

Receiving

Painting

Shipping

Milling   Drill Press   Inspection

Process   Flow
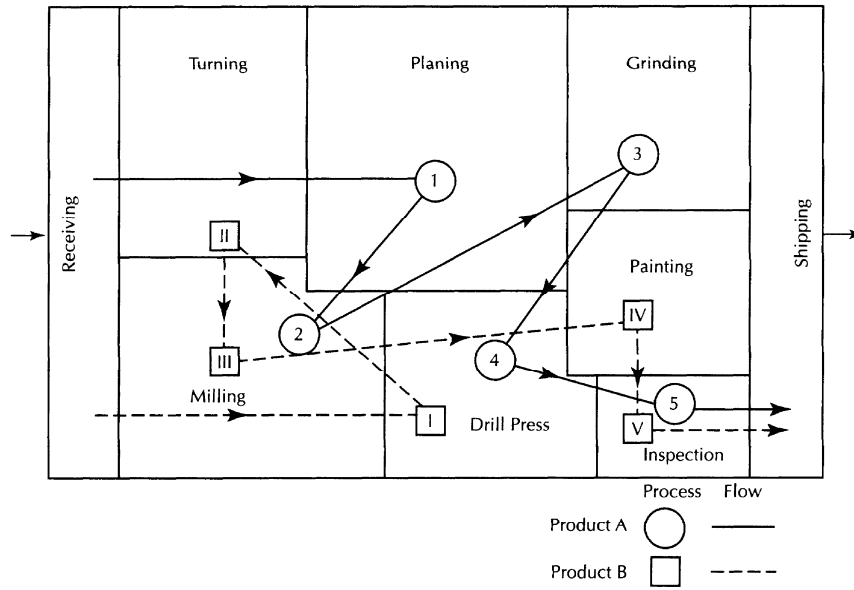
Product A   ○   ——

Product B   □   - - - -

CELLULAR LAYOUT
      This is also a product-oriented layout, and is useful when volumes do not warrant a specialized line to produce one product. Several operations are grouped together to produce one item or a family of goods, which use the same sequential set of operations. Cells are often formed by "stealing" equipment from various process-oriented areas and personnel are cross-trained for several jobs. This is typical of just-in-time (JIT) manufacturing.

FIXED-POSITION LAYOUT
      This is a layout in which very large items such as large aircraft or residential construction product stays in a fixed location, and all the equipment and personnel are brought to it.

NOTE:

	Advantages	Disadvantages
Product layout	▪ High utilization of equipment ▪ Reduced material handling ▪ Less in-process inventory ▪ Simplified production planning and control	▪ Lack of process flexibility ▪ High-cost specialized equipment ▪ Worker monotony ▪ Interdependent operations
Process layout	▪ Flexibility of equipment and worker ▪ Low cost general purpose equipment ▪ Higher job satisfaction ▪ Low work breakdowns	▪ Costly material handling ▪ Low equipment utilization ▪ Complex control and supervision ▪ High cost skilled labor
Fixed position	▪ Lower movement of the work item ▪ More continuity of assigned work	▪ Need of skilled and versatile workers

	force		▪ Costly movement of equipment
			▪ Low equipment utilization

MINIMIZATION OF MATERIAL HANDLING COST

The major criterion for selecting good arrangements is material handling cost. Since each product may take different routes through the system, the relative location chosen can result in very large material handling cost or relatively small cost. Our objective, then, is to minimize the total incremental material handling cost, C, that is:

$$C = \Sigma\Sigma_{ij}\ A_{ij}\ X_{ij} = \text{minimum}$$

where A_{ij} is the number of loads per unit of time transported between departments i and j, and X_{ij} is the distance between departments i and j. Thus, it is only the distance-related material handling cost with which we are concerned. The pickup and set-down costs are presumed to be the same for all alternative arrangements.

SYSTEMATIC LAYOUT PLANNING

Systematic layout planning is a generalized approach to layout that indicates nearness priorities, taking into account factors other than transportation cost. Developed by Richard Muther, the method uses a half matrix or a similar equivalent grid to display the relative importance of the distance between locations such as departments (see Figure 3 below). The diamond-shaped boxes at the right-hand side of the figure are used to indicate the desired relationships between the two departments that intersect. A letter (*a, e, i, o,* or *x*) is used to depict the desired relationship and a number is used to indicate a reason for the relationship.

FIGURE 3
NEARNESS PRIORITIES IN A MUTHER GRID
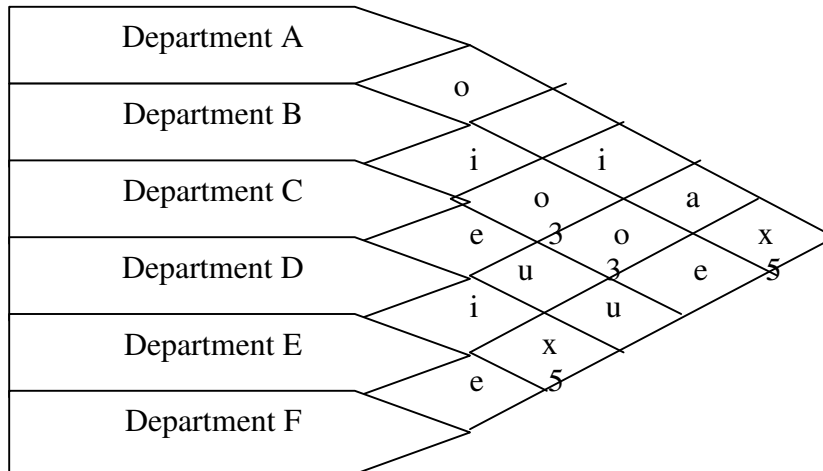
Nearness priority code	Degree of importance	Reason code	Possible reasons
a	Absolutely necessary	1	Use same equipment
e	Very important	2	Use same records or personnel
i	Important	3	Work flow facilitated
o	OK, ordinary importance	4	Ease of communication or supervision
u	Unimportant	5	Unsafe conditions
x	Undesirable		

The *a* in the matrix indicates that it is absolutely necessary that departments E and A be near each other. The *e*'s indicate that department F should be near department E and B and that department C should be near D. The *x*'s indicate that department F should be near D or A. An example layout of a facility that meets these conditions is shown in Figure 4.

FIGURE 4
A LAYOUT THAT MEETS THE PRIORITIES OF FIGURE 3
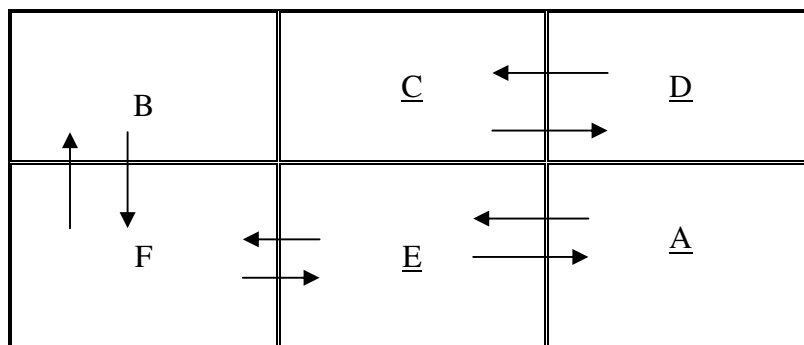
COMPUTERIZED PLANT LAYOUTS

The number of possible layout designs, even with a small number of departments, is so large that evaluating a considerable number of possibilities require the aid of a computer. Several computer software are available for developing and analyzing process layouts, including the ALDEP (Automated Layout Design Program), CORELAP (computerized relationship layout planning) and CRAFT (computerized relative allocation of facilities technique) programs. The first two programs employ the ranking of the desirability of closeness of departments to each other, while the CRAFT program uses the quantitative measure of minimizing the total transportation costs between them and material-handling costs.

NOTE:

Computer-generated layout plans may not be implemented directly. Constraints such as the shape of departments, existing ventilation and sewage systems, natural lighting requirements, etc. have to be superimposed upon these results.

PRODUCT LAYOUT AND LINE BALANCING

Because all operations are geared to the flow of the product in product layout, the central problem in design is to divide the necessary operations in such a way that smooth flow results. We attempt to assign the work in a manner, which minimizes the number of work stations and labor and other resources to perform all the operations. This attempt will therefore minimize idle time.

Balance refers to the equality of output at each stage in the sequence of a line. If the outputs are all equal, balance is assumed to be perfect, and if they are unequal, we know that the maximum possible output for the line as a whole will be determined by the slowest operation in the line, the bottleneck operation. Thus, where imbalance exists, we have idle capacity in all other operations except the bottleneck operation.

Given a solution to the line balance problem for a particular application, the necessary detailed layout of lines and support areas, aisles, service area, and so on, must follow.

THE LINE BALANCE PROBLEM

Line balancing is the process of distributing the workloads evenly, that is to group and/or subdivide activities or tasks in such a way that all job stations have an equal amount of work to do in terms of the time required to perform the tasks. The idea is to obtain the desired level of output with the minimum input of labor and other resources.

In order to start with the greatest flexibility in alternatives to *achieve balance for a specified rate of output*, we need to know the performance times for the smallest possible whole units of activity called tasks, such as tightening a nut, attaching a wire, or soldering a wire. We also need to know the technological constraints, which may require certain sequences of these activities. Simple examples of these technological sequence constraints might be: a hole must be drilled before it can be reamed, before it can be tapped; a washer must go on the bolt before the nut; and wheel nuts must be assembled and tightened before the hub cap is placed on. But not all tasks have restricted sequences, and this represents the remaining flexibility.

Figure 5 shows a network drawing of a *precedence* relationship given in Table 1.

TABLE 1
WORK TASKS SEQUENCE

Task	*Immediate predecessor*	*Task time*
A	-	.3
B	a	.9
C	a	1
D	b,c	.4
E	d	.8

FIGURE 5
NETWORK
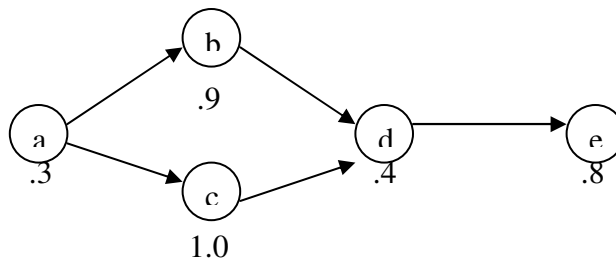
The network suggests, for example, that task b cannot be started until a is completed; b must be done before d can be started; and b can occur either before or after c. The figures below the nodes give the average task performance time in minutes. Consider now the assignment of the tasks to work stations. The total time available at each station depends on the required output of the process, which in turn depends on the expected sales or usage rate of the output.

EXAMPLE 1
In Figure 5, suppose that a unit must be produced every 1 minute. A quick examination of the network reveals that no two tasks could be combined within a single station. Tasks a and d, if combined, would fall within the 1 minute time limit. They cannot be assigned to the same station, however, since tasks b and c must be performed between a and d. Thus, the job would require 5 separate work stations. This results in a rather low labor utilization level. The total amount of actual work accomplished is equal to the sum of the task times, or 3.4 minutes. However, five workers are occupied for 1 minutes each for a total labor time of 5 minutes or a labor utilization rate of 3.5/5 = .7 = 70%.

Despite the problem of balancing the line, the continuous process has economic advantages, such as reduced materials handling, smaller facility and tool investment, and lower skill requirements that can be achieved when sales volume is sufficiently large.
For line balancing, two important pieces of information are required:
(a) The sum of the task times, indicating the *maximum* cycle time of the line.

(b) The length of the longest elemental task, indicating the *minimum* possible cycle time. These are important because they can be used to determine the upper and lower bounds on a line's output potential.

We will need to compute the following:

(1) Daily capacity can be determined by dividing operating time per day by a line's cycle time:

$$\text{Output} = \frac{OT}{CT}$$

where OT = operating time per day and CT = cycle time.

(2) The minimum number of stations necessary to provide a specified rate of output is:

$$N = \frac{D x \sum t}{OT}$$

where N = minimum number of stations, D = desired output rate, $\sum t$ = sum of task times, and OT = operating time.

(3) The cycle time needed to obtain a desired level of output can be found:

$$CT = \frac{OT}{D}$$

where OT = operating time per day and D = desired output rate.

(4) To calculate the percentage of idle time, we need to compute the idle time per cycle per station. This is:

Idle time per station = cycle time – station time

(5) The percentage of idle time is the ratio of idle time per cycle to total time available per cycle:

Percentage of idle time = Idle time per cycle/(N x CT)

EXAMPLE 2

Suppose the work required to fabricate a certain product can be divided up into five elemental tasks, with the task times (in minutes) and precedent relationships as shown below.
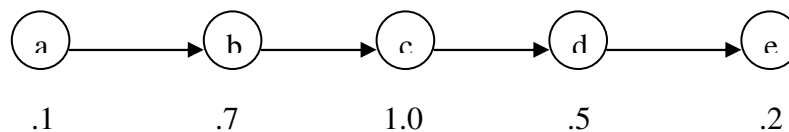
Assume that the line will operate for 8 hours per day (480 minutes). With a cycle time of 1 minute, output is:

$$\text{Output} = \frac{OT}{CT} = 480 \text{ minutes per day/1 minute per unit} = 480 \text{ units per day.}$$

Suppose the desired rate of output is the maximum of 480 units per day. The minimum number of stations required to achieve this goal is:

$N = \frac{Dx\sum t}{OT}$ = (480 units per day x 2.5 minutes per unit)/480 minutes per day per station = 2.5 stations. Because 2.5 stations is *not* feasible, we usually *round up* to 3 stations.

Combining the five tasks into 3 work stations with a cycle time of 1 minute results in the following assignments.

Station 1 a and b	→	Station 2 c	→	Station 3 d and e
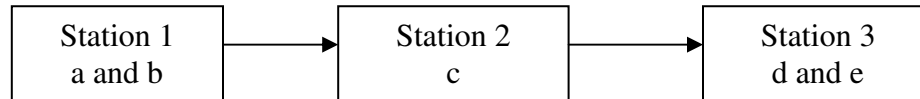
The idle times for the above assignments are shown below:

Station	*Station time*	*Station idle time*
1	.8 (.1 + .7)	.2 (1 - .8)
2	1.0	0 (1 – 1)
3	.7 (.5 + .2)	.3 (1 - .7)
	Total	.5

Percentage of idle time = Idle time per cycle/(N x CT) = .5/3(1.0) = 16.7%

BALANCING TECHNIQUES

Much work has been done to develop models that produce optimally balanced lines. There have been a large number of proposals for theoretical and practical methods for solving the line balance problem. Some of the proposals have been attempts to deal with large-scale balance problems, particularly those involving 75-100 tasks or more and line lengths involving 10-15 or more stations. We will discuss first a method useful in handling problems of moderate size, called *heuristic line balancing* and then a model for handling very large problems, known as *the COMSOAL technique*, which is a computer-based sampling methodology.

The Heuristic Line Balancing Technique

The heuristic line balancing technique involves the generation of a precedence diagram (technological sequencing requirements) in a particular way, which indicates the flexibility available for shifting tasks from column to column to achieve the desired balance. The heuristic rules are effective in reducing the number of alternatives that must be considered, but they do not guarantee an optimal solution. The heuristic method has been applied to television assembly line problems with 45 and 133 tasks and has achieved excellent results.

Some of the heuristic rules widely used are:
(a) Assign tasks to work stations, longest tasks first, and continue until all tasks have been assigned.
(b) Assign tasks in order of most number of following tasks.
(c) Assign tasks in order of most number of preceding tasks.

(d) Assign tasks according to *positional weights*, which is the sum of a task's time and the times of all the following tasks.

EXAMPLE 3

Consider the tasks in the table below. Management wishes to balance the line with the intent of minimizing idle time. Assume an output rate of 275 units and 440 minutes available per day. Task times are in minutes.

Task	Immediate predecessor	Task time
a	-	.3
b	-	.6
c	a	.4
d	b	1.2
e	c	.2
f	d	.6
g	e	.1
h	g	.5
i	h	.3

The precedent diagram looks like this:
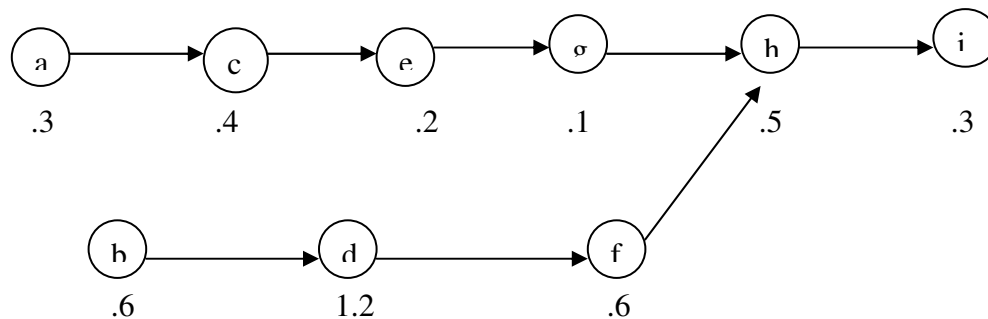
The appropriate cycle time CT is

$$CT = \frac{OT}{D} = 440 \text{ minutes per day}/275 \text{ units per day} = 1.6 \text{ minutes}$$

The minimum number of stations required is:

$$N = \frac{Dx\sum t}{OT} = (275 \text{ units per day x } 4.2)/ 440 \text{ minutes per day} = 2.6 \text{ (rounded to 3)}$$

For illustrative purposes, we will assign tasks using the positional weight rule. That is, (1) assign tasks with highest following times (including its own time) first and in case of a tie, use the greatest number of the following tasks.

Station	Task	Time remaining	Feasible next task
1	b	3.2	a
	a	1.8	c
	c	1.5	None
2	d	2.6	c
	c	1.1	g
	g	.9	None
3	f	1.4	h
	h	.8	i
	i	.3	None

The resulting assignments are shown below.

Station 1 a, c, b (1.3 minutes)	→	Station 2 e, g, d (1.5 minutes)	→	Station 3 h, i, f (1.4 minutes)
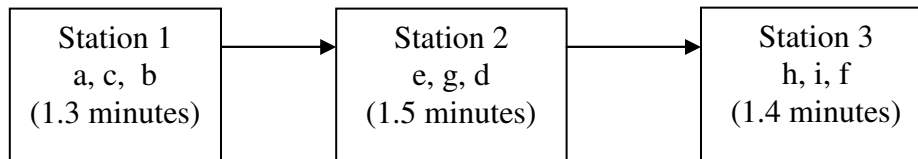
Note that the time needed to produce 275 units will be 275 x 1.5 minutes = 412.5 minutes. With 440 minutes per day available, this leaves 27.5 minutes of " slack." This time could be used for work breaks, for equipment maintenance, or to produce additional units.

The COMSOAL Technique

COMSOAL uses a computer routine, which generates a fairly large number of feasible solutions through a biased sampling method. The best solutions in the set become alternative solutions to the line balance problem. The universe from which we are sampling is, of course, all the possible feasible solutions to the particular line balance problem. There is a finite probability that we can turn up optimal solutions in this fashion, a slightly large probability that we can turn up the next best solutions, and so on. The probability of developing excellent solutions is related to the size of the sample. Obviously, the trick is to generate feasible solutions rapidly and to bias the generation of these solutions toward the better ones rather than to simply generate feasible solutions at random. The COMSOAL technique has been implemented by Chrysler Corporation and other concerns. It has been applied to a hypothetical line with 1,000 tasks and a known optimum of 200 stations with zero idle time, and a sequence requiring 203 stations resulting in 1.48 percent idle time.

Auxiliary Balancing Techniques

If the bottleneck operation is substantially out of balance, careful motion studies and/or the design of special tools may result in a time reduction. Also, when there are operations with large idle time, which cannot be combined into a single station, as is often true for machine operations, material banks before and after the fast operations may be required. These operations

may then be run for only a small portion of the day, and where the work is compatible, a single operator can man them all by a schedule. The material banks provide work for the subsequent operations when the fast operations are shut down.

> **NOTE:**
> Line balancing solutions offered by the heuristic approach are abstract and for real problems. The grouping of tasks requires consideration of factors other than precedence relationships, (for example, space limitations, technical problems and incompatible operations) that complicate the problem and restrict alternatives.

A PLANT-LAYOUT DECISION

As was discussed earlier, many plants utilize a combination of process and product layouts. The most common types of layouts found in industry are process and product layouts. A less common but basic type of layout exits, known as a fixed-position layout. In this type of layout the product being manufactured remains in a fixed position while machine, employees, materials, and supporting services are brought to it.

Fixed-position layouts, process layouts, and product layouts can be compared in terms of fixed costs and variable costs. Typically, fixed-position layouts have the lowest fixed costs, process layouts have higher fixed costs, and product layouts have the highest fixed costs. Offsetting this situation is the fact that the situation is usually the opposite with respect to variable costs.

Because of these cost relationships, the break-even point increases as one moves from fixed-position layouts to process layouts to product layouts. Further, the volume at which a product layout becomes more economical than a process layout is higher than the volume at which a process layout becomes more economical than a fixed-position layout.

EXAMPLE 4

The Levy Furniture Company is contemplating a new production facility for its Distressed Products line. A fixed-position layout involves a fixed cost of $15,000 and a variable cost of $50 per unit. A process layout involves a higher fixed cost of $24,000. However, variable costs are only $30 per unit. A product layout has the highest fixed cost at $32,500, but variable costs are only $20 per unit. The selling price is $150 per unit. Using the break-even analysis discussed in Chapter 4, the break-even point can be computed as follows:

Recall that

$$X_{be} = \frac{FC}{(P - V)}$$

where X_{be} = break-even point, P = price or average revenue per unit, V = unit variable cost, and FC = total fixed costs.

For a fixed-position layout, X_{be} = 15,000/(150 - 50) = 150 units
For a process layout, X_{be} = 24,000/(150 - 30) = 200 units

For a product layout, $X_{be} = 32,500/(150 - 20) = 250$ units

The fixed-position layout is most economical. The process layout is best when production exceeds 450 units, and the product layout is best when production exceeds 850 units. These production levels are derived as follows:

$$24,000 + 30X = 15,000 + 50X$$
$$X = 450$$
$$32,500 + 20X = 24,000 + 30X$$
$$X = 850$$

These relationships are plotted and compared in Figure 6.

FIGURE 6
THE BREAK-EVEN CHART
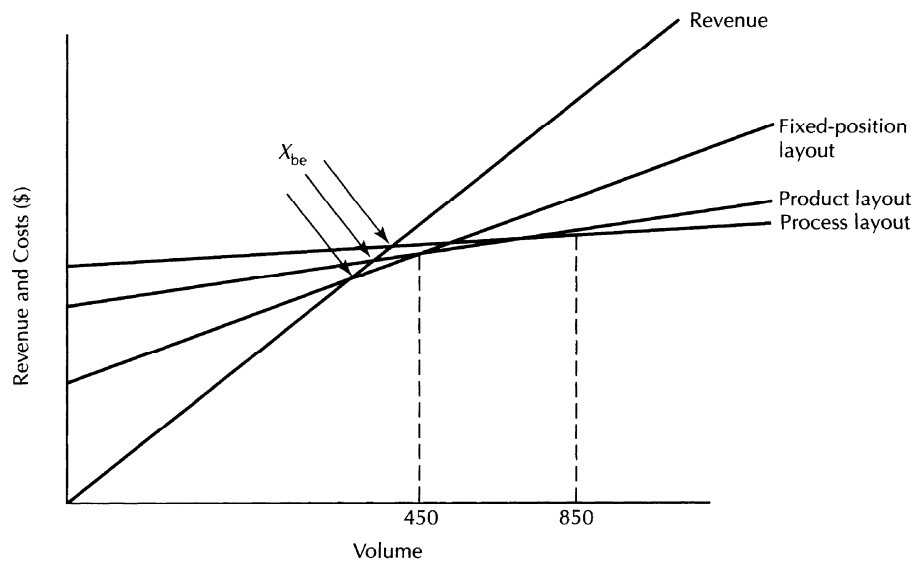
QUESTIONS
1. Describe the goals of process design and layout. Give some of the reasons why such studies are initiated.
2. List the major types of facilities layouts used in production.
3. Discuss some of the problems associated with designing production lines.
4. Discuss the concept of *group technology* and its importance in production.
5. What kind of layout is used in a physical fitness center?
6. What is the objective of assembly line balancing? How would you deal with the situation where one worker, although trying hard, is 20 percent slower than the other ten people on a line?

PROBLEMS

1. A small part can be made (1) on an ordinary general-purpose lathe which is easy to set up but not very efficient in production, (2) on a turret lathe which is more costly but which produces at lower unit cost once it is set up, or (3) with automatic screw machines where volume begins to count and where setup costs are much higher, but operating costs are much lower. It costs $2.50 to set up an ordinary lathe, after which operating, material, and scrap cost is $.45 per unit; turret lathes cost $5.00 to setup and $.20 per unit; and automatic screw machines cost $15.00 to set up but only $.04 per unit. Determine the crossover point among lathes, turret lathes, and automatic screw machines.

2. Given the following data:

Station	Station time (in minutes)
1	4.2
2	4.7
3	4.4
4	4.8

Cycle time = 5.1 minutes.
   (a) Compute the station idle time and the total idle time per cycle.
   (b) Determine the percentage idle time.

3. Determine the minimum number of work stations needed for the following data:
   - Operating time = 480 minutes per day.
   - Desired output = 80 units per day.
   - The sum of task times (Σt) = 56 minutes.

   10. Departments A, C, D, and E should be 40 feet x 40 feet. department B should be 40 feet x 80 feet. Arrange these five departments in an 80 x 12—foot space so that the layout meets the conditions specified in the matrix.
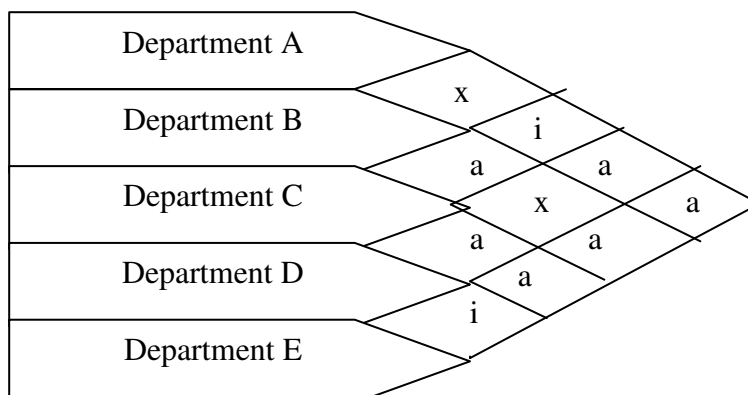
ANSWERS

1. The objectives of process design and layouts are to improve the flow and control of work, reduce costs due to handling and inventory, minimize facilities investment, improve space utilization, and improve worker morale. Such studies are initiated when a new facility is built, a change in production volume arises, new products are introduced, or new process/equipment is installed.
2. They are product layout, process layout, fixed-position layout, and group layout.
3. There are a number of design alternatives and several types of material handling equipment to choose from. Furthermore, the performance of a system design is often unpredictable due to the complex interaction of equipment and parts in process.
4. Group technology is designed to utilize mass production layout and production techniques for small batch systems in order to reduce setups and handling. The idea is to group families of parts requiring similar operations and treats them as a batch of similar parts.
5. In process layout similar equipment or functions are grouped together, such as rowing machines in one area and weight machines in another. The exercise enthusiasts move through the fitness center, following an established sequence of operations.
6. The goal is to create an efficient balance between the tasks and workstations to minimize idle time. If the employee is deemed valuable, training may enhance his/her speed. It is also possible to place a worker in the "choice" job, i.e., that workstation which has most idle time to adjust for the slowness. Also faster workers may assist the slowpoke if the balance and physical features of the line permit.

SOLUTIONS TO PROBLEMS

1.

The cost formulas for making this part on these three kinds of machines are (with x being the quantity to be made each time the machine is set up):

Lathes	$ 2.50 + $.45x
Turret lathes	5.00 + .20x
Automatic screw machine	15.00 + .04x

To find the exact crossover points, it is necessary to set the equations for the two methods being compared and solve for x. For example, the comparison of lathes to turret lathes is:

$ 2.50 + $.45x = $5.00 + $.20x.
.25x = $2.50
x = 10

Similar calculations comparing lathes to automatic screw machines and turret lathes to automatic screw machine yields the other two crossover points at 30 units and at 63 units.

So, for orders under 10 units, a lathe should be used, for 10 to 63 units, a turret lathe, and above 63, an automatic screw machine.

2.
(a)

Station	Station time (in minutes)	Station idle time
1	4.2	.9
2	4.7	.4
3	4.4	.7
4	4.8	.3
Total	18.1	2.3

(b) Percentage of idle time = Idle time per cycle/(N x CT) = 2.3 min./4(5.1 min.) = 11.27%

3.
The minimum number of stations required is:

$N = \frac{Dx\sum t}{OT}$ = (80 units per day x 56 minutes per unit)/480 minutes per day per station = 9.33. (rounded to 10 stations).

4.

B	
C	E
D	A

CHAPTER 8
PRODUCTION PLANNING SYSTEMS:
AGGREGATE PLANNING AND MASTER PRODUCTION SCHEDULING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Develop an aggregate production plan.
2. Distinguish between a level plan and a chase plan.
3. Explain the process to achieve rough-cut capacity planning.
4. Illustrate a trial-end-error method for aggregate planning.
5. Diagram a master production schedule (MPS).
6. Formulate a process for loading.
7. Illustrate an assignment problem.
8. Explain the priority rules.
9. Implement an operations scheduling procedure.
10. Describe briefly Johnson's rule.

Production planning and master scheduling involve the determination of future production levels over a time horizon of several months to one year. The production plan sets an intermediate-range goal for the company's products and capacity utilization in total, while the master schedule provides the input for detailed scheduling and control at the operational level.

Poor production planning can lead to excessive inventory levels or back orders and thus increase cost or reduce customer service. Therefore, production planning is important in helping a firm to achieve its productivity goals. In this chapter, we discuss basic concepts and tools used in aggregate production planning and master scheduling. This provides the basis for material requirements planning (MRP), which is discussed in a later chapter.

THE PRODUCTION PLANNING PROCESS

Aggregate production planning is the development of monthly or quarterly production requirements that will meet the estimates of demand. Gross capacity considerations must be taken into account during production planning.

Once a production plan is made, it must be desegregated into time-phased requirements for individual products. This plan is called the *master production schedule (MPS).* The MPS usually states weekly product requirements over a 6- to 12-month time horizon. The MPS is not a forecast, but rather a schedule of when production should be completed. Operating personnel make detailed plans for the procurement of materials, the production of components, and final assembly of the finished goods using the MPS.

The final element of the production planning process is called *rough-cut capacity planning*. This involves the analysis of the MPS to determine if sufficient capacity is available at critical points in the production process and any potential bottlenecks might occur. This provides a rapid determination of the feasibility of the MPS. Rough-cut capacity planning generally covers a 3-month time horizon. Figure 1 illustrates the essential elements of the production-planning process.

AGGREGATE PLANNING

Aggregate production planning and scheduling has to do with the overall planning and scheduling of the use of various sources of capacity in relation to demand. Stated slightly differently, it deals with the allocation of the various sources of capacity to demand over some planning horizon. The various sources of capacity to which we refer are:

1. Variations in the size of the work force.
2. Variations in the production rate, including the number of hours worked (overtime and undertime).
3. Variations in inventory level, including the possibility of negative inventory (lost sales and/or back orders).
4. Variable use of subcontracting.
5. Combinations of two or more of the above.

Thus, aggregate planning and scheduling is an expression of the policies and procedures by which the enterprise will absorb fluctuations in demand.

A few methods of aggregate planning are listed below, grouped in the four major categories.

1. Trial-and error method
2. Methods attempting to model cost and selecting the least-cost program.
   (a) Transportation method of linear programming
   (b) Linear decision rule (LDR)
3. Heuristic decision rules
   (a) Management coefficients model.
   (b) Search decision rule (SDR)
4. Rough-cut capacity planning

TRIAL-AND-ERROR METHOD

This is perhaps the most widely used. A graphic development of a master production plan and schedule serves to illustrate the nature of the problem. Table 1 shows a year's forecast of production requirements for a seasonal product. Figure 2 shows the production requirements graphs in relation to available production days and illustrates schematically the impact of the seasonal demand.

FIGURE 1
THE PRODUCTION-PLANNING PROCESS

```
                        ┌─────────────┐
                        │  Forecasts  │
                        └─────────────┘
                                              ┌──────────┐
┌────────────────────────┐                    │  Orders  │
│ Inventory adjustments  │                    └──────────┘
└────────────────────────┘
                        ┌───────────────────┐
                        │ Demand estimation │
                        └───────────────────┘
                                 │
                                 ▼
                ┌──────────────────────────────────┐
                │   Aggregate production planning   │
                └──────────────────────────────────┘
                                 │
                                 ▼                    ┌────────────────────────┐
                ┌──────────────────────────────────┐ │ Rough-cut    capacity  │
                │ Master production schedule (MPS)  │◄──►│ planning               │
                └──────────────────────────────────┘ └────────────────────────┘
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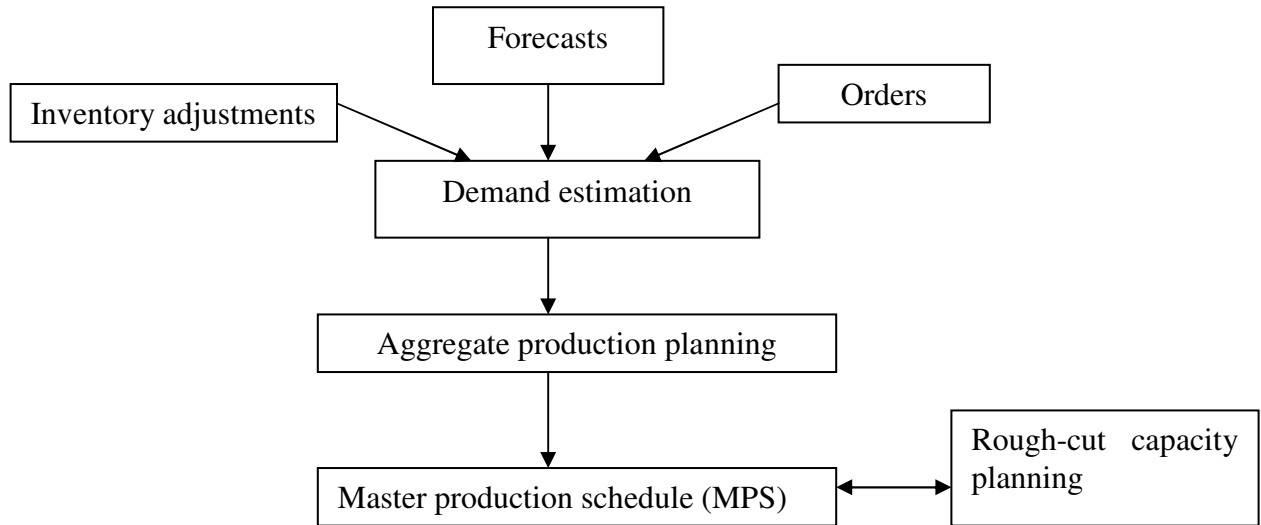
TABLE 1
PRODUCTION REQUIREMENTS

Month	Monthly demand forecast (units)	Cumulative demand forecast	Normal production days in month	Cumulative normal production days
April	1600	1600	21	21
May	1400	3000	22	43
June	1200	4200	22	65
July	1000	5200	21	86
August	1500	6700	23	109
September	2000	8700	21	130
October	2500	11200	21	151
November	2500	13700	20	171
December	3000	16700	20	191
January	3000	19700	20	211
February	2500	22200	19	230
March	2000	24200	22	252
	24200		252	

For planning purposes, plotting the requirements on a cumulative basis is simpler and more effective. Figure 2 also shows the graph of cumulative production requirements and cumulative maximum requirements, together with three feasible production programs.

We will discuss trial-and-error method of aggregate planning by an example. This example considers three alternative operating strategies. The three strategies are:

1. Uniform Output Rate (Level) Plan
2. Variable Output Rate (Chase) Plan
3. Considering a mixed strategy

We assume the following data for Giant Sail Company, a maker of boat sails:

   (a) The typical sail requires 20 hours to make.
   (b) Each employee's working hours is 80 per day.
   (c) 1,000 units of inventory will be on hand at the start of the planning horizon, i.e., April.
   (d) The costs of hire and lay off are $300 and $200, respectively.
   (e) The cost of holding an item in inventory is $6 per month for the average amount in inventory, including work-in-process.
   (f) The number of employees at the beginning of the planning year will be set equal to the number of employees at the end.

FIGURE 2

Cumulative Production vs. Cumulative Produciton Days

	1	3	4	6	7	9	10	12
Plan 1- Level	2024	6266	8290	12532	14556	18412	20340	24293
Plan 2 - Work force	1600	4200	5200	8700	11200	16700	19700	24200
Plan 3 - Mixed	1680	5200	6880	11005	13290	17642	19818	24278
Production days	21	65	86	130	151	191	211	252
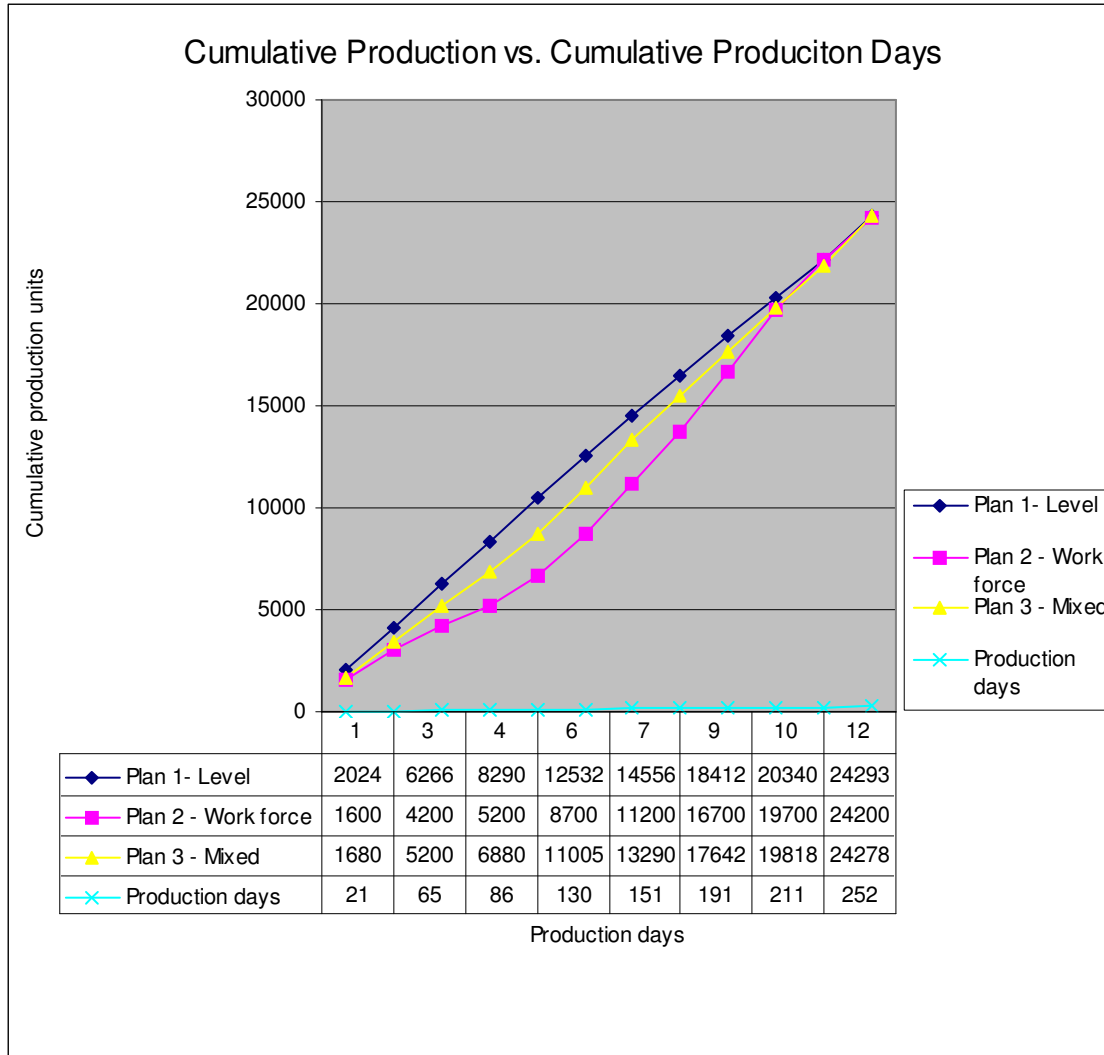
Production days

Plan 1 - Uniform Output Rate (Level) Plan (Varying The Inventory Level)

This plan considers maintaining a uniform (level) production rate, so that all of the variation in demand is accommodated by inventory that will be accumulated during part of the year. This strategy thus keeps constant labor force. This strategy is indicated by the blue color line in Figure 2. Note that this plan is feasible if backordering is permitted or if inventory is held.

Since the company needs to make 24,200 units in 252 days, it must produce at an average rate of at least 96.03 units per day. A work force of 241 employees will be required, which will provide a production rate of 96.4 units per day. The monthly inventory levels and the resulting cost of $209,266 are developed in Table 2.

TABLE 2

CALCULATION OF COST TO USE INVENTORY AND A UNIFORM PRODUCITON RATE

Month	Monthly demand forecast (units) (1)	Cumulative demand forecast (2)	Normal production days in month (3)	Cumulative normal production days (4)	Cumulative production (5)=(4)x96.4	Ending inventory (6) =(5)-(2)+1000*	Inventory holding cost =$6 (beginning + ending)/2
Apr	1600	1600	21	21	2024	1424	$ 7,273
May	1400	3000	22	43	4145	2145	$ 10,709
June	1200	4200	22	65	6266	3066	$ 15,634
July	1000	5200	21	86	8290	4090	$ 21,469
Aug	1500	6700	23	109	10508	4808	$ 26,694
Sept	2000	8700	21	130	12532	4832	$ 28,919
Oct	2500	11200	21	151	14556	4356	$ 27,565
Nov	2500	13700	20	171	16484	3784	$ 24,422
Dec	3000	16700	20	191	18412	2712	$ 19,490
Jan	3000	19700	20	211	20340	1640	$ 13,058
Feb	2500	22200	19	230	22172	972	$ 7,837
Mar	2000	24200	22	252	24293	1093	$ 6,194
	24200		252				$ 209,266

Note : 1,000 units will be on hand at the start of the planning horizon.

Plan 2 - Variable Output Rate (Chase) Plan (Varying The Work Force)

This plan is a plan that changes period-to-period output to match capacity with the demand fluctuation by hiring additional employees in periods of high demand and cutting the labor force in low-demand periods. It assumes that employees with the necessary skills can be employed when they are needed and that they will be hired or laid off to keep the direct labor hours that are available equal to the demanded production hours. When graphed, the cumulative production curve coincides with the cumulative demand curve and is indicated by the pink line in Figure 2. the cost of implementing this plan is developed in Table 3 and is estimated to be $199,976.

Plan 3 - A Mixed Strategy

This strategy assumes a combined strategy—to set a relatively low but uniform production rate for the first part of the year and a higher but uniform rate for the latter part of the year. The first month demand of 1,600 units would require a minimum production rate of 76 units per day (1,600/21 days). If the production rate were set at 80 units per day for the early part of the planning horizon, it would require 200 employees (80 units x 20 hours per day, divided by 8 hours per day per person). At the end of 109 days, the company would have produced 8,720 units (80 units x 109 days).

Note that at the end of production day 252, the company needs to have a total production of 24,200 units. This means that Giant will need to make 15,480 units during the last 143 days, or an average of about 108.3 units per day. The work fore required for this rate of production is

about 272 employees, which will provide a production rate of 108.8 units per day. Thus, 72 employees should be hired at the beginning of September and laid off at the end of the year to achieve these employment levels and end the year with the same employment level.

TABLE 3

COST TO VARY WORK FORCE IN ACCORDANCE WITH MONTHLY PRODUCTION REQUIREMENTS*									
				Production hours per employee during month	Direct employee needed during month rounded	Employees added at start of month	Employees laid off at start of month	Cost of changing employment load	
	Monthly demand forecast (units)	Production hours needed (2) =	Normal production days in month						
Month	(1)	(1) x 20 hrs	(3)	(4)=(3) x 8 hrs	(5)=(2)/(4)	(6)	(7)	(8) = $300 x (6) + $200 x (7)	
Apr	1600	32000	21	168	190		37	7359	
May	1400	28000	22	176	159		31	6277	
June	1200	24000	22	176	136		23	4545	
July	1000	20000	21	168	119		17	3463	
Aug	1500	30000	23	184	163	44		13199	
Sept	2000	40000	21	168	238	75		22516	
Oct	2500	50000	21	168	298	60		17857	
Nov	2500	50000	20	160	313	15		4464	
Dec	3000	60000	20	160	375	63		18750	
Jan	3000	60000	20	160	375		0	0	
Feb	2500	50000	19	152	329		46	9211	
Mar	2000	40000	22	176	227		102	20335	
	24200		252			256	256	127976	**

*Note : It is assumed that the firm would have 227 direct emeployees at the beginning of the planning if this strategy were used.

** Total cost is:

Cost of changing employment level	= $127,976	
Cost of maintaining 1,000 units of inventory	= 72,000	
	$199,976	

The cost of this mixed strategy, which is developed and presented in Table 4, is estimated to be $180,979. Notice that the cost of this strategy is lower than using only inventory changes (Plan 1) or only work force changes (Plan 2). This strategy is indicated by the yellow color line in Figure 2.

TABLE 4

	Monthly demand forecast (units)	Cumulative demand forecast	Normal production days in month	Cumulative normal production days	Production rate units/day	Normal production	Cumulative production	Ending inventory	Inventory holding cost =$6 (beginning + ending)/2	Cost of changing work force
Month	(1)	(2)	(3)	(4)	(5)*	(6)=(3) x (5)	(7)	=(7)-(2)+1000**	(8)	(9)
Apr	1600	1600	21	21	80.0	1680	1680	1080	$ 6,240	
May	1400	3000	22	43	80.0	1760	3440	1440	$ 7,560	
June	1200	4200	22	65	80.0	1760	5200	2000	$ 10,320	
July	1000	5200	21	86	80.0	1680	6880	2680	$ 14,040	
Aug	1500	6700	23	109	80.0	1840	8720	3020	$ 17,100	
Sept	2000	8700	21	130	108.8	2285	11005	3305	$ 18,974	$ 21,600 (72 x $300)
Oct	2500	11200	21	151	108.8	2285	13290	3090	$ 19,183	
Nov	2500	13700	20	171	108.8	2176	15466	2766	$ 17,566	
Dec	3000	16700	20	191	108.8	2176	17642	1942	$ 14,122	
Jan	3000	19700	20	211	108.8	2176	19818	1118	$ 9,178	
Feb	2500	22200	19	230	108.8	2067	21885	685	$ 5,407	
Mar	2000	24200	22	252	108.8	2394	24278	1078	$ 5,290	$ 14,400 (72 x $200)
	24200		252						$ 144,979	$ 36,000

COST OF MIXED STRATEGY TO CHANGE WORK FORCE AND USE INVENTORY

*80 units means 200 employees (80 units x 20 hours per unit divided by 8 hours per employee day)

108.8 units means 272 employees (108.8 x 20 hours per unit divided by 8 hours per employee day)

**Note : 1,000 units will be on hand at the start of the planning horizon.

Total cost is = $144,979 + $36,000 = $180,979.

NOTE:

	Level-Output Strategy	Chase-Output Strategy
Advantages	▪ Lower hiring, layoff, and training costs ▪ Retain skilled employees	▪ No need to backlog ▪ Low costs of carrying inventory ▪ Impossible to build inventories of most services
Disadvantages	▪ Must build costly inventories and/or backlog or refuse orders	▪ High costs of hiring and layoffs ▪ High training costs ▪ Loss of skilled employees ▪ Quality and productivity problems.

METHODS ATTEMPTING TO MODEL COST AND SELECTING THE LEAST-COST PROGRAM

There are several methods that attempt to model cost and selecting the least-cost program, including the transportation method of linear programming (LP) and linear decision rule (LDR).

Aggregate Planning by The Transportation Method of LP

The goal here is to minimize the sum of costs associated with regular labor time, overtime, subcontracting, inventory carrying costs, and costs related to changing the size of the work force. Constraints involve capacities of work force, inventories, and outsourcing. The problem can be

formulated in terms of a transportation-type programming model as a way to obtain aggregate plans that would match capacities with demand requirements and minimize costs.

EXAMPLE 1

Using the following data, we will show the formulation in a transportation format and the final solution.

		Period	
	January	*February*	*March*
Demand	550	700	750
Capacity			
Regular	500	500	500
Overtime	50	50	50
Subcontracting	120	120	120

Costs:
Regular time: $60
Overtime: 80
Subcontracting: 90
Carrying: 1
Backorder: 3
Beginning inventory: 100 units

Since supply (capacity) and demand must be equal, a "dummy" (unused capacity in this example) column has been added to satisfy this requirement. The costs associated with these columns are obviously zeros.

		Demand for				
Supply from		*January*	*February*	*March*	Unused capacity (dummy)	Total capacity available (Supply)
Period	Beginning inventory	0 100	1	2	0	100
January1	Regular	60 450	61 50	62	0	500
	Overtime	80	81 50	82	0	50
	Subcontract	90	91 30	92	0 90	120

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February	Regular	63	60 500	61	0	500
	Overtime	83	80 50	81	0	50
	Subcontract	93	90 20	91 100	0	120
March	Regular	66	63	60 500	0	500
	Overtime	86	83	80 50	0	50
	Subcontract	96	93	90 100	0	100
Demand		550	700	750	90	2090

Costs are shown in the upper right-hand corner of each cell in the above table. The total cost is:
(100 x \$0) + (450 x 60) + (50 x 61) + (50 x 81) + (30 x 91) + (500 x 60) + (50 x 80) + (20 x 90) + (100 x 91) + (500 x 60) + (50 x 90) + (100 x 90) = \$124,730.

THE LINEAR DECISION RULE

Another optimizing technique, the *linear decision rule* (LDR), was developed in 1955 and applied initially at the Pittsburgh Paint Company. The LDR would be classed as a quadratic programming approach to the aggregate planning problem. The cost model for the company is the sum of four cost functions: (1) regular payroll, (2) hiring and layoff, (3) overtime costs, and (4) inventory holding, back ordering, and machine setup costs. With the exception of the regular payroll, these cost functions are idealized as quadratic in form. The equations for each of the cost functions state each cost function in terms of the size of the work force and/or the production rate. The mathematical methodology is then based on the fact that the total incremental cost equation (which is the sum of the four cost functions) is subjected to partial differentiation with respect to work force (W) and with respect to production rate (P), the resulting functions being set to 0 in order to derive the minimum or optimum point. The result is two optimum linear decision rules, one to compute production rate. These two rules require as inputs the forecast for each period of the planning horizon in aggregate terms, the ending size of the work force, and inventory level in the last period. Once the two rules have been developed for a specific situation, the computations required to produce the decisions recommended by the model require only a few minutes by manual methods.

The advantages of LDR are that it is optimizing and that the two decision rules, once derived, are simple to apply. Also, the model is dynamic and representative of the multistage decision system, which we outlined. The principal disadvantage of LDR is that the quadratic cost structure may not represent the actual cost structure very well. In addition, there are no constraints on the size of the work force, overtime, inventory, and capital, and it is possible to generate decisions that are not feasible from some points of view.

NOTE:
SOME ADVANTAGES AND LIMITATIONS OF AGGREGATE PLANNING METHODS

Method	Solution approach	Advantages	Limitations
Trial and error	Alternative plans through trial and error	Simple to develop and easy to understand	Nonoptimal
Transportation method of Linear programming (LP)	Optimizing	Will find optimum solution to stated problem	Actual problem may not fit the linear model; assume constant workforce
Linear decision rule	Optimizing	Will find optimum solution to stated problem	Actual problem may not fit the quadratic cost model; complex to use
Management coefficients	Heuristic	Use multiple regression to incorporate past managerial performance into a model	Nonoptimal
Rough-cut capacity planning	Trial and error	Simple to understand and apply; intuitively appealing	Relies on judgment to determine the most desirable master schedule; does not guarantee optimum solution

MASTER SCHEDULING

Master scheduling involves planning the production of individual products or services to fill orders and meet forecasts of other demand. A master schedule, often called *a master production schedule* (MPS), is a schedule of planned completion of end-items. That means that it is concerned only with the final product (planning the production of parts and components will be left for detailed plans to follow). In services, the appointment book serves as the master schedule.

Rough-Cut Capacity Planning

The first step in master scheduling is to make a trial master schedule. Rough-cut capacity planning is the process of testing whether certain key resources are adequate to produce this schedule. If not, the trial MPS is revised until it is feasible. The first choice would be to try to move some of the production to an earlier period, so as to not disappoint customers. When a workable plan is found, it becomes the final master schedule.

EXAMPLE 2

Zeller Wood Company produces several types of furniture-grade plywood to stock. It wants to test its trial master schedule to see whether it might overload the laminating machine, which has been an occasional bottleneck in the plant. The laminating machine can laminate a high-density plastic surface to 4 x 8 sheets of particle board at a rate of 12 sheets per hour. The trial MPS for the next five weeks is as follows:

Week	1	2	3	4	5
Sheets of 4 x 8 laminates	290	420	600	380	500

The number of sheets that can be run on five 8-hour shifts is 480 sheets per week (5 shifts x 8 hours x 12 sheets). So we can shift production from weeks 3 and 5 to earlier weeks, so that no week exceeds 480 sheets. The company's final MPS becomes:

Week	1	2	3	4	5
Sheets of 4 x 8 laminates	350	480	480	400	480

COMPUTERIZED SCHEDULING SYSTEMS

In many cases computer software packages for master production scheduling are an integral part of a large manufacturing information system—cost analysis, inventory information, and scheduling. IBM's *Communications Oriented Production and Control System (COPICS)* is an example of such systems. The system integrates forecasting, scheduling, inventory, and purchasing decisions into one large information system or planning and controlling all facets of the production system. Many computer programs also perform 'what-if" (or sensitivity) analysis, which allows a production planner to determine how the production schedule would change with different assumptions concerning demand forecasts or cost figures.

Some recent computerized scheduling systems are gaining in popularity. Noteworthy among those are *Optimized Production Technology (OPT), Disaster*, and *Q-Control*, all of which concentrate their scheduling efforts on bottleneck operations. Dr. Eli Goldratt in Israel developed the first two and William E. Sandman developed the third one.

OPERATIONS SCHEDULING

Master scheduling is concerned only with end-items such as finished goods or sometimes major components and only with completion dates. Operations scheduling, also called *detailed scheduling,* or simply *scheduling* is concerned with starts and completion of each part or

component through each operation. Scheduling is the management of organizational resources to achieve an orderly uninterrupted work flow process.

A schedule is a time table for performing activities, utilizing resources, or allocating facilities. Examples include a physician's appointment schedules, class schedules at a university, hospital admission scheduling, surgery scheduling, airline scheduling, or bus scheduling. The purpose of scheduling is to:

(a) Desegregate the general production plan into time-phased weekly, daily, or hourly activities.
(b) Specify in precise terms the planned workload on the production system in the very short run.

Some of the goals that must be considered for scheduling the job shop are:
    (a) Minimize the average lateness.
    (b) Minimize idle labor and facilities.
    (c) Minimize setup costs.
    (d) Deliver the maximum number of jobs before the due date.

All of these criteria that may conflict with each other can not be achieved at the same time. A trade-off among these conflicting goals exists. But scheduling and control must take place with some goal or goals kept in mind. In general, two steps are involved in scheduling: loading and sequencing.

LOADING
Loading involves allocating workloads to specific work. A number of approaches are used for loading. The two are: the use of *Gantt charts* and *assignment method* of linear programming.

Gantt Charts
Gantt charts is a visual aid. The purpose is to organize and classify the actual or intended use of resources in a time framework. In most cases, a time scale is represented *horizontally* and resources to be scheduled are listed *vertically*. There are two kinds of Gantt charts: load chart which depicts the loading and idle times of a group of machines or departments and schedule chart which is used to monitor the progress of jobs.

Assignment Problem
The problem is to determine how the assignments should be made in order to minimize total costs.

Step 1: For each row select the smallest number in that row and then subtract it from every element in that row. Repeat this step for all rows, entering the results in a new matrix.
Step 2: For each column select the smallest number in that column and then subtract it from every element in that column. Repeat this step for all columns, entering the results in a new matrix.

Step 3: (a) Search for a solution having all zero-cost assignments. If one is found, it is an optimal solution.

(b) Otherwise, draw a set of lines through rows or columns (each line covering one row or one column) such that all zero elements are covered using as *few lines* as possible. Let m = the minimum number of lines that cover all zero elements at least once. If m < n then a solution with all zero-cost elements is not yet present.

Step 4: Select the smallest uncovered element. Subtract it from all uncovered elements. Add it to *all twice-covered elements*. Do not change the singly covered elements. Return to step 3.

EXAMPLE 3

Consider an assignment problem having 3 jobs and 3 facilities. The costs of all possible assignments are given by the following cost matrix.

			Job	
		J1	J2	J3
Facility	F1	5	4	6
	F2	9	3	7
	F3	3	2	1

Step 1 gives the following table, often called an *opportunity cost matrix*.

1	0	2
6	0	4
2	1	0

Step 2 yields:

0	0	2
5	0	4
1	1	0

Step 3 : W found all zero-cost assignments in Step 2:

0*	0	2
5	0*	4
1	1	0*

The optimal solution is: F1-J1; F2-J2, and F3-J3 with total cost of $9.

EXAMPLE 4

Consider the following assignment problem:

3	5	7	1
9	8	12	10
13	8	14	2
5	7	10	6

After doing step 1, row and column substations, the opportunity cost matrix becomes the following:

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2	4	2	0
1	0	0	2
11	6	8	0
0	2	1	1

The zero elements of this matrix can be covered by 3 lines but *not* by 2. Hence, m=3 while n=4.

Step 3(b) concludes with the knowledge that a zero-cost solution is *not yet* present. Hence, we must go to step 4:

Select the smallest uncovered element. Subtract it from all uncovered elements. Add it to *all twice-covered elements*. Do not change the singly covered elements. Return to step 3.

0	2	0*	0
1	0*	0	4
9	4	6	0*
0*	2	1	3

Now we found a zero-cost solution: F1-J3; F2-J2; F3-J4, and F4-J1 with a total cost of $22.

SEQUENCING
 Operations sequencing is the situation in which one or several products must go through one particular machine or process. Sequencing involves determining the sequence in which operations are to be performed. It indicates the order in which the jobs waiting at a given work center are to be processed. Here the objective is to decide on the order in which several jobs should be scheduled on the same machine in an optimum manner. There are two basic rules:

(a) Priority rules
(b) Johnson's rules

Priority Rules
 Priority rules are simple heuristics used to select the order in which the jobs will be processed. Some of the common rules are:

(a) First come, first served (FCFS): Jobs are processed in the order that they arrive at a machine or work center.
(b) Shortest processing time (SPT): Jobs are processed according to processing time at a machine, that is, shortest jobs first.
(c) Due date (DD): Jobs are selected according to due date, that is, earliest due date first.
(d) Least slack (LS): Defined as time until due date minus remaining time to process. The job with the least slack goes first.
(e) Rush: Emergency or preferred customers first.

Performance measures that can be used to compare different priority rules are:

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(a) Average completion time (average flow time): the average time each job spends at the work center.

(b) Average job lateness (tardiness)

(c) Average number of jobs in the system.

EXAMPLE 5

Consider the following jobs and their processing time and due dates:

Job	Processing time (days)	Due date (days)
A	2	7
B	8	16
C	4	4
D	10	17
E	5	15
F	12	18

Assume that job setup costs and times are *independent* of processing sequence.

(a) The FCFS sequence is simply A-B-C-D-E-F. Assume jobs arrived in the alphabetical order.

Job	Processing time (days) (1)	Flow time (2)	Due date (days) (3)	Dues late (2) – (3)
A	2	2	7	0
B	8	10	16	0
C	4	14	4	10
D	10	24	17	7
E	5	29	15	14
F	12	41	18	23
Total	41	120		54

1) Average completion time: 120/6 jobs = 20 days
2) Average job lateness (tardiness): 54/6 jobs = 9 days
3) Average number of jobs in the system: 120/41 = 2.93 jobs

(b) Using the SPT rule, the sequence is A-C-E-B-D-F

Job	Processing time (days) (1)	Flow time (2)	Due date (days) (3)	Dues late (2) – (3)
A	2	2	7	0
C	4	6	4	2
E	5	11	15	0

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B	8	19	16	3
D	10	29	17	12
F	12	41	18	23
Total	41	108		40

1) Average completion time: 108/6 = 18 days
2) Average job lateness (tardiness): 40/6 = 6.67 days
3) Average number of jobs in the system: 108/41 = 2.63 jobs

(c) Using the DD rule, the sequence is C-A-E-B-D-F

Job	Processing time (days) (1)	Flow time (2)	Due date (days) (3)	Dues late (2) – (3)
C	4	4	4	0
A	2	6	7	0
E	5	11	15	0
B	8	19	16	3
D	10	29	17	12
F	12	41	18	23
Total	41	110		38

1)   Average completion time: 110/6 = 18.33 days
2)   Average job lateness (tardiness): 38/6 = 6.33 days
3)   Average number of jobs in the system: 110/41 = 2.68 jobs

(d) Using the LS, the sequence is C-A-F-D-B-E

Job	Processing time (days) (1)	Flow time (2)	Due date (days) (3)	Slack (days) (3) – (1)	Dues late (2) – (3)
C	4	4	4	0	0
A	2	6	7	5	0
F	12	18	18	6	0
D	10	28	17	7	11
B	8	36	16	8	20
E	5	41	15	10	26
Total	41	133			57

1) Average completion time: 133/6 = 22.17 days
2) Average job lateness (tardiness): 57/6 = 9.5 days
3) Average number of jobs in the system: 133/41 = 3.24 jobs

Johnson's Rule

Johnson's rule is a technique that can be used to minimize the completion time for a group of jobs that are to be processed on two machines or at two successive work centers. Using this rule saves time since it is impractical to enumerate all possible sequences.

Determination of the optimum sequence involves the following steps:

1) List all jobs with their corresponding times on both work centers.
2) Find the minimum time among all listed times.
3) If this time belongs to the first work center, schedule the corresponding job first; if the time is at the second center, schedule the job last. Break ties arbitrarily. In either case, eliminate the job from further consideration.
4) Go to steps 2 and 3 and continue this process until all jobs are scheduled.

EXAMPLE 6

Presented below are processing times for 6 jobs in two work centers:

Job	Processing time	(hours)
	WC1	WC2
A	5	5
B	4	3
C	8	9
D	2	7
E	6	8
F	12	15

Steps 1 and 2:

1st	2nd	3rd	4th	5th	6th
D					B

Step 3: The remaining jobs and their times are:

Job	Processing time	(hours)
	WC1	WC2
A	5	5
C	8	9
E	6	8
F	12	15

Repeating steps 1, 2, and 3, we obtain:

1st	2nd	3rd	4th	5th	6th
D	E	C	F	A	B

The following chart displays the throughput time and idle times at two work centers.

Time   0   2   8   16   28   33   37

WC1	D	E	C	F	A	B	

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WC2	██	D	E	C		F		

██████

Idle

The group will take 51 hours to complete. The WC2 will wait 2 hours for its first job. WC1 will be finished in37 hours.

QUESTIONS
1. Briefly explain the production-planning process.
2. Why is aggregate planning much more difficult with seasonal demand?
3. List the basic controllable variables (strategies) of a production planning problem. What are the four major costs?
4. What is a *master production schedule* (MPS)? Why is it necessary?
5. Define *level* output strategy. How does it differ from the *chase plan* in aggregate production planning?
6. Briefly discuss the conditions under which you would be better off using the LP simplex method rather than the period model in aggregate planning?
7. How important is forecast accuracy to the problems of the aggregate planning models?
8. What are the objectives of scheduling?
9. Describe the conditions under which the assignment method is appropriate.

PROBLEMS
1. A firm producing one product is scheduling (allocating) its January-March production capabilities. Part of the decision involves scheduling overtime work. A unit produced on overtime costs an extra $300. Similarly, a unit made one month before it is needed incurred an inventory carrying cost of $100; two months costs $200 per unit. The units delivered according to this schedule follows:

January   80 units
February   120 units
March   150 units
Production capacities are:

	Regular Time	*Overtime*
January	100	50
February	100	40
March	100	30

Formulate the production scheduling problem as a transportation problem and solve it by the Northwest Corner Rule.

2. The production planner of Omega Research, a maker of industrial lenses, devised the following level output aggregate plan for the next 4 periods.

Period	Demand forecast	*Planned production*	*Beginning inventory*	*Ending inventory*
1	40,000	48,000	9,000	
2	70,000	48,000		

3	30,000	48,000		
4	55,000	48,000		

Calculate the projected beginning and ending inventory for each period. Possible backorders may be shown by a negative number.

3. Refer to problem 2.
   (a) Develop a chase demand strategy that gradually increases the inventory level to 14,000 units by the end of period 4. Show the effect of the plan on inventory level for each period.
   (b) Assume that the company currently has 10 employees and each employee, on average, can produce 4,000 units per period. Develop a staffing plan showing the number of employees that should be hired or laid off at the beginning period, using the following worksheet format.

Period	Required work force	Required number of employees	Available at the end of previous period	Hire	Layoff
1					
2					
3					
4					

4. Refer to problem 2. The company wishes to develop a master production schedule (MPS) for the next 4 periods. The trial MPS allocates the planned production (48,000 units) equally (12,000 units per week). While the company has sufficient employee time to carry out the schedule, the capacity of an automatic machine that polishes the lenses may not be adequate. The machine is scheduled for regular maintenance and has a maximum capacity of 13,200 units per week.
   (a) Check the feasibility of the trial MPS.
   (b) If this trial MPS exceeds the available capacity of the polishing machine in any week, devise a feasible MPS.

5. The costs to do each of the three jobs on three alternate pieces of equipment are given below. Determine a job-equipment combination that will minimize total cost.

		Equipment		
		A	B	C
Job	1	8	7	4
	2	9	6	9
	3	12	5	8

6. Consider the following assignment problem:

		Job		
		X	Y	Z
Facility	A	25	31	35
	B	15	20	24
	C	22	19	17

Find an optimal assignment.

7. Consider the following jobs and their processing time and due dates:

Job	Processing time (days)	Flow time (days)	Due date (days)
A	4	4	6
B	17	21	20
C	14	35	18
D	9	44	13
E	11	55	12

Assume that jobs arrived in the alphabetical order.

(a) Determine processing sequence using the FCFS and average completion time, average job lateness, and average number of jobs in the system.
(b) Determine the same using the SPT rule.
(c) Determine the same using the DD rule.
(d) Determine the same using the LS rule.

ANSWERS

1. First, estimate demand including demand forecasts and customer orders. Next, monthly or quarterly production plans are developed on an aggregate basis. These are then desegregated into time-phase requirements for individual products (the master production schedule MPS) over a 6-12 month planning horizon. Rough-cut capacity planning is performed to determine if sufficient capacity is available at critical points in the production process. The MPS may then have to be adjusted.
2. With seasonal demand, it is more difficult to control inventory levels and shortage conditions.
3. Basic controllable variables are production rate, work force levels, and inventories. Major costs involved are production costs (fixed and variable), production rate change costs, inventory holding costs, and backlogging costs.
4. An MPS states how many finished products are to be produced and when. This is necessary in order to make specific plans and schedules at shop floor level, establish delivery dates, and plan short-term capacity adjustments.
5. Level output strategy focuses on holding production constant over a period of time. It is more like a combination of strategies in that for the period it keeps work force constant, inventory low and depends on a demand backlog to pull products through.
6. The basic simplex model is needed if changes in work force size (hiring/firing) is an option over the planning horizon.
7. An accurate forecast encourages the use of deterministic techniques such as LP which in turn permits the development of near optimal plans. Any reduction in uncertainty enhances the likely accuracy of any production planning method.
8. Operations scheduling are intended to a) meet due dates, b)minimize lead times, c)minimize set up times and cost, d) minimize work-in-process inventory, and e) maximize machine utilization.

9. The assignment method is appropriate when a) there are n "things" to be distributed to n "destinations," each thing must be assigned to one and only one destination, and only one evaluation criterion can be used.

SOLUTIONS TO PROBLEMS

1.

		Demand for				
Supply from		*January*	*February*	*March*	*Unused capacity (dummy)*	*Total capacity available (Supply)*
January	Regular	80	20			100
	Overtime		50			50
February	Regular		50	50		100
	Overtime			40		40
March	Regular			60	40	100
	Overtime				30	30
Demand		80	120	150	70	420

2.

Period	Demand forecast	Planned production	Beginning inventory	Ending inventory
1	40,000	48,000	9,000	17,000
2	70,000	48,000	17,000	-5,000
3	30,000	48,000	-5,000	13,000
4	55,000	48,000	13,000	6,000

Note that ending inventory = beginning inventory + planned production – demand forecast

3.

(a) Inventory is increased by 1250 units in each period:. (14,000 – 9,000)/4

		Planned	*Beginning*	
		production		

Period	Demand forecast	production	inventory	Ending inventory
1	40,000	41,250	9,000	10,250
2	70,000	71,250	10,250	11,500
3	30,000	31,250	11,500	12,750
4	55,000	56,250	12,750	14,000

(b)

Period	Required work force	Required number of employees	Available at the end of previous period	Hire	Layoff
1	41,250/4,000= 10.3	10	10		
2	71.250/4,000= 17.8	18	10	8	
3	31,250/4,000= 7.8	8	18		10
4	56,250/4,000= 14.1	14	8	6	

4.

(a)

Week	1	2	3	4
Trial MPS	12,000	12,000	12,000	12,000
Capacity	13,200	13,200	11,000	13,200

The trial MPS exceeds the capacity of the polishing machine which is a bottleneck in week 3 . The machine runs only for 5 days and can produce 11,000 units (13,200 x 5/6).
(b) The 1,000 units shortage in week 3 may be produced in an earlier week preferably in week 2. A revised MPS may look like:

Week	1	2	3	4
Trial MPS	12,000	13,000	11,000	12,000
Capacity	13,200	13,200	11,000	13,200

5.

8	7	4	
9	6	9	row reduction
12	5	8	⟶

Using row and column reductions we obtain the following opportunity cost matrices.

4	3	0	
3	0	3	column reduction
7	0	3	⟶

1	3	0*

0*	0	3
4	0*	3

So we found a zero-cost solution, which is optimal:
1 to C; 2 to A; 3 to B with a total cost of $18.

6.
Using Step 1 we obtain the following opportunity cost matrix:

0	6	10
0	5	9
5	2	0

We cannot find a zero-cost solution, so we go to step 2, which gives:

0	4	10
0	3	9
~~5~~	~~0~~	~~0~~

Since m=2 < n=3, we go to step 4.

0*	1	7
0	0*	6
8	0	0*

Note that m=n=3, we find an optimal solution:

A to X	$25
B to Y	20
C to Z	17
	$62

7.
(a) Using the FCFS rule, the sequence is A-B-C-D-E.

Job	Processing time (days) (1)	Flow time (days) (2)	Due date (days) (3)	Due late (days) (2) – (3)
A	4	4	6	0
B	17	21	20	1
C	14	35	18	17
D	9	44	13	31
E	11	55	12	43
	55	159		92

1) Average completion time: 159/5 jobs = 31.8 days
2) Average job lateness (tardiness): 92/5 jobs = 18.4 days
3) Average number of jobs in the system: 159/55 = 2.89 jobs

(b) Using the SPT rule, the sequence is A-D-E-C-B.

Job	Processing time (days) (1)	Flow time (days) (2)	Due date (days) (3)	Due late (days) (2) – (3)
A	4	4	6	0

D	9	13	13	0
E	11	24	12	12
C	14	38	18	20
B	17	55	20	35
	55	134		67

1) Average completion time: 134/5 jobs = 26.8 days
2) Average job lateness (tardiness): 67/5 jobs = 13.4 days
3) Average number of jobs in the system: 134/55 = 2.44 jobs

(c) Using the DD rule, the sequence is A-E-D-C-B, which is the same as the one by the SPT rule.

Job	Processing time (days) (1)	Flow time (days) (2)	Due date (days) (3)	Due late (days) (2) – (3)
A	4	4	6	0
E	11	15	12	3
D	9	24	13	11
C	14	38	18	20
B	17	55	20	35
	55	136		69

1) Average completion time: 136/5 jobs = 27.2 days
2) Average job lateness (tardiness): 69/5 jobs = 13.8 days
3) Average number of jobs in the system: 136/55 = 2.47 jobs

(a) Using the LS rule the sequence is: E-A-B-C-D (or E-A-B-D-C)

Job	Processing time (days) (1)	Flow time (days) (2)	Due date (days) (3)	Slack (3) – (1)	Due late (days) (2) – (3)
E	11	11	12	1	0
A	4	15	6	2	9
B	17	32	20	3	12
C	14	46	18	4	24
D	9	55	13	4	42
Total	55	159			87

1) Average completion time: 159/5 jobs = 31.8 days
2) Average job lateness (tardiness): 87/5 jobs = 17.4 days
3) Average number of jobs in the system: 159/55 = 2.89 jobs

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CHAPTER 9
INDEPENDENT DEMAND INVENTORY SYSTEMS

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Explain what is meant by an independent demand.
2. Compute the economic order quantity (EOQ).
3. Show how to determine EOQ with a quantity discounts schedule.
4. Determine optimal safety stock.
5. Calculate the optimum reorder point.
6. Discuss the marginal approach to inventory.
7. Demonstrate the Monte Carlo simulation method.
8. Describe the ABC analysis method to control inventory control.

One of the most common problems facing operations managers is inventory planning. This is understandable since inventory usually represents a sizable portion of a firm's total assets and, more specifically, on the average, more than 30% of total current assets in the U.S. industry. Excessive money tied up in inventory is a drag on profitability.

Inventories may contain materials that have either *dependent demand* or *independent demand*. Dependent demand inventories consist of items whose demand depends on the demands for other items also held in inventory. Demand (or usage) of subassemblies and component parts is derived from the number of finished units that will be assembled. A classic example is demand for wheels for new automobiles. Independent demand items are the finished goods or other end items. Its demand is independent of the demand for any other item carried in inventory.

This chapter focuses on management of independent demand items. The next chapter deals with inventory systems for dependent demand.

ECONOMIC ORDER QUANTITY (EOQ) AND REORDER POINT

The purpose of inventory planning is to develop policies which will achieve an optimal investment in inventory. This objective is achieved by determining the optimal level of inventory necessary to minimize inventory related costs.

Inventory related costs fall into three categories:
(1) *Ordering costs*, which includes all costs associated with preparing a purchase order.
(2) *Carrying (holding) costs*, which include storage costs for inventory items plus the cost of money tied up in inventory.
(3) *Shortage (stockout) costs*, which include those costs incurred when an item is out of stock. These include the lost contribution margin on sales plus lost customer goodwill.

There are many inventory planning models available which try to answer basically the following two questions:
(1) How much to order?
(2) When to order?

They include the economic order quantity (EOQ) model, the reorder point, and the determination of safety stock.

BASIC ECONOMIC ORDER QUANTITY (EOQ) MODEL
The economic order quantity (EOQ) determines the order quantity that results in the lowest sum of carrying and ordering costs. The EOQ is computed as:

$$EOQ = \sqrt{\frac{2DO}{C}}$$

where C = carrying cost per unit, O = ordering cost per order, D = annual demand (requirements) in units.
If the carrying cost is expressed as a percentage of average inventory value (say, 12 percent per year to hold inventory), then the denominator value in the EOQ formula would be 12 percent times the price of an item.

EXAMPLE 1
Assume the Los Alamitos Store buys sets of steel at $40 per set from an outside vendor. It will sell 6,400 sets evenly throughout the year. The store's carrying cost is $8.00 per unit per year. The ordering cost is $100 per order. Therefore,

$$EOQ = \sqrt{\frac{2(6,400)(\$100)}{\$8.00}} = \sqrt{160,000} = 400 \text{ sets}$$

Total number of orders per year = D/EOQ = 6,400/400 = 16 orders
Total inventory costs = Carrying cost + Ordering cost
$\qquad$ = C x (EOQ/2) + O (D/EOQ)
$\qquad$ = ($8.00)(400/2) + ($100)(6,400/400)
$\qquad$ = $1,600 + $1,600 = $3,200
Based on these calculations, the Los Alamitos Store's inventory policy should be the following:
(1) The store should order 400 sets of steel each time it places an order and order 16 times during a year.
(2) This policy will be most economical and cost the store $3,200 per year.

NOTE:
When an item is made instead of purchasing it, the EOQ model is used to determine the economic production run size where O = cost per setup.

Reorder Point

Reorder point (ROP), which answers when to place a new order, requires a knowledge about the lead time, which is the time interval between placing an order and receiving delivery. Reorder point (ROP) can be calculated as follows:

Reorder point = (average demand per unit of lead time x lead time) + safety stock

First, multiply average daily (or weekly) demand by the lead time in days (or weeks) yielding the lead time demand. Then add safety stock to this to provide for the variation in lead time demand to determine the reorder point. If average demand and lead time are both certain, no safety stock is necessary and should be dropped from the formula.

EXAMPLE 2

Assume in Example 1, lead time is constant at one week, and that there are 50 working weeks in a year.

Then the reorder point is 128 sets = (6,400 sets/50 weeks) x 1 week.

Therefore, when the inventory level drops to 128 sets, the new order should be placed. Suppose, however, that the store is faced with variable demand for its steel and requires a safety stock of 150 additional sets to carry. Then the reorder point will be 128 sets plus 150 sets, or 278 sets.

Figure 1 shows this inventory system when the order quantity is 400 sets and the reorder point is 128 sets.

FIGURE 1

BASIC INVENTORY SYSTEM WITH EOQ AND REORDER POINT
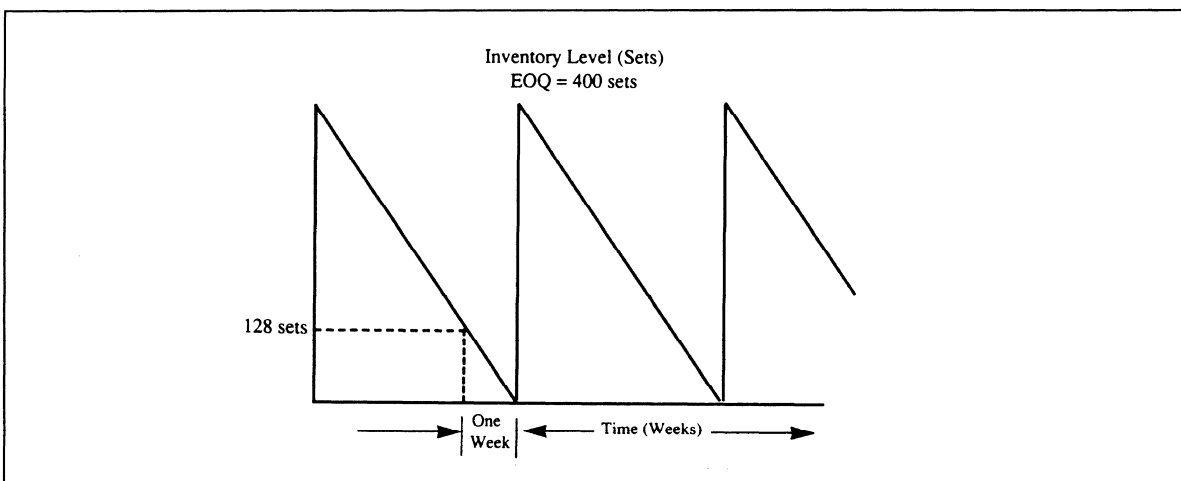
Assumptions and Applications

The EOQ model makes some strong assumptions. They are:

1.   Demand is fixed and constant throughout the year.
2.   Lead time is known with certainty.
3.   No quantity discounts are allowed.
4.   No shortages are permitted.

NOTE:

The assumptions may be unrealistic. However, the model still proves useful in inventory planning for many firms. In fact, many situations exist where a certain assumption holds or nearly holds. For example, subcontractors who must supply parts on a regular basis to a primary contractor face a constant demand. Even where demand varies, the assumption of uniform demand is not unrealistic. Demand for automobiles, for example, varies from week to week over a season, but the weekly fluctuations tend to cancel out each other so that seasonal demand can be assumed constant.

EOQ With Noninstantaneous Replenishment

So far we assumed that the inventory replenishment is instantaneously received. Now we consider the case where the inventory is being manufactured while demands are being met. The following is assumed:

1. The product held in inventory is not purchased from an outside source but manufactured.
2. Units are continuously being added to inventory during the production run.
3. When this inventory is completely depleted, a new production run is started.

Let us define:

O = setup cost, D = annual demand, p = production rate, u = usage rate, and $p > s$.

The costs associated with operating this system are the carrying costs and the production setup costs (instead of ordering costs). Note that during a production run, inventory accumulates at a rate of $(p - u)$ units per period. Afterwards it is depleted at a rate of u units. The situation is depicted in Figure 2.

FIGURE 2
EOQ WITH NONINSTANTANEOUS REPLENISHMENT
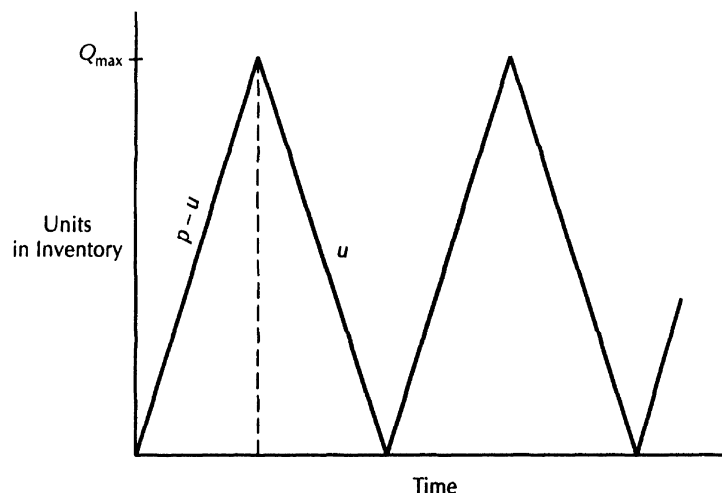
Then setup costs = O (D/Q)
Maximum inventory level = Inventory buildup rate x Period of delivery = (p - u)(Q/p)
Minimum inventory level = 0

Average inventory level = $\dfrac{\text{Maximum inventory + Minimum inventory}}{2}$

= 1/2[(p - u)(Q/p) + 0] = Q/2[(p - u)p]
Total annual inventory costs = C Q/2[(p - u)p] + S(D/Q). Using the calculus yields

$$EOQ = \sqrt{(2DS/C)[p/(p-u)]} = \sqrt{2DS/C(1-u/p)}$$

EXAMPLE 3

Jog Plumbing, Inc. developed the following estimates for the #123 valves.
D = 800 valves per year, C = $.05 per valve per year, S = $1.00 per order or setup, p = 100
valves per week, and u = 60 valves per week. Then

$$EOQ = \sqrt{\dfrac{2DS}{C}\cdot\dfrac{p}{(p-u)}} = \sqrt{\dfrac{2(800)(1)}{(.05)}\cdot\dfrac{100}{(100-60)}} = 283 \text{ valves}$$

The maximum inventory level = (p - u)(Q/p) = (100 - 60)(283/100) = 113.2 valves
Total annual inventory costs = C Q/2[(p - u)p] + S(D/Q)
    = $.05(283/2)[(100 - 60)/100] + $1(800/283)
    = $2.83 + $2.83 = $5.66 per year.

The production run time (the production phase of the cycle) = EOQ/p = 283 valves/100 valves
per week = 2.83 weeks. Thus, each run will require 2.83 weeks to complete.
The cycle time (the time between orders or between the beginnings of runs) = EOQ/u =283
valves/60 valves per week = 4.72 weeks. Thus, a run of valves will be made every 4.72 weeks.

EOQ with Quantity Discounts
The economic order quantity (EOQ) model does not take into account quantity discounts,
which is not realistic in many real world cases. Usually, the more you order, the lower the unit
price you pay. Quantity discounts are price reductions for large orders offered to buyers to
induce them to buy in large quantities. If quantity discounts are offered, the buyer must weigh
the potential benefits of reduced purchase price and fewer orders that will result from buying in
large quantities against the increase in carrying costs caused by higher average inventories.
Hence, the buyer's goal in this case is to select the order quantity which will minimize total costs,
where total cost is the sum of carrying cost, ordering cost, and product cost:

Total cost = Carrying cost + Ordering cost + Product cost
    = C x (Q/2)   + O x (D/Q)   + PD

where P = unit price, and Q = order quantity.

There are two general cases:

(a) Carrying costs are constant.

(b) Carrying costs are stated as a percentage of purchase price.

When carrying costs are constant. there will be a single EOQ that is the same for all of the cost curves. When carrying costs are stated as a percentage, each curve will have a different EOQ.

Case 1 - Constant carrying costs

A step by step approach in computing economic order quantity with quantity discounts is summarized below.

1. Compute the common EOQ when price discounts are ignored.
2. Only one of the curves will have the EOQ in its feasible range. Identify that curve.
   (a) If the feasible EOQ is the lowest price curve, this is the overall EOQ.
   (b) If the EOQ is on any other curve, compute the total cost for the EOQ and for the quantities for which price reductions will occur.
3. Select the value of Q which will result in the lowest total cost.

EXAMPLE 4

In Example 1, assume that the Los Alamitos Store was offered the following price discount schedule:

Order quantity (Q)	Unit price (P)
1 to 499	$40.00
500 to 999	39.90
1000 or more	39.80

First, the EOQ with no discounts is computed as follows:

$$EOQ = \sqrt{\frac{2(6,400)(\$100)}{\$8.00}} = \sqrt{160,000} = 400 \text{ sets}$$

$$\text{Total cost} = \$8.00(400/2) + \$100(6,400/400) + \$40.00(6,400)$$
$$= \$1,600 + 1,600 + 256,000 = \$259,200$$

We see that the value which minimized the sum of the carrying cost and the ordering cost but not the purchase cost was EOQ=400 sets. The further we move from the point 400, the greater will be the sum of the carrying and ordering costs. Thus, 400 is obviously the only candidate for the minimum total cost value within the first price range. Q=500 is the only candidate within the $39.90 price range and Q=1,000 is the only candidate within the $39.80 price bracket. These three quantities are evaluated in Table 1 and illustrated in Figure 3.

TABLE 1
ANNUAL COSTS WITH VARYING ORDER QUANTITIES

Order Quantity (Q)	400	500	1,000
Purchase price (P)	$40	$39.90	$39.80
Carrying cost (C x Q/2) $8 x (order quantity/2)	$1,600	$2,000	$4,000
Ordering cost (O x D/Q)			
$100 x (6,400/order quantity)	1,600	1,280	640
Product cost (PD) Unit price x 6,400	256,000	255,360	254,720
Total cost	$259,200	$258,640	$259,360

Note that C = $8.00, O = $100, and D = 6,400 for all possible orders.

FIGURE 2
INVENTORY COST AND QUANTITY
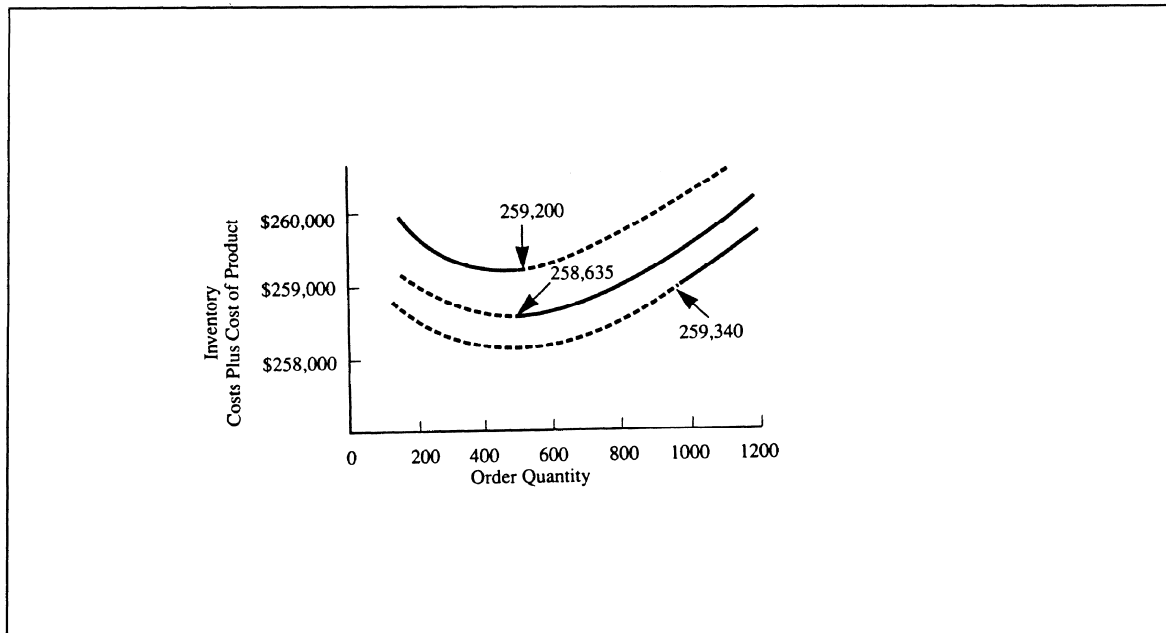
We find that the EOQ with price discounts is 500 sets. Hence, ABC store is justified in going to the first price break but the extra carrying cost of going to the second price break more than outweighs the savings in ordering and in the cost of the product itself.

Case 2 - Carrying costs stated as a percentage of purchase price
    The procedure is follows:
    1. Calculate EOQs for each price. Reject any EOQ that is not within the allowable quantity range for the price used.

2. Calculate total annual cost for feasible EOQs
   (a) If the feasible EOQ is the lowest price curve, this is the overall EOQ.
   (b) If the EOQ is not the lowest price range, compute the total cost for the EOQ and for the next quantities for which price reductions will occur.
3. Select the value of Q which will result in the lowest total cost.

EXAMPLE 5

Discount Plumbing Industries, inc., a maker of the No. 510 valve, has offered quantity discounts. The volumes and prices are:

Order quantity (Q)	Unit price (P)
1 to 399	$2.20
400 to 699	2.00
700 or more	1.80

The company developed the following estimates: $D = 10,000$ valves per year, $S = \$5.50$ per order, and $C = 20\%$ of unit price (P).

First, the EOQs are computed for each of the prices:

$EOQ_{2.20} = \sqrt{2(10,000(5.5)/.2(2.20)} = 500$ (reject--too large)

$EOQ_{2.00} = \sqrt{2(10,000(5.5)/.2(2.00)} = 524.4$ (feasible)

$EOQ_{1.80} = \sqrt{2(10,000(5.5)/.2(1.80)} = 552.8$ (reject--too small)

The total annual cost at two quantities is therefore investigated: 524.2 and 700 units per order:

At Q = 524.4, total annual cost = (.2)($2)(524.4/2) + $5.5(10,000/524.4) + $2(10,000)
$$= \$104.88 + \$104.88 + \$20,000 = \$20,209.76$$
At Q = 700, total annual cost = (.2)($1.8)(700/2) + $5.5(10,000/700) + $1.8(10,000)
$$= \$126 + \$78.57 + \$18,000 = \$18,204.57$$
700 valves are a more economical order quantity since the total annual cost is lower than that associated with the EOQ.

NOTE:
Buying in large quantities has some favorable and some unfavorable features. The advantages are lower unit costs, lower ordering costs, fewer stockouts, and lower transportation costs. On the other hand, there are disadvantages such as higher inventory carrying costs, greater capital requirement, and higher probability of obsolescence and deterioration.

DETERMINATION OF SAFETY STOCK
When lead time and demand are not certain, the firm must carry extra units of inventory, called safety stock as protection against possible stockouts. To determine the appropriate level of safety stock size, you must consider the service level or stockout costs.

Service level can be defined as the probability that demand will not exceed supply during the lead time. Thus, a service level of 90 percent implies a probability of 90 percent that demand will not exceed supply during lead time. Figure 4 shows a service level of 90%.
Here are two cases for computing the safety stock.

Case 1: Variable demand rate, constant lead time
  ROP = Expected demand during lead time + safety stock
    $= \bar{d}\ LT + z\ \sqrt{LT}\ (\sigma_d)$
where
    $\bar{d}$ = average demand
    LT=lead time
    σ_d =standard deviation of demand rate
    z = standard normal variate (See Table 1 - Normal Distribution table in the Appendix)

FIGURE 4
SERVICE LEVEL OF 90 PERCENT
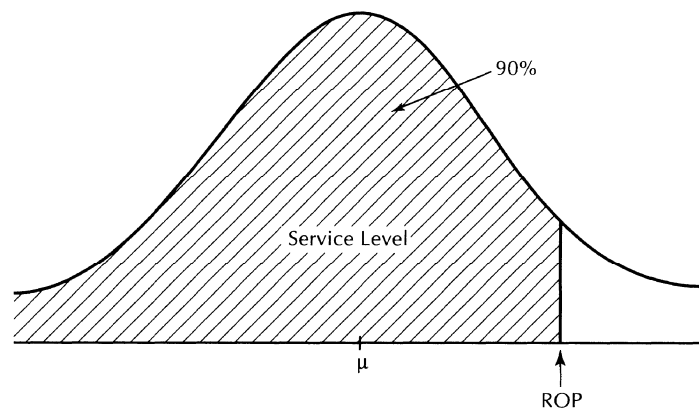
EXAMPLE 6
    Norman's Pizza uses large cases of tomatoes at an average rate of 50 cans per day. The demand can be approximated by a normal distribution with a standard deviation of 5 cans per day. Lead time is 4 days. Thus,
    $\bar{d}$ = 50 cans per day.
    LT= 4 days
    σ_d = 5 cans
How much safety stock is necessary for a service level of 99%? And what is the ROP?
For a service level of 99%, z = 2.33 (from Table 1--Normal Distribution--in the Appendix). Thus,
    Safety stock = 2.33 $\sqrt{4}$ (5) = 23.3 cans
    ROP = 50(4) + 23.3 = 223.3 cans

Case 2: Constant demand, variable lead time
  ROP = Expected demand during lead time + safety stock
    $= d\ \overline{LT} + z\ d\ (\sigma_{LT})$
where
    d = constant demand

$\overline{LT}$ = average lead time

σ_{LT} =standard deviation of lead time

EXAMPLE 7

SVL's Hamburger Shop uses 10 gallons of cola per day. The lead time is normally distributed with a mean of 6 days and a standard deviation of 2 days. Thus,

d = 10 gallons per day.

$\overline{LT}$ = 6 days

σ_{LT} = 2 days

How much safety stock is necessary for a service level of 99%? And what is the ROP?

For a service level of 99%, z = 2.33. Thus,

Safety stock = 2.33 (10)(2) = 46.6 gallons

ROP = 10(6) + 46.6 = 106.6 gallons

COMPUTERS AND INVENTORY PLANNING

Inventory planning, control, and management is done routinely by computers. IBM's *Inventory Management Program and Control Techniques (IMPACT)* and *Communications Oriented Production and Control System (COPICS)* are two prime examples of management information systems with embedded inventory packages. IMPACT is based *on independent demand* and, therefore, uses traditional or classical inventory analysis. The goal of IMPACT is to provide operating rules to minimize cost. In order to do this, the following functions are performed.

1. Forecast demand using various forecasting models such as exponential smoothing, trend, and seasonal (or cyclical) models. Forecasts are monitored based on *the mean absolute deviation (MAD)* and the tracking signal, all of which was discussed in Chapter 3 (Forecasting).
2. Determine the safety stock required for a specified level of service.
3. Determine the order quantity and time for reorder, using the EOQ and quantity discount models.
4. Consider the effects of freight rates and quantity discounts.
5. Estimate the expected results of the inventory plan.

SIMULATION

Many specific operations problems cannot be fitted into the various types of optimization models. The reasons for this include:

1. Many operations management problems may have too many variables.
2. The system being analyzed is so complex that mathematical formulas cannot be developed.
3. The variables differ extensively with respect to their linearity or nonlinearity.
4. The constraints involved in the model also limit the usable models.
5. Sometimes, no known programming technique is available to solve a model.

Fortunately, operations managers have available to them a technique which has been useful in overcoming the problems. This technique, called *Monte Carlo simulation*, enables managers to

avoid a trial and error approach, but at the same time to investigate the effects of alternative courses having to make a final decision. Especially with the availability of computers, simulation has emerged as a powerful tool for analyzing decision problems.

Through simulation we can observe the behavior of systems under controlled conditions, and run experiments to predict system behavior. Simulation provides managers with a laboratory for analysis of decision problems that often cannot be solved by other means and provides a way in which the computer can be used to improve the process of management decision making.

Simulation refers to the use of a numerical model which represents the dynamic relationships in a system to predict the behavior of the system. In a simulation, values that describe initial conditions of a system are used with values that describe changes in the system during a time interval to generate the behavior of the system during that time interval. The results are values of variables which describe the state of the system at the end of the time interval. This process is then repeated until the desired length of time has been represented. For example, in a simulation of an inventory system, values of beginning inventory are used with receipts and disbursements during a time interval to calculate the value of the ending inventory.

A simulation model, then, imitates reality. If the imitation is sufficiently realistic we can infer behavior of the system from observations of behavior of the simulation model. We can easily alter conditions in the model and infer what the impact of those changes would be on the system. In this way a manager may ask a series of "what if" questions about the system. An advantage of this process is that we can use simulation to analyze systems and problems that are too complex for other mathematical techniques. An example is a system in which we would like to explore the effect of the interactions of several probability distributions.

Simulation involves the following steps:
Step 1: Determine the distribution that describes the statistical property of concern.
Step 2: Convert the probability distribution to a cumulative probability distribution.
Step 3: Sample at random (using the random numbers from Table 4 in the Appendix) from the cumulative probability distribution to produce outcomes.
Step 4: Simulate the process
A simulation of an elementary inventory problem is used to illustrate how this one type of simulation model works.

INVENTORY SIMULATION
A company is faced with a problem of determining the size of orders and when to reorder, but in the face of sales that vary randomly from day to day. The company studied sales records for 500 days and found that demand varied between 17 and 26 units per day according to the frequency shown in Table 2. The number of days on which each level of demand occurred was converted into relative frequencies in column 3, and since management felt that this same pattern of demand would continue for the immediate future, these relative frequencies were taken to be the probabilities of occurrence. From the table we find that .15 is the probability for a demand of 19 units on any given day.

<u>Monte Carlo Process</u>

We can simulate sales which vary randomly according to this pattern by the Monte Carlo process. The Monte Carlo process is a technique of selecting numbers randomly from a probability distribution. In the last column of Table 2 we assigned sets of two-digit numbers to each demand. One number (01) is assigned to a demand of 17 since it has a .01 probability of occurrence; thirteen numbers (02-14) are assigned to a demand of 18 units since it has a .13 probability of occurrence; and so forth.

TABLE 2
PROBABILITY DISTRIBUTION OF DAILY DEMAND

Number of Units of Demanded	*Number of Occurrences*	*Probability of Occurrence*	*Cumulative Probability of Occurrence*	*Corresponding 2-Digit Numbers*
17	5	.01	.01	01
18	65	.13	.14	02-14
19	75	.15	.29	15-29
20	140	.28	.57	30-57
21	60	.12	.69	58-69
22	50	.1	.79	70-79
23	40	.08	.87	80-87
24	40	.08	.95	88-95
25	15	.03	.98	96-98
26	10	.02	1.00	99-00
Total	<u>500</u>	<u>1.00</u>		

Average demand = 20.71 units per day

We now obtain two-digit random numbers by some means such as rolling dice, drawing numbers from a hat, generating them on a computer, or selecting them from a table of uniformly distributed random numbers like the one in the appendix. We use them to select demands from the distribution of demands in the table. If the number selected is 60, the demand would be 21, since 60 falls into the 57-68 set of numbers in the last column of the table. In Table 4 we have drawn five random numbers and use them to determine simulated demand for five days. If we repeat this process many times, we would have a randomly varying pattern of demands which would occur with the relative frequencies shown in Table 3.

TABLE 3
SIMULATED DEMAND FOR FIVE DAYS

Day number	Random number	Demand (units)
1	60	21
2	18	19
2	18	19
3	10	18

4	85	23
5	55	20

There is another probability distribution with which the company is concerned. That is the distribution of lead times, or the time between placing an order and receiving the goods, as indicated in Table 4. Mathematical analysis of this type of problem is difficult because of the interaction between the demand and lead time probability distributions, but we can simulate the behavior of this system using the Monte Carlo method and determine the cost of various purchasing policies. We could simulate this situation by hand using the method described above, but the amount of calculation required to simulate, say, a year's operation of the system would be rather tedious. This is the type of calculation for which a digital computer is suited.

TABLE 4
PROBABILITY DISTRIBUTION OF LEAD TIMES

Lead Time (days)	Probability of Occurrence	Cumulative Probability of Occurrence
6	.10	.10
7	.20	.30
8	.30	.60
9	.25	.85
10	.15	1.00

NOTE:

Simulation has been applied to a wide variety of *operations management* activities, such as maintenance operations, scheduling service facilities, corporate planning, distribution systems, location of facilities, personnel planning, and facilities investment decisions. The use of a computer is often the only feasible way of performing simulation. Many special purpose simulation languages such as SIMSCRIPT, GPSS, and GASP have been developed and are suitable for queuing and scheduling problems.

USING THE ABC SYSTEM FOR INVENTORY CONTROL

ABC analysis focuses on the most critical items-gross profitability, sensitive price or demand patterns, and supply excesses or shortages. The ABC method requires the classification of inventory into one of three groups-A, B, or C, according to the potential savings associated with a proper level of inventory control. Class A items, needing close control, are the high-dollar-volume group. They may include 80 percent of total inventory cost but only 1 percent of total items stocked. Class B is an intermediate-dollar-volume group--perhaps 15 percent of dollars and 30 percent of items. Class C is the rest--5 percent of dollars and 69 percent of items. Table 5 illustrates an ABC distribution.

TABLE 5
ABC INVENTORY DISTRIBUTION

Inventory Classification	Population (percent)	Dollar usage (percent)

A	1	80
B	30	15
C	69	5

To institute the ABC method:

1. Compute annual dollar volume by inventory type anticipated (annual demand times unit cost).

2. Segregate merchandise into components based on annual dollar value.

3. Rank inventory in terms of annual dollar volume, ranging from high to low (e.g., As in the top 80 percent, Bs in the next 15 percent and Cs in the last 5 percent).

Tag inventory with the appropriate classification and record the classifications in the inventory records. The following example illustrates the ABC system.

EXAMPLE 8

Garner Auto Supply Co. has arranged its ten inventory items in order of annual dollar volume. Figure 5 shows the ordered list, with dollar-volume expressed in percentages. The ordered list is examined in order to arrive at an ABC classification of the items.

Figure 6 shows the same ten items grouped into classes A, B, and C. The two A items account for over 80 percent—almost five times as much annual dollar-volume as the two B items, while the two B items account for almost six times as much as the five C items. Figure 7 graphically illustrates the ABC classification for this example.

FIGURE 5
INVENTORY ITEMS IN ANNUAL DOLLAR VOLUME ORDER

Item Number	Annual Dollar Usage	Percent of Total Dollar Usage
113	130,000	47.5%
103	90,000	32.9%
123	31,000	11.3%
134	14,500	5.3%
301	6,200	2.3%
721	650	0.2%
764	525	0.2%
402	325	0.1%
520	300	0.1%
Total	273,500	100.0%

FIGURE 6
ABC CLASSIFICATION

	Percent of Total	Percent of	Cumulative

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Classification	Item Number	Annual Dollar Usage	Dollar Usage	Number of Items	Total Number of Items	Percent of Total Number
A	103, 113	220,000	80.5%	2	22.2%	22.2%
B	123, 134	45,500	16.6%	2	22.2%	44.4%
C	301. 721, 520, 402, 764	8,000	2.9%	5	55.6%	100.0%
Total		273,500	100.0%	9	100.0%	

FIGURE 7
ABC CLASSIFICATION PERCENT VERSUS PERCENT OF ITEMS
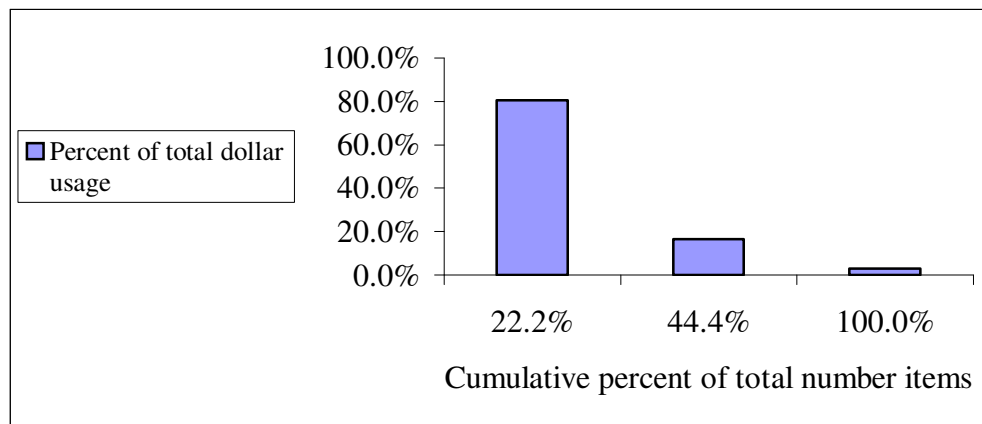
It is clear that A items should receive major attention, B items moderate attention, and C items little attention. Perpetual inventory records should be maintained for class A items, which require accuracy and frequent, often daily, attention. Class B items are less expensive than A items but are still important and require intermediate control. Class C items include most of the inventory items. Since they are usually less expensive and less used, they require less attention. There is usually a high safety stock level for C items. Blanket purchase orders should exist for A items and only "spot buys" for Bs and Cs.

Examples of inventory controls that may be based on ABC classification are:
Purchasing
A purchase order for a class A item might be signed by the president, for a class B item by the head of the purchasing department, and for a class C item by any purchasing agent.
Physical Inventory Check
Count A items monthly, B items twice a year, and C items annually.
Forecasting
Forecast A items by several methods with resolution by a prediction committee, B items by simple trend projection, and C items by best guess of the responsible purchasing agent.

Safety Stock
       No safety stock for A items, one month's supply for B items, and three months' supply for C items.

QUESTIONS
1. List inventory-related costs. Explain each briefly.
2. What are two basic questions regarding inventory management?
3. Distinguish between independent demand and dependent demand.
4. What is the reorder point? How do you determine this?
5. Write down the economic order quantity formula.
6. Describe the basic steps to finding EOQ with quantity discounts in the case where the carrying cost is stated as a percentage of the unit price.
7. List four cases of safety stock determination.
8. Explain how ABC analysis works. List some of the control strategies.
9. What is *simulation*?
10. List the steps involved in simulation.

PROBLEMS
1. The following information relates to the Janie Company:

Units required per year	30,000
Cost of placing an order	$400
Unit carrying cost per year	$600

Assuming that the units will be required evenly throughout the year, what is the economic order quantity?

2. No-nonsense Engineering, a maker of the No. 562 valve, has offered quantity discounts. The volumes and prices are:

Order quantity (Q)	Unit price (P)
1 to 99	$10.00
100 to 499	9.50
500 or more	9.00

The company developed the following estimates: D = 2,000 valves per year, S = $30 per order, and C = 35% of unit price (P). Determine the company's true EOQ.

3. DKT Electronics, Inc. makes part number 562 for one of its computers. The annual demand is 10,000 units. The annual carrying cost is $10 per unit, and the cost of preparing an order and making production setup for the order is $100. The firm operates 250 days per year. The machine used to make this part has a production rate of 200 units per day.
   (a) Calculate the economic production run size.
   (b) How many lots are to be produced in a year?
   (c) What is the annual cost of setups?
   (d) What is the average inventory?
   (e) What is the annual cost of carrying inventory of part 562?

4. Davidson's Restaurant uses cooking oil at an average rate of 15 gallons per day. The demand can be approximated by a normal distribution with a standard deviation of 2 gallons per day. Lead time is 8 days. The restaurant wants to achieve a service level which is seven times the risk of a stockout. If cooking oil can be ordered as needed, what reorder point should be used if lead time is eight days?

5. Constas Hamburger Shop uses 20 gallons of cola per day. The lead time is normally distributed with a mean of 5 days and a standard deviation of 2 days. Determine the level of safety stock and optimal reorder point. Assume a service level of 99%.

6. Given the data for an inventory item:

Demand per hour	Probability
0 units	.2
1	.4
2	.3
3	.1

Beginning inventory	5 units
Order quantity	4 units
Lead time	2 hours
Reorder point (checked at the end of each hour)	3 units

Simulate 10 hours of operation for demand, beginning and ending inventories, and order placements and arrivals, using the following random digits: 07 34 35 23 17 20 72 59 05 68

ANSWERS
1. Inventory related costs fall into three categories: (a) *ordering costs*, which includes all costs associated with preparing a purchase order, (b) *carrying (holding) costs*, which include storage costs for inventory items plus the cost of money tied up in inventory, and (c) *Shortage (stockout) costs*, which include those costs incurred when an item is out of stock. These include the lost contribution margin on sales plus lost customer goodwill.
2. There are many inventory planning models available, which try to answer basically the following two questions: (a) how much to order? and (b) when to order?
3. Dependent demand inventories consist of items whose demand depends on the demands for other items held in inventory. Independent demand items are the finished goods or other end items. Its demand is independent of the demand for any other item carried in inventory.
4. Reorder point (ROP) answers when to place a new order, requires a knowledge about the lead time, which is the time interval between placing an order and receiving delivery. Reorder point (ROP) can be calculated as follows: Reorder point = (average demand per unit of lead time x lead time + safety stock).
5. The EOQ is computed as:

$$EOQ = \sqrt{\frac{2DO}{C}}$$

where C = carrying cost per unit, O = ordering cost per order, D = annual demand (requirements) in units.

6. The procedure is as follows: (a) calculate EOQs for each price. Reject any EOQ that is not within the allowable quantity range for the price used. (b) calculate total annual cost for feasible EOQs. (i) if the feasible EOQ is the lowest price curve, this is the overall EOQ and (ii) if the EOQ is not the lowest price range, compute the total cost for the EOQ and for the next quantities for which price reductions will occur, and (c) select the value of Q which will result in the lowest total cost.

7. There are four cases: (a) known maximum demand rate, constant lead time, (b) variable demand rate, constant lead time, (c) constant demand, variable lead time, and (d) incorporation of stockout costs.

8. ABC analysis involves the following steps: (a) compute annual dollar volume by inventory type anticipated (annual demand times unit cost), (b) segregate merchandise into components based on annual dollar value, and (c) rank inventory in terms of annual dollar volume, ranging from high to low (e.g., As in top 80 percent, Bs in next 15 percent and Cs in last 5 percent). Examples of inventory controls that may be based on ABC classification are:

Purchasing: A purchase order for a class A item might be signed by the president, for a class B item by the head of the purchasing department, and for a class C item by any purchasing agent.
Physical Inventory Check: Count A items monthly, B items twice a year, and C items annually.
Forecasting: Forecast A items by several methods with resolution by a prediction committee, B items by simple trend projection, and C items by best guess of the responsible purchasing agent.
Safety Stock: No safety stock for A items, one month's supply for B items, and three months' supply for C items.

9. Simulation refers to the use of a numerical model which represents the dynamic relationships in a system to predict the behavior of the system.

Simulation involves the following steps: (1) Determine the distribution that describe the statistical property of concern. (2) Convert the probability distribution to a cumulative probability distribution. (3) Sample at random (using the random number table) from the cumulative probability distribution to produce outcomes. (4) Simulate the process.

PROBLEMS
1

$$EOQ = \sqrt{\frac{2DO}{C}}$$

where C = carrying cost per unit, O = ordering cost per order, D = annual demand in units.

$$EOQ = \sqrt{\frac{2(\$400)(30,000)}{\$600}} = \sqrt{40,000} = 200$$

2.
First, the EOQs are computed for each of the prices:

$EOQ_{10.00} = \sqrt{2(2,000)(30)/.35(10.00)} = 185$ (reject--too large)

$EOQ_{9.50} = \sqrt{2(2,000)(30)/.35(9.50)} = 190$ (feasible)

$EOQ_{9.00} = \sqrt{2(2,000)(30)/.35(9.00)} = 195$ (reject--too small)

The total annual cost at two quantities is therefore investigated: 190 and 500 units per order:

At Q = 190, total annual cost = (.35)($9.50)(190/2) + $30(2,000/190) + $9.50(2,000)

$= \$315.88 + \$315.79 + \$19,000 = \$19631.67$

At Q = 500, total annual cost = (.35)($9.00)(500/2) + $30(2,000/500) + $9.00(2,000)

$= \$787.50 + \$120 + \$18,000 = \$18,907.50$

500 valves is a more economical order quantity since the total annual cost is lower than that associated with the EOQ.

3.

O = setup cost = $100 per setup,

C = carrying cost = $10 per unit

D = annual demand = 10,000 units,

p = production rate = 200 units,

u = usage rate 40 units (10,000 units/ 250 working days)

(a)

$$EOQ = \sqrt{\frac{2DS}{C} \cdot \frac{p}{(p-u)}} = \sqrt{\frac{2(10,000)(100)}{(10)} \cdot \frac{200}{(200-40)}} = 500 \text{ units}$$

(b) Number of lots per year = D/Q = 10,000/500 = 20 lots

(c) Annual setup costs = S(D/Q) = (100)(10,000/500) = $2,000

(d) Average inventory level = Q/2[(p - u)p] = (500/2)[(200 -40)/200] = 200 units

(e) Annual cost of carrying this inventory = 200 units x $10 per unit = $2,000

4.

ROP = Expected demand during lead time + safety stock

$$= \bar{d} \; LT + z \; \sqrt{LT} \; (\sigma_d)$$

$\bar{d}$ = 15 gallons per day.

LT= 8 days

σ_d = 2 gallons per day

Service level is 7/8 = 0.875 (from normal distribution table--Table 1 in the Appendix z = 1.15)

Safety stock = $1.15 \sqrt{8} \; (2) = 6.8$ gallons

ROP = 15(8) + 6.8 = 126.8 gallons

5.

ROP = Expected demand during lead time + safety stock

$$= d \; \overline{LT} + z \, d \, (\sigma_{LT})$$

d = 20 gallons per day.

$\overline{LT}$ = 5 days

σ_{LT} = 2 days

For a service level of 99%, z = 2.33. Thus,

Safety stock = 2.33 (20)(2) = 93.2 gallons
ROP = 20(5) + 93.2 = 193.2 gallons

6.

Demand per hour	Probability	Cumulative probability	Corresponding Random 2-digits
0 units	.2	.2	1-19
1	.4	.6	20-59
2	.3	.9	60-89
3	.1	1.0	90-99

Based on the random digits assigned, we obtain demand units in column (2).

Hours	Demand	Beginning inventory	Ending inventory	Order point*	Order arrivals*
1	0	5	5		
2	1	5	4		
3	1	4	3	4	
4	1	3	2		
5	0	2	2		4
6	1	6	5		
7	2	5	3	4	
8	1	3	2		
9	0	2	2		4
10	2	6	4		

*end of hour

CHAPTER 10
MATERIAL REQUIREMENT PLANNING AND JUST-IN-TIME SYSTEMS

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Define a dependent demand.
2. Initiate a Material Requirements Planning (MRP) process.
3. Prepare a bill of materials (BOM).
4. Design a product structure file.
5. Develop an Inventory-status file.
6. Develop a planned order release.
7. Schedule receipts.
8. Demonstrate lot-for-lot ordering procedure.
9. Differentiate between the gross requirements and the net requirements.
10. Develop a manufacturing resource planning (MRP II) procedure.
11. Demonstrate Just-in-time (JIT) planning system.
12. Outline manufacturing information systems.

The previous chapter focused on *independent-demand inventories*, which enable a company to respond to demand from outside the production system more quickly than it could if it had to buy or produce an item before selling it. The extent of external demand is usually not known ahead of time; it must be forecast and some uncertainty is inherent in these forecasts. Quite often safety stock is required to ensure that sufficient quantities of these items will be available.

Many types of organizations such as make-to-stock manufacturers, hospitals, wholesale distributors, and retail businesses, must keep independent-demand items on hand. On the other hand, many manufacturers deal with dependent-demand inventories. *Dependent-demand items* are those *components* that are assembled to become part of some *parent item* or in some similar way become part of a set of components. Dependent-demand inventories typically are consumed within the production system, not by some outside demand.

In this chapter, we present *material requirements planning (MRP)*, a system that works backwards from the scheduled quantities and need dates for *end items* specified in a *master production schedule (MPS)* to determine the requirements for components needed to meet the MPS. In a latter part of the chapter we will discuss the *just-in-time (JIT) system* of inventory, a Japanese contribution.

MATERIAL REQUIREMENTS PLANNING (MRP)
Material Requirements Planning (MRP) is a flow-control system design to ensure parts and components (items with dependent demand) are available in the period when they are needed, with little or none present at other times. The theme of MRP is "getting the right

component parts and materials to the right place at the right time." Figure 1 depicts an MRP computer system.

The overall objective of MRP is to provide a more effective, responsive, and disciplined approach to determining the material requirements of the organization. Employed properly, MRP may serve as a communication device as well as a planning tool, allowing various subfunctions of the firm to operate with a common, integrated plan. Fundamentally MRP attempts to answer the following questions (given a master production schedule):
  a.   What material is needed?
  b.   When is the material needed?
  c.   How much is needed?
  d.   When should orders be placed?
Correct answers to these questions are vital for effective operations in the manufacturing context.

FIGURE 1
AN MRP COMPUTER SYSTEM
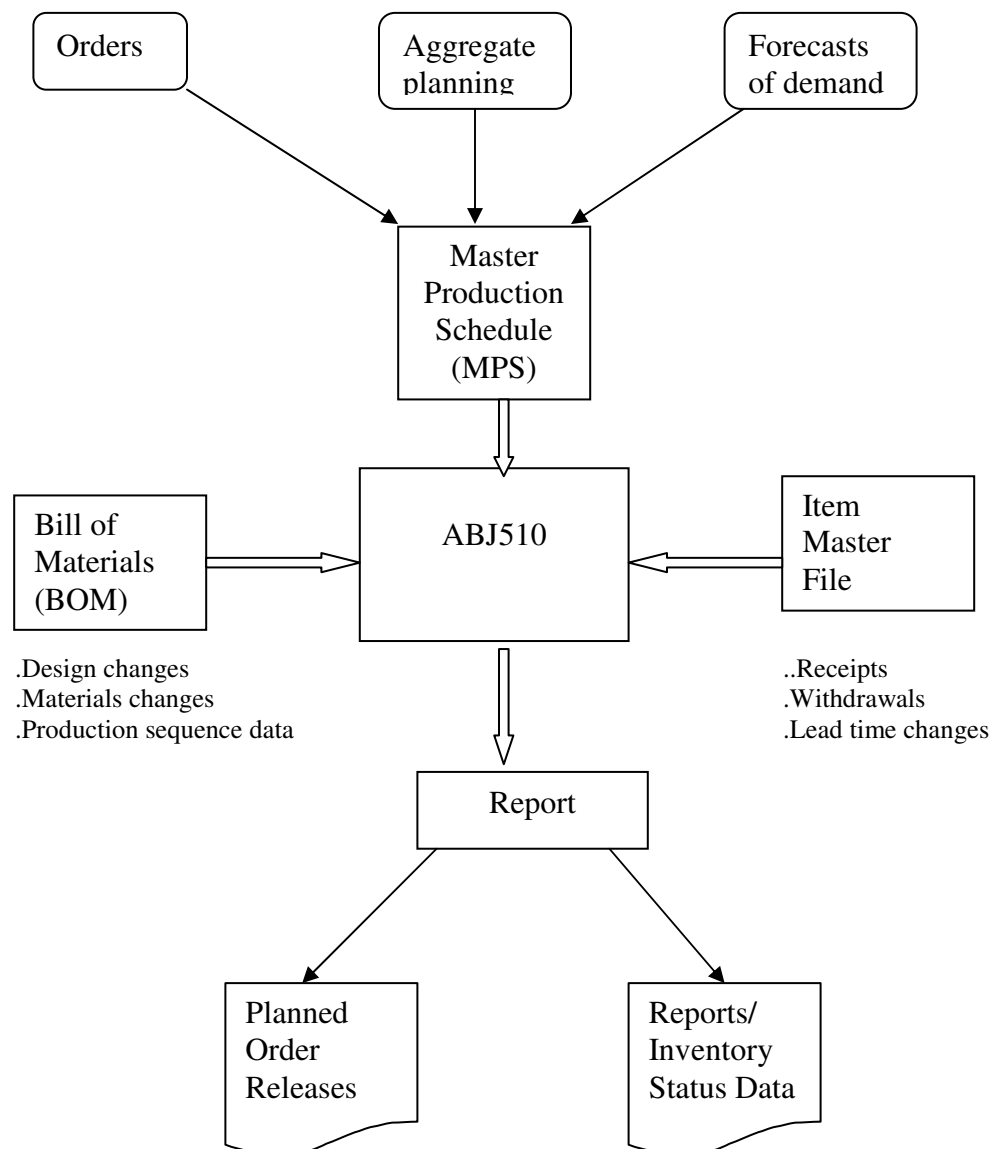
SYSTEM LOGIC

Fundamental is the concept of dependent demand. Demands for end items (final products) create demands for assemblies, which in turn create demands for components, etc., etc. Take the telephone stands, for example. Demands for stands create demands for legs; sills are manufactured; these parts create demands for the basic raw material, wood, in several different forms. Additionally, demand for the end items or products will occur as a function of scheduled production and customer demands. Therefore, it is not necessary to forecast independently the need for parts and components, since the explosion of the end item will provide this information. The amount of material available for use in the production process is a function of material on hand and material on order (pipeline inventory). MRP operates on a perpetual inventory concept. The key to the use of MRP is an understanding of the netting process. The principle is illustrated in Figure 2.

FIGURE 2
NETTING PROCESS*

	Inventory Units
W: End item	25
X: Assembly X	100
Y: Subassembly Y	50
Z: Part Z	10

*Assume 1:1 relationships.

EXAMPLE 1

If the demand for end item W is 200 units and the current inventory equals 25 units, the netting process would operate as follows:

Net requirement for W = Gross requirement (W) - Inventory (W)
= 200 - 25 = 175 units

If the net requirement for W = 175, then the gross requirement for assembly X would also be 175:

Net requirement for X = Gross requirement (X) - Inventory (X)
= 175 - 100 = 75 units

The net requirement for assembly X becomes the gross requirement for subassembly Y; substituting:

Net requirement for Y = Gross requirement (Y) - Inventory (Y)

$$= 75 - 50 = 25 \text{ units}$$

The net requirement for subassembly Y becomes the gross requirement for part Z; substituting:

Net requirement for Z = Gross requirement (Z) - Inventory (Z)
$$= 25 - 10 = 15 \text{ units}$$

The netting process is based on the fact that, for example, a subassembly contains all the parts or items that define it as a subassembly. Therefore, if we have a stock of subassemblies on hand we must also count (consider) the parts in that subassembly, in effect, netting out these parts from the computations to avoid double counting. Double counting would occur if the inventory levels of W, X, Y, and Z were simply subtracted from the gross requirement of W, as shown in Figure 3.

FIGURE 3
IMPACT ON REQUIREMENTS WITH AND WITHOUT NETTING

	With Netting	*Without Netting*
W	175	175
X	75	100
Y	25	150
Z	15	190

SYSTEM COMPONENTS

The components of the MRP system in its simplest form are shown in Figure 1. As seen in Figure 1, the MRP component parts feed into the MRP processor—the computer program. Yet each component plays a vital role.

1. The *bill of materials (BOM) file* tells what a finished product is composed of. It provides the basic relationships among parts, assemblies, subassemblies, and finished items. Thus, each product has its own BOM. The listing is hierarchical. It shows that the quantity of each item needed to complete one unit of the next-highest level of assembly. The product-structure tree shows this relationship (see Figure 4). The end product is assigned a level 0 designation. Levels 1…n indicate the relationship between items. For example, subassembly 1 is composed of parts 1 and 2. The bill of materials also specifies the quantities required to make each item. These values are shown in parentheses.

2. The *master schedule* tells how much a finished product is desired and when. It states (a) which end items are to be produced, (b) when these end items are needed, and (c) what quantities are needed. Generally master production schedules are developed for periods ranging from 26 to 104 weeks, with revisions or updates on a weekly or biweekly basis. Master schedules are set forth in standard planning periods called time buckets and are most commonly specified in weeks.

FIGURE 4
PRODUCT-STRUCTURE TREE

Level

0   X

1   A (2)   B   C (3)

2   E (3)   D   D(2)   F (3)   E(2)   D (2)

3   D(4)
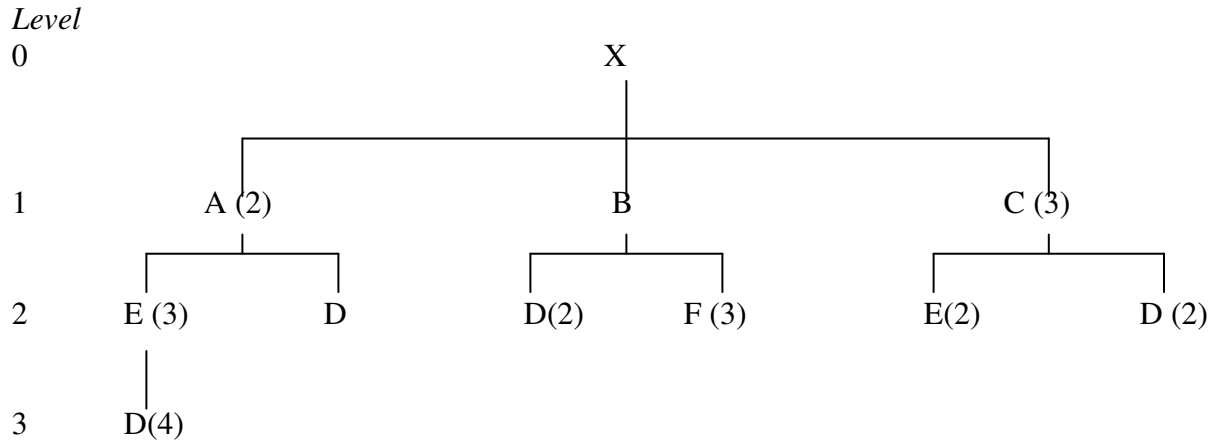
3. The *inventory status file* indicates how much inventory is on hand or on order. It contains such information as gross requirements, scheduled receipts, expected amount on hand, and other information such as supplier, lot size, and lead times for acquisition of purchased parts and internal operations on these parts plus the waiting time between operations.

MRP COMPUTER PROGRAM

The MRP processor itself performs the explosion process and the netting process and offsets the lead times to provide reports on what to buy, when to buy, and when to expedite, de-expedite, cancel, and increase or decrease orders. It involves taking the end-item requirements that are specified by the master schedule and "exploding" them into *time-phased* requirements for the components using the bill of materials offset by lead times. The net requirement of each material are computed as follows:

Net material = Gross material -   Inventory on   -   Planned order
requirement   requirements   hand   receipts (scheduled receipts)

Scheduled receipts (planned order receipts) indicate the amount to order or to start producing in each period in order to be available for the next level of production or assembly. This entire computer procedure results in inventory transaction data (orders released, changes in orders and so on), which are used to update the inventory status file, the primary output reports, and secondary output reports. Note that usually,

Inventory on = In   – Safety – Inventory allocated
hand   stock   stock   to other uses

EXAMPLE 2

Donna is the MRP manager for Gadgets, Inc. A MPS is given to her showing gross requirements for 250 units of the Model A gadget in week 4 and 100 units in week 6. These are the only items on the MPS. The following is a product structure diagram based on the bill of materials.

Level

0   X

1   B (1)   C (2)

2   D(3)   E (1)
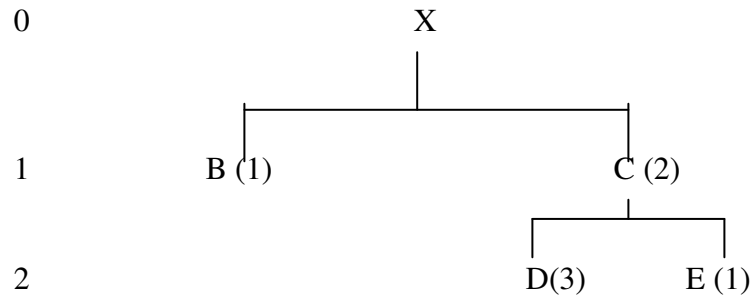
The Item Master File shows the inventory levels and other planning data for every item.

| | | | | | | Scheduled Receipts | |
	In Stock	Safety Stock	Allocated	Lead Time Weeks	Lot Size	Amount	Week
A	150	50	0	1	200		
B	200	100	100	2	500		
C	400	100	0	1	300		
D	400	200	100	2	2,000	2,000	2
E	100	50	0	1	500		

Item Master File

Note the following:
- (a) Safety Stock is a reserve and not available for planned use.
- (b) Allocated is committed to another use and hence not available for planned use.
- (c) Lot size is the minimum order quantity; one may order more for the current period, but not less.
- (d) Scheduled Receipts is the order that has already been released.

Donna follows a routine, which is shown below.

(a)

Inventory on = In – Safety – Inventory allocated
hand   stock   stock   to other uses

For example, for item A: 150 – 50 – 0 = 100

(b)

Net material = Gross material -   Inventory on -   Planned order
requirement   requirements   hand   receipts (scheduled receipts)

For example, for item A in week 4:

$$150 = 250 – 100 – 0$$

(c) Planned order receipts: Plan to receive order of the amount of net requirement (more if required by lot size).

(d) Planned order release: same as planned order receipt, offset by lead time. For example, units of A (lead time = 1 week) required in week 4 must be ordered in week 3. Note also that a planned order release for the parent generates gross requirements in the same week for the "children." (lower level).

For example, order releases for A week 3 and 5 generate gross requirements for B and C in those weeks; order releases for C in weeks 2 and 4 generate gross requirements for D and E in those weeks. Note also that gross requirements for "children" are dictated by the bill of materials amount. For example, gross requirements for D is 900 units (planned order release units of 300 for C x 3 units of D required for each unit of C)

Item Code	Level Code	Lead Time	On Hand	Safety Stock	Alloc ated		Week 1	2	3	4	5	6
A	0	1	150	50	0	Gross Requirements				250		100
						Scheduled Receipts						
						On Hand **100**	100	100	100	100	50	150
						Net Requirements				150		50
						Planned Order Receipts				200		200
						Planned Order Releases			200		200	
B	1	2	200	100	100	Gross Requirements			200		200	
						Scheduled Receipts						
						On Hand **0**	0	0	0	300	100	100
						Net Requirements			200			
						Planned Order Receipts			500			
						Planned Order Releases	500					
C	1	1	400	100	0	Gross Requirements			400		400	
						Scheduled Receipts						
						On Hand **300**	300	300	300	200	100	100
						Net Requirements			100		300	
						Planned Order Receipts			300		300	
						Planned Order Releases		300		300		
D	1	2	400	200	100	Gross Requirements		900		900		
						Scheduled Receipts		2000				
						On Hand **100**	100	100	1200	300	300	300
						Net Requirements						
						Planned Order Receipts						
						Planned Order Releases						
E	1	1	100	50	0	Gross Requirements		300		300		
						Scheduled Receipts						

						On Hand **50**	50	50	250	250	450	450
						Net Requirements		250		50		
						Planned Order Receipts		500		500		
						Planned Order Releases	500		500			

Donna has completed her MRP plan. She plans to release the following orders:
Week 1: 500 units of B and 500 units of E
Week 2: 300 units of C
Week 3: 200 units of A and 500 units of E
Week 4: 300 units of C
Week 5: 200 units of A
Week 6: None

NOTE:

QUESTIONS ADDRESSED IN MRP PROCESSING

Questions	Remarks
What do we want to produce and when?	Input to the MRP program through the *master schedule*
What components are required to make and how many does it take?	Provided by the *bill of materials*
How many are already scheduled to be available in each future period?	Obtained from the *inventory status file*
How many more do we need to obtain for each future period?	Subtract B from A, if A is larger
When do we need to order these amounts so that they will be available when needed?	Move earlier in time by the production or procurement lead time for each time

---

OUTPUTS OF MRP

The outputs of MRP systems dynamically provide the schedule of materials for the future—amount of each material required in each time period to support the master planning schedule. Two primary outputs result:

1. Planned order schedule. A plan of the quantity of each material to be ordered in each time period.
2. Changes in planned orders. Modification of previous planned orders.

The secondary MRP outputs provide this information:

1. Exception reports. Reports that flag items requiring management attention in order to provide the right quantity of materials in each time period., such as reporting errors, out-of-bound situations, and excessive scrap.
2. Performance reports. Reports that indicate how well the system is operating, such as inventory turns, percentage of delivery promises kept, and stockout incidences.

3. Planning reports. Reports to be used in future inventory planning activities, such as inventory forecasts, purchase commitments reports., traces to demand sources (pegging), and long-range material requirements planning.

INVENTORY DECISION RULES FOR MRP

There are a large number of decision rules which can be employed for lot sizing under MRP. They include:

Rule 1: Lot-size ordering—minimum order quantity needed.
Rule 2: Lot-for-lot ordering—ordering the exact quantity to satisfy the requirements of each time bucket.
Rule 3: Period order quantities—selection of a fixed time interval over which to purchase and determine requirements.
Rule 4: Economic order quantity—using the standard EOQ formula, the annual usage is determined by proportioning.
Rule 5: Least total cost method—attempts to select the quantity to order which balances the cost of possession and the cost of acquisition.

There are additional rules which can be used, including least unit cost, period order quantity and dynamic programming plus variations on these. Which is best is impossible to answer since they all have the major constraint of discontinuous (lumpy) demand for items.

BENEFITS AND LIMITATIONS OF MRP

The benefits of MRP include:
      (a) The reduction of inventory investment
      (b) The reduction of shortages
      (c) The achievement of more reliable delivery schedules
      (d) The improvement of work flow.

But MRP is not without shortcomings. It may use outdated bill of materials, not incorporating design changes. Further, MRP may lack accurate and up-to-date master schedules.

MANUFACTURING RESOURCE PLANNING (MRP II)

Manufacturing Resource Planning (MRP II, or "closed loop" MRP) is an integrated information system that steps beyond first-generation MRP to synchronize all aspects (not just manufacturing) of the business. The MRP II system coordinates sales, purchasing, manufacturing, finance, and engineering by adopting a focal production plan and by using one unified database to plan and update in all systems. Manufacturing resources planning (MRPII) integrates such information as work force levels, inventory investment, and "what if" analyses.

JUST-IN-TIME MANUFACTURING

The inventory control problem occurs in almost every type of organization. It exists whenever products are held to meet some expected future demand. In most industries, cost of inventory represents the largest liquid asset under the control of management. Therefore, it is very important to develop a production and inventory planning system that will minimize both purchasing and carrying costs.

During the 1960s and 1970s, material requirements planning (MRP) was adopted by many U.S. manufacturing companies as the key component of their production and inventory planning systems. While success has not been universal, users typically agreed that the inventory approach inherent in an MRP system generally is more effective than the classical approach to inventory planning. Aside from the manufacturing aspects, the purchasing function also is of major importance to the overall success of the system. Effective purchasing and management of materials is a high priority in most manufacturing firms. Material cost, as a proportion of total product cost, has continued to rise significantly during the last few years and hence is a primary concern of top management.

Even though MRP has received a great deal of attention, effective purchasing and management of materials is still a high priority activity in most manufacturing firms. Material cost, as a proportion of total product cost, has continued to rise significantly during the last few years and hence is a primary concern of top management.

Competing on the basis of both price and quality, the Japanese have demonstrated the ability to manage their production systems effectively. Much of their success has been attributed to what is known as the *Just-In-Time (JIT)* approach to production and inventory control, which has generated a great deal of interest among practitioners. The "Kanban" system--as they call it-- has been a focal point of interest, with its dramatic impact on the inventory performance and productivity of the Japanese auto industry.

This chapter provides an overview of the Just-In-Time (JIT) approach. It also highlights the impact that JIT implementation might have on inventory control, the purchasing function, and production costs.

WHAT IS JUST-IN-TIME (JIT)?
JIT is a demand-pull system. Demand for customer output (not plans for using input resources) triggers production. Production activities are "pulled", not "pushed," into action. JIT production, in its purest sense, is buying and producing in very small quantities just in time for use. The basic idea has its roots in Japan's densely populated industrial areas and its lack of resources, both of which have produced frugal personal habits among the Japanese people. The idea was developed into a formal management system by Toyota in order to meet the precise demands of customers for various vehicle models and colors with minimum delivery delays.

As a philosophy, JIT targets inventory as an evil presence that obscures problems that should be solved, and that by contributing significantly to costs, large inventories keep a company from being as competitive or profitable as it otherwise might be. Practically speaking, JIT has as its principal goal the elimination of waste, and the principal measure of success is how much or how little inventory there is. Virtually anything that achieves this end can be considered a JIT innovation.

Furthermore, the little inventory that exists in a JIT system must be of good quality. This requirement has led to JIT purchasing practices uniquely able to deliver high-quality materials. JIT systems integrate five functions of the production process--sourcing, storage, transportation, operations, and quality control--into one controlled manufacturing process. In manufacturing,

JIT means that a company produces only the quantity needed for delivery to dealers or customers. In purchasing, it means suppliers deliver subassemblies just in time to be assembled into finished goods. In delivery, it requires selecting a transportation mode that will deliver purchased components and materials in small-lot sizes at the loading dock of the manufacturing facilities just in time to support the manufacturing process.

The Japanese believe that human error, machine breakdowns, and defective parts can be prevented and that inventory simply hides these problems and keeps companies from achieving their goals. During the 1950s, the Japanese recognized that they would have to upgrade their manufacturing expertise significantly if they were to make additional inroads in world markets. The targeted goals were quality and the elimination of waste. Development of new techniques occurred, among which JIT is the most publicized. It (aka: "Kanban") makes use of simple tags to track the flow of work-in-process inventory. The word Kanban literally means "signboard" or "ticket" in the Japanese language. Tickets control the flow of materials through the system. The goal in using Kanban is to have each material arrive just in time for its use in the production operation. The ability of Kanban in achieving this goal is dependent upon the characteristics of the environment in which it operates. These characteristics have been divided into major categories in Table 1.

The flow of materials is always associated with the relationship between two work centers; this interrelationship is crucial to the efficient flow of materials. The consuming work center is independent of the producing department for its necessary components. The notion of a producing work center likewise is extended to the distribution system for the finished product. All communication is accomplished through the movement of Kanban tickets that identify products, routing, and order quantity information. All activities dealing with materials flow or conversion are associated with Kanbans. Thus, the total quantity of material is controlled by the number of Kanbans in the system. A reduction in the number of Kanbans circuiting in the system will result in a reduction in the inventory. No material-based activity is permitted without an attached Kanban card.

TABLE 1
MAJOR CHARACTERISTICS OF THE JAPANESE JUST-IN-TIME SYSTEM

Technical Factors	Behavioral/Environmental Factors
Group technology	Factory--unions
Minimized set-up times	Focused factory
Smoothing of master production schedule/aggregate plan	Quality at source
Flow-type shop employment	Job security/ lifetime

Visible control, pull-up/ management	Group decision making/ bottom-up system with Kanban
Automation	Supporting supplier network
Total preventive maintenance	

PURCHASING ASPECTS OF JIT

The basic objective of a JIT production control system is to minimize work-in-process and raw materials inventories by providing each work center with the exact quantity of parts or materials at the precise time they are needed. Therefore, the ideal-state of JIT production would be a stockless production system, in which each unit of output is produced as it is needed at each succeeding work station.

Implementation of such a production system, however, requires heavy involvement of the purchasing function which, in reality, is the starting point for the materials flow cycle. The concept of JIT purchasing is very similar to the JIT production system previously described. Under the JIT purchasing system, suppliers are required to deliver a small quantity of required parts of materials to the buyer's plant as they are needed. This can mean daily or sometimes twice a day deliveries of purchased items. The critical elements of JIT purchasing are:
- Reduced order quantities
- Frequent and reliable delivery schedules
- Reduced and highly reliable lead times
- Consistently high quality levels for purchased materials.

JIT COMPARED WITH TRADITIONAL MANUFACTURING

JIT manufacturing is a demand-pull, rather than the traditional "push" approach. The philosophy underlying JIT manufacturing is to produce a product when it is needed and only in the quantities demanded by customers. Demand pulls products through the manufacturing process. Each operation produces only what is necessary to satisfy the demand of the succeeding operation. No production takes place until a signal from a succeeding process indicates a need to produce. Parts and materials arrive just in time to be used in production. To illustrate the differences between pull and push systems of material control, the example of a fast food restaurant is used:

"At McDonald's, the customer orders a hamburger, the server gets one from the rack, the hamburger maker keeps an eye on the rack and makes new burgers when the number gets too low. The manager orders more ground beef when the maker's inventory gets too low. In effect, the customer's purchase triggers the pull of materials through the system...... In a push system, the caterer estimates how many steaks are likely to be ordered in any given week. He/she reckons how long it takes to broil a steak: he/she can figure out roughly how many meals are needed in a certain week..... "

Reduced Inventories. The primary goal of JIT is to reduce inventories to insignificant or zero levels. In traditional manufacturing, inventories result whenever production exceeds demand. Inventories are needed as a buffer when production does not meet expected demand.

Manufacturing Cells and Multifunction Labor. In traditional manufacturing, products are moved from one group of identical machines to another. Typically, machines with identical functions are located together in an area referred to as a department or process. Workers who specialize in the operation of a specific machine are located in each department. JIT replaces this traditional pattern with a pattern of manufacturing cells or work centers. Robots supplement people to do many routine operations.

Manufacturing cells contain machines that are grouped in families, usually in a semicircle. The machines are arranged so that they can be used to perform a variety of operations in sequence. Each cell is set up to produce a particular product or product family. Products move from one machine to another from start to finish. Workers are assigned to cells and are trained to operate all machines within the cell. Thus, labor in a JIT environment is multifunction labor, not specialized labor. Each manufacturing cell is basically a minifactory or a factory within a factory. A comparison of the physical layout of JIT with the traditional system is shown in Figure 5.

Total Quality Control. JIT has a stronger emphasis on quality control. A defective part brings production to a grinding halt. Poor quality simply cannot be tolerated in a stockless manufacturing environment. In other words, JIT cannot be implemented without a commitment to *total quality control (TQC).* TQC is essentially an endless quest for perfect quality. This approach to quality is opposed to the traditional belief, *called acceptable quality level (AQL).* AQL allows defects to occur provided they are within a predetermined level.

Decentralization of Services. JIT requires easy and quick access to support services, which means that centralized service departments must be scaled down and their personnel assigned to work directly to support production. For example, with respect to raw materials, JIT calls for multiple stock points, each one near where the material will be used. There is no need for a central warehouse location.

Suppliers as Outside Partners. The most important aspects of the JIT purchasing concept focus on (1) new ways of dealing with suppliers, and (2) a clear-cut recognition of the appropriate purchasing role in developing corporate strategy. Suppliers should be viewed as "outside partners" who can contribute to the long-run welfare of the buying firm rather than as outside adversaries.

Better Cost Management. Cost management differs from cost accounting in that it refers to the management of cost, whether or not the cost has direct impact on inventory or the financial statements. The JIT philosophy simplifies the cost accounting procedure and helps managers manage and control their costs, which will be discussed in detail later in the chapter.

JIT recognizes that with simplification comes better management, better quality, better service, and better cost. Traditional cost accounting systems have a tendency to be very complex, with many transactions and reporting of data. Simplification of this process will transform a cost "accounting" system into a cost "management" system that can be used to support management's needs for better decisions about product design, pricing, marketing, and mix, and to encourage continual operating improvements.

FIGURE 5
PHYSICAL LAYOUT
TRADITIONAL VS. JIT MANUFACTURING

Traditional Manufacturing		
Department A	Department B	Department C
<P1 > X X	< P1 > Y Y	< P1 > Z Z
<P2 >	< P2 >	< P2 >

Each product passes through departments which specialize in one process. Departments process multiple products.

JIT Manufacturing	
Product 1 (P1)	Product 2 (P2)
Manufacturing Cell 1	Manufacturing Cell 2
Y <P1 > X Z	Y <P2 > X Z

Notice that each product passes through its own cell. All machines necessary to process each product are placed within the cell. Each cell is dedicated to the production of one product or one subassembly.
Symbols:

X = Machine A   P1 = Product 1
Y = Machine B   P2 = Product 2
Z = Machine C

NOTE:

COMPARISON OF JIT AND TRADITIONAL MANUFACTURING

JIT	_Traditional_
1. Pull system	1. Push system

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2. Insignificant or zero inventories   2. Significant inventories
3. Manufacturing cells   3. "Process" structure
4. Multifunction labor   4. Specialized labor
5. Total quality control (TQC)   5. Acceptable quality level (AQL)
6. Decentralized services   6. Centralized services
7. Complex cost accounting   7. Simple cost accounting

BENEFITS OF JIT

The potential benefits of JIT are numerous. First, JIT practice reduces inventory levels, which means lower investments in inventories. Since the system requires only the smallest quantity of materials needed immediately, it reduces the overall inventory level substantially. In many Japanese companies that use the JIT concept, inventory levels have been reduced to the point that makes the annual working capital turnover ratio much higher than that experienced by U.S. counterparts. For instance, Toyota reported inventory turnover ratios of 41 to 63, while comparable U.S. companies reported inventory turnover ratios of 5 to 8.

Second, since purchasing under JIT requires a significantly shorter delivery lead time, lead time reliability is greatly improved. Reduced lead time and increased reliability also contribute to a significant reduction in the safety stock requirements.

Third, reduced lead times and set-up times increase scheduling flexibility. The cumulative lead time, which includes both purchasing and production lead times, is reduced. Thus, the firm schedule within the production planning horizon is reduced. This results in a longer "look-ahead" time that can be used to meet shifts in market demand. The smaller lot size production made possible by reduced set-up time, also adds flexibility.

Fourth, improved quality levels have been reported by many companies. When the order quantity is small, sources of quality problems are quickly identifiable, and can be corrected immediately. In many cases, employee quality consciousness also tends to improve, producing an improvement in quality at the production source.

Fifth, the costs of purchased materials may be reduced through more extensive value analysis and cooperative supplier development activities.

Sixth, other financial benefits reported include:
(1) Lower investments in factory space for inventories and production.
(2) Less obsolescence risk in inventories
(3) Reduction in scrap and rework
(4) Decline in paperwork
(5) Reduction in direct material costs through quantity purchases.

COMPUTERIZED JIT

Using *Electronic Data Exchange (EDI)* can greatly enhance JIT implementation, especially when internal business partners are involved. Notable computer software for JIT includes:

- *HP Manufacturing Management II* which supports multilocation tracking and JIT component ordering, extensive MRP and inventory control, and interactions with budgeting, costing, and CDA/CAM applications.
- *Control Manufacturing* by Cincom Systems which supports multiple location JIT inventory control, MRP, financial management, and production scheduling

MANUFACTURING INFORMATION SYSTEMS:

Manufacturing information systems support the *production/operations* function, which includes all activities concerned with the planning and control of the processes that produce goods or services. The production/operations function is concerned with the management of the operational systems of all business firms. Information systems used for operations management and transaction processing support all firms that must plan, monitor, and control inventories, purchases, and the flow of goods and services.

COMPUTER-INTEGRATED MANUFACTURING (CIM)

Computer-based manufacturing information systems use several major techniques to support **computer-integrated manufacturing** (CIM). CIM is an overall concept that stresses that the goals of computer use in factory automation must be to:

- *Simplify* - Production processes, product designs, and factory organization as a vital foundation to automation and integration.
- *Automate* **-** Production processes and the business functions that support them with computers, machines, and robots.
- *Integrate* - All production and support processes using computers, telecommunications networks, and other information technologies.

Overall goal of CIM: - Is to create flexible, agile, manufacturing processes that efficiently produce products of the highest quality. Thus, CIM supports the concepts of:
- Flexible manufacturing systems
- Agile manufacturing and agile technology
- Total quality management

Results of CIM: - Implementing such manufacturing concepts enables a company to quickly respond to and fulfil customer requirements with high-quality products and services.

Uses of computers in manufacturing include
- Computer-aided engineering (CAE)
- Computer-aided design (CAD)
- Computer-aided process planning (CAPP)
- Material requirements planning (MRP)
- Manufacturing resource planning (MRP-II)
- Computer-aided manufacturing (CAM)

Computer-aided manufacturing - (CAM) systems are those that automate the production process. For example, this could be accomplished by monitoring and controlling the production process in a factory (manufacturing execution systems) or by directly controlling a physical process (process control), a machine tool (machine control), or machines with some humanlike work capabilities (robots).

Manufacturing execution systems - (MES) are performance monitoring information systems for factory floor operations. They monitor, track, and control the five essential components involved in a production process:
- Materials
- Equipment
- Personnel
- Instructions and specifications
- Production facilities.

MES includes:
- Shop floor scheduling control systems
- Machine control systems
- Robotics control systems
- Process control systems

QUESTIONS

1. Distinguish between independent and dependent demand.
2. When is MRP appropriate?
3. Briefly explain the requirements of effective MRP.
4. List some of the main advantages and limitations of MRP.
5. Define in MRP "planned order release."
6. How important is the *master production schedule* (MPS) in an MRP system?
7. Distinguish between advanced versions of MRP (MRP II) and the basic system.
8. Compare MRP II and a Kanban system.
9. Describe the roles of suppliers and customers in a JIT system.

PROBLEMS

1.The following is a list of the components required to produce one unit of end item P:
P: 2 A's, 3B's, 3C's.
A: 5 M's, 2 R's.
B: 1 D, 3 N's.
C: 1 T, 4 N's.
M: 1 N.
    (1) Draw the product-structure tree.

(2) Determine the number of N's that will be needed to make 60 P's in each of these cases:
    (a) There are currently 10 P's on hand.
    (b) On-hand inventory consists of 15 P's, 10 A's, 20 B's, 10 C's, 100 N's, 300 T's and 200 M's.

2. Assume that you are the new manager of a shop that assembles power tools. An order has just been received for 50 band saws, which are to be shipped at the beginning of week eight. Information concerning saw assembly is given below.

Item	Lead time (weeks)	On-hand	Components
Saw	2	15	A(2),B, C(3)
A	1	10	E(3),D
B	2	5	D(2),F(3)
C	2	30	E(2),D(2)
D	1	20	
E	1	10	
F	2	30	

Develop the following:
    (a) A product-structure tree.
    (b) A master schedule for saws.
    (c) A material requirements plan for component E.
Assume a minimum order size of 300 units.

3. End item P is composed of three subassemblies, K, L, and W. K is assembled using 3 G's and 4 H's; L is made of 2 M's and 2 N's; and W is made using 3 Z's. On-hand inventories are: K, 10; L. 20; and Z, 200. One hundred P's are to be shipped at the start of week seven. Lead times are two weeks for subassemblies and one week for components (e.g., G, H, M). Final assembly of P requires two weeks. Determine the following:
    (a) A product-structure tree.
    (b) A master schedule for P.
    (c) A material requirements plan for K, G, and H.

4. The product structures for end items M and N are shown below. All items have a one-week lead time. Presently, there are 20 units of M available, 15 units of N, and 90 units of C. The standard lot sizes are 50 for M, 35 for N, and 100 for C. The MPS calls for 20 units of item M and 15 units of item S for each of the next five weeks. An open order for 100 units of item C is scheduled for receipt in week 1. Develop the MRP records for items M, N, and C.
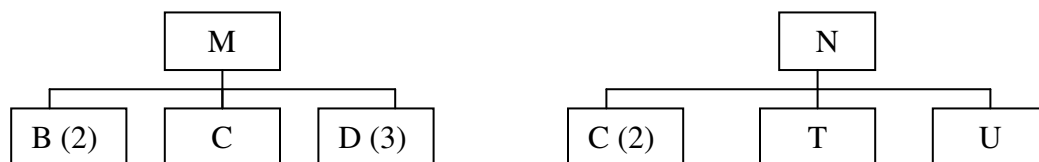
ANSWERS

1. Independent demand refers to demand for end items and is thus often random and unpredictable, while dependent demand is derived from demand for end items and is somewhat predictable.
2. MRP is appropriate when inventory requirements planning must be accomplished for *dependent* demand.
3. Effective MPR requires accurate inputs (master schedule, bills of materials, and inventory status). It also requires a computer to process information and generate material requirement plans and related reports.
4. Advantages of MRP include: low levels of in-process inventories and the ability to track material requirements for derived demand. Unfortunately, it takes much longer and costs much more than expected to implement MRP due to inaccurate or outdated records and/or personnel problems.
5. A planned order release is planning to meet the schedule. This does not mean the order will actually be released that period. It may be released earlier or later; the order quantity may be rounded to some even number or lot size. The planned order may be combined with net requirements in other periods to a larger order size.
6. The Master Production Schedule "drives" the system. It states the planned due dates for end items. MRP computer runs, however, involve an iterative process. The Master Production Schedule "proposes" or "hypothesizes" a tentative schedule. After the MRP run with this schedule, the shop scheduler examines the MRP plan for impractical loads on the productive system-either by stating excessive demands on personnel or equipment, or in excessive idle time. Then the master production schedule is revised and the program is run again.
7. Many of the advanced versions such as manufacturing resources systems (MRP II) and closed loop MRP are more comprehensive in that they are used to plan and control all aspects of the manufacturing firm. This might include design, CIM, financial personnel planning and purchasing systems. Newer systems use EDI with MRP systems that include: client/server architecture, relational databases with structured query language, graphical user interfaces, decision support systems, multiple platforms, and user friendly programming interfaces
8. The goals of MRP II and Kanban are essentially the same (i.e., to improve customer service, reduce inventories, and increase productivity). MRP II is basically a computerized system, handling complex planning and scheduling, while Kanban is a manual system involving very small lot sizes, short lead times, and a high quality output.
9. JIT involves customers and suppliers as an integral part of the process. Customers provide product enhancement, modification, and usage data. Suppliers work with the manufacturing organization to coordinate delivery and raw material or other input production. Both groups may sit on JIT teams and participate in improvement activities as all groups will benefit from changes.

PROBLEMS

1.
(1) The product-structure tree is as follows:

P

```
                A (2)                    B (3)                   C (3)
          ┌───────┴───────┐        ┌───────┴───────┐       ┌───────┴───────┐
        M (5)           R (2)      D             N (3)      T             N (4)
          │
          N
```
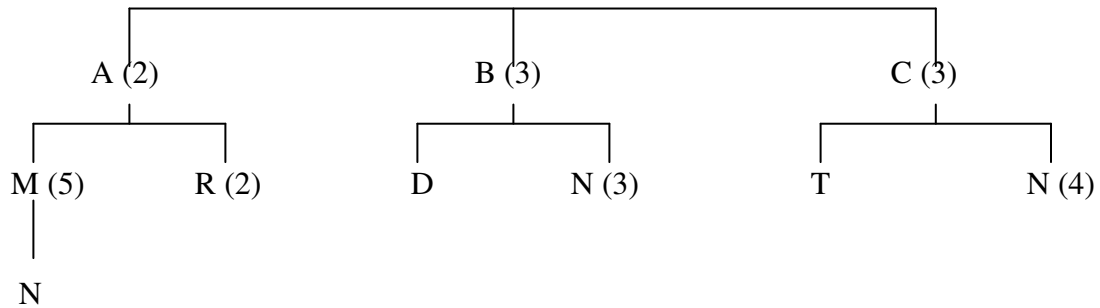
(2) (a)

A leg: 2 A's x 5 M's   = 10 N's
B leg: 3 B's x 3 N's   =   9 N's
C leg: 3 C's x 4 N's   = <u>12 N's</u>
                          31 N's x (60 A's - 10 A's on hand) = 1,550 N's.

(b) 45 P's needed:

A leg: A: 2 x 45 - 10 = 80. M: 80 x 5 - 200 = 200. N: 200 - 100 on hand = 100
B leg: B 3 x 45 - 20 = 115. N: 3 x 115 =345.
C leg: C: 3 x 45 - 10 = 125. N: 4 x 125 = 600.

Thus, 100 + 345 + 600 = 1,045 N's needed.

2.

(a) The product-structure tree is as follows:

```
                               Saw
          ┌─────────────────────┼─────────────────────┐
        A (2)                    B                    C (3)
      ┌───┴───┐              ┌───┴───┐            ┌───┴───┐
    E (3)     D            D(2)    F (3)        E(2)     D (2)
```
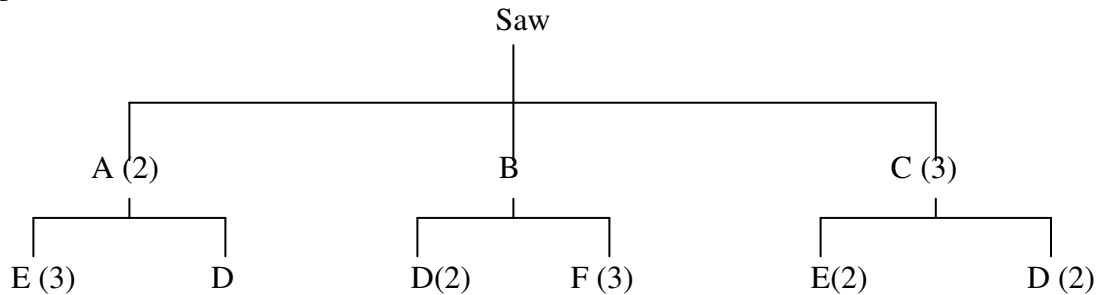
(b)

	1	2	3	4	5	6	7	8
Master schedule for saws								35

(c)
Item: E

	1	2	3	4	5	6	7	8
Gross requirements				330				
Schedule receipts								
On-hand				10				
New requirements				320				
Planned order receipts				320				
Planned order release			320					

3.

(a)
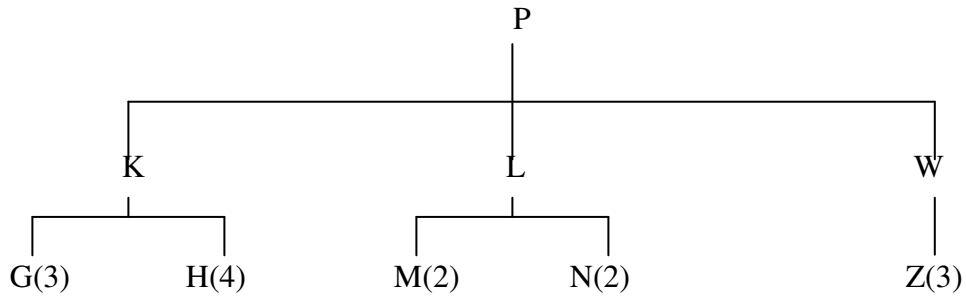
(b)

	1	2	3	4	5	6	7
Master schedule for saws							100

(c)

Item: P, LT = 2 weeks

	1	2	3	4	5	6	7
Gross requirements							100
Schedule receipts							
On-hand							0
New requirements							100
Planned order receipts							
Planned order release					100		

Item: K, LT = 2 weeks

	1	2	3	4	5	6	7
Gross requirements					100		
Schedule receipts							
On-hand					10		
New requirements					90		
Planned order receipts					90		
Planned order release			90				

Item: G, LT = 1 week

	1	2	3	4	5	6	7
Gross requirements			270				
Schedule receipts							
On-hand			40				
New requirements			230				
Planned order receipts			230				
Planned order release		230					

Item: H, LT = 1 week

	1	2	3	4	5	6	7
Gross requirements			360				

			0				
Schedule receipts							
On-hand			0				
New requirements			360				
Planned order receipts			360				
Planned order release		360					

4.

Item: M, LT = 1 week

	1	*2*	*3*	*4*	*5*
Gross requirements	20	20	20	20	20
Schedule receipts					
On-hand	20	0	30	10	40
New requirements	0	20	10	10	
Planned order receipts		50		50	
Planned order release	50		50		

Item: N, LT = 1 week

	1	*2*	*3*	*4*	*5*
Gross requirements	15	15	15	15	15
Schedule receipts					
On-hand	15	0	20	5	25
New requirements	0	15		10	
Planned order receipts		35		35	
Planned order release	35		35		

Item: C, LT = 1 week

	1	*2*	*3*	*4*	*5*
Gross requirements	120		120		
Schedule receipts	100				
On-hand	90	70	70	50	
New requirements			50		
Planned order receipts			100		
Planned order release		100			

CHAPTER 11
PLANNING AND CONTROLLING PROJECTS

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Define a Gantt chart.
2. Define dummy activity.
3. Compute the Critical Path.
4. Compute the earliest start time, the earliest finish time, the latest start time, and the latest finish time.
5. Illustrate a Backward pass.
6. Define and explain the PERT/COST
7. Demonstrate the Critical Path Method (CPM).
8. Discuss the concept of *crashing.*

Project management involves planning and scheduling. *Project planning* includes all activities that result in a course of action for a project. Goals for the project must be set and their priorities established. Goals include resources to be committed, completion times, and activities. Areas of responsibility must be identified and assigned. Time and resource requirements to perform the work activities must be projected and budgeted. Project scheduling, compared to project planning, is more specific. Scheduling establishes time and sequences of the various phases of the project.

PROJECT SCHEDULING MODELS
There are various methods for scheduling projects. Presented in this chapter are two popular scheduling models--Gantt charting and the Program Evaluation and Review Technique (PERT). Both are schematic models, but the PERT also is a mathematical model.

GANTT CHARTS
A Gantt chart is a bar chart that depicts the relationship of activities over time. Table 1 provides the symbols frequently used in a Gantt chart. An open bracket indicates the scheduled start of the activity, and closing bracket indicates the scheduled completion. The symbol [--] indicates the currently completed portion of the activity. A caret at the top of the chart indicates current time.

Figure 1 shows a Gantt chart of a business student preparing for final exams. Project activities are listed down the page and time across the page. The project activities are studying for exams in Marketing, Human Resource Management (HRM), Operations Management (OM), and Information Systems (IS). OM is broken into two subactivities—studying concepts new since the last exam and studying concepts covered on previous exams, for review. By examining the horizontal time axis, we see that all activities must be completed in three and one-half weeks.

Studying Human Resource Management, for example, is scheduled to start at the beginning of week 1 and end after one and one-half weeks. The caret at the top indicates that one and one-half weeks have already passed. The heavy lines show how much of each activity has already been done. Students can use this chart to visualize their progress and to adjust their study activities. As you can see, one of the strengths of project scheduling with Gantt charts is the simplicity of the schematic model.

TABLE 1
GANTT CHART SYMBOLS

Symbol	Meaning
[	Start of an activity
]	End of an activity
[—]	Actual progress of the activity
ν	Point in time where the project is now

FIGURE 1
GANTT CHART FOR PROJECT SCHEDULING

Project activity	Week 1	Week 2	Week 3	Week 4
Study HRM	[———————	]		
Study Marketing		[———————	]	
Study OM				
Study concepts new since last exam		[—	]	
Study concepts covered on previous exams			[ ]	
Study IS				[ ]

PROGRAM EVALUATION AND REVIEW TECHNIQUE (PERT)

Program Evaluation and Review Technique (PERT) is a useful management tool for planning, scheduling, costing, coordinating, and controlling complex projects such as (a) construction of buildings, (b) installation of computers, (c) assembly of a machine, (d) research and development activities, and (e) new product development.

Questions to be answered by PERT include:
• When will the project be finished?
• What is the probability that the project will be completed by any given time?

The PERT technique involves the diagrammatic representation of the sequence of activities comprising a project by means of a network. The network (1) visualizes all of the individual tasks (activities) to complete a given job or program; (2) points out interrelationships;

and (3) consists of activities (represented by arrows) and events (represented by circles), as shown below.

1. *Arrows*. Arrows represent "tasks" or "activities," which are distinct segments of the project consuming time and resources.

2. *Nodes (circles).* Nodes symbolizes "events," or milestone points in the project representing the completion of one or more activities and/or the initiation of one or more subsequent activities. An event is a point in time and does not consume any time in itself as does an activity.

RULES OF NETWORK CONSTRUCTION
      Fundamental to PERT is the construction of a network. The rules for its construction follow:

Rule 1: Each arrow should represent only one activity.
Rule 2: The length of the arrow is determined only by convenience and clarity, and is not related to the time needed for that activity.
Rule 3: Each activity except the first must have an activity preceding it.
Rule 4: Each activity except the last must have an activity following it.
Rule 5: For any activity to begin, all preceding activities must be completed.

EXAMPLE 1
      Consider the activities, A, B, C, D, E, F, and G. The following network
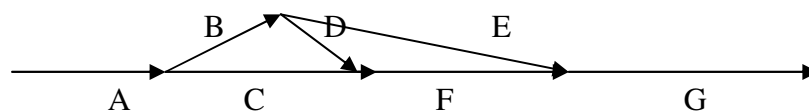
is interpreted as:
1. Perform activity A.
2. Start B and C after A is performed. B and C can be performed concurrently.
3. Start D and E after B is completed.
4. Start F only after C *and* D are completed.
5. Start G only after E and F are completed.

NOTE:
      It is evident that a network can represent the most complex relationship of activities conceivable and yet permit the tracking of all activities with little trouble.

An additional important rule must be noted:
Rule 6: No two activities can have the same origin and ending.
EXAMPLE 2
      Assume that we are to perform A and B concurrently. Because of Rule 6, the following network is illegal:

A

B
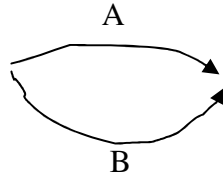
Because of Rule 4, the following network is illegal as it stands:

A

B
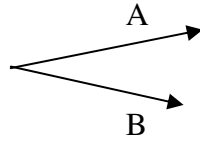
However, the problem can be resolved by what is called a *dummy activity* in the following way:

A

B

or

A

B
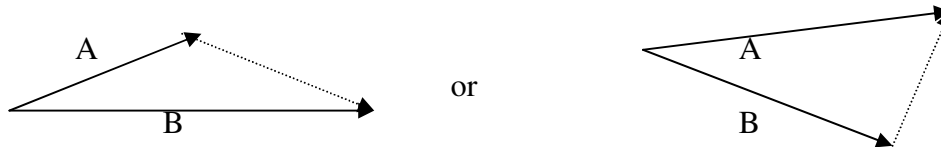
A dummy activity represents *no* work, but permits observance of Rule 4 and Rule 6.

In a real world situation, the estimates of completion times of activities will seldom be certain. To cope with the uncertainty in activity time estimates, the PERT proceeds by estimating three possible duration times for each activity. As shown in Figure 2, the numbers appearing on the arrows represent these three time estimates for activities needed to complete the various events. These time estimates are:

- the most optimistic time, labeled a
- the most likely time, m
- the most pessimistic time, b

FIGURE 2
NETWORK DIAGRAM
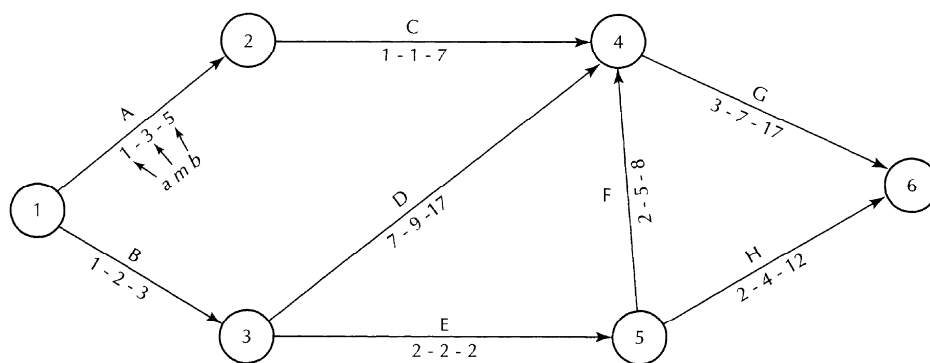
For example, the optimistic time for completing activity H is 2 days, the most likely time is 4 days, but the pessimistic time is 12 days. The next step is to calculate an expected time, which is determined as follows:

t_e (expected time) = (a + 4m + b) / 6

For example, for activity H, the expected time is

(2 + 4(4) + 12) / 6 = 30 / 6 = 5 days

Note that this formula is based on the assumption that the uncertain activity times are best described by a *beta probability distribution*. This distribution assumption, which was judged to be reasonable by the developers of PERT, provides the time distribution for activity H as shown in Figure 3.

FIGURE 3
ACTIVITY TIME DISTRIBUTION FOR ACTIVITY H
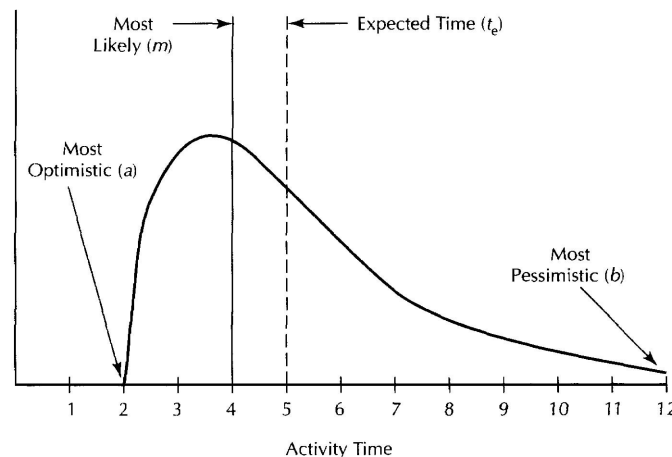
As a measure of variation (uncertainty) about the expected time, the standard deviation is calculated as follows:

$$\sigma = (b - a) / 6$$

For example, the standard deviation of completion time for activity H is:

$$\sigma = (12 - 2) / 6 = 10 / 6 = 1.67 \text{ days}$$

Note: This formula is based on the notion that a standard deviation is approximately 1/6 of the difference between the extreme values of the distribution.

Expected activity times and their standard deviations are computed in this manner for all the activities of the network and arranged in the tabular format as shown in Table 2.

TABLE 2
COMPUTATIONS OF EXPECTED TIME AND STANDARD DEVIATION

Activity	Predecessors	a	m	b	t_e	σ
A	None	1	3	5	3.0	.67
B	None	1	2	3	2.0	.33
C	A	1	1	7	2.0	1.00
D	B	7	9	17	10.0	1.67
E	B	2	2	2	2.0	0.00
F	E	2	5	8	5.0	.67
G	C,D,F	3	7	17	8.0	2.33
H	E	2	4	12	5.0	1.67

To answer the first question, we need to determine the network's critical path. A path is a sequence of connected activities. In Figure 2, 1-2-4-6 would be an example of a path. The critical path for a project is the path that takes the longest amount of time. The sum of the estimated times for all activities on the critical path is the total time required to complete the project. These activities are "critical" because any delay in their completion will cause a delay in the project.

The time to do all the activities on the critical path represents the minimum amount of time needed for the completion of the project. Thus, to speed up the project, the activities along this path must be shortened. Activities not on the critical path are not critical, since they will be worked on simultaneously with critical path activities and their completion could be delayed up to a point without delaying the project as a whole.

An easy way to find the critical path involves the following two steps:

1. Identify all possible paths of a project and calculate their completion times.
2. Pick the one with the longest amount of completion time, which is the critical path.
In the example, we have:

Path	Completion time
A-C-G	13 days (3 + 2 + 8)
B-D-G	20 days (2 + 10 + 8)
B-E-F-G	17 days (2 + 2 + 5 + 8)
B-E-H	9 days (2 + 2 + 5)

The critical path is B-D-G, which means it takes 20 days to complete the project.

The next important information we want to obtain is "what is the chance that the project will be completed within a contract time, say, 21 days?" To answer the question, we introduce the standard deviation of total project time around the expected time, which is determined as follows:

- Standard deviation (project) = $\sqrt{\text{the sum of the squares of the standard deviations of all critical path activities}}$

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Using the formula above, the standard deviation of completion time (the path B-D-G) for the project is as follows:

$$\sqrt{(.33)^2 + (1.67)^2 + (2.33)^2} = \sqrt{.1089 + 2.7889 + 5.4289}$$

$$= \sqrt{8.3267} = 2.885 \text{ days}$$

Using the standard deviation and table of areas under the normal distribution curve (Table 1 of the Appendix), the probability of completing the project within any given time period can be determined. Assume the expected delivery time is say, 21 days. The first step is to compute z, which is the number of standard deviations from the mean represented by our given time of 21 days. The formula for z is:

$$z = \frac{(\text{delivery time - expected time})}{\text{standard deviation}}$$

Therefore,

$$z = \frac{(21 \text{ days - 20 days})}{2.885 \text{ days}} = .35$$

The next step is to find the probability associated with the calculated value of z by referring to a table of areas under a normal curve.

From Table 1 in the Appendix we see the probability is .6368, which means there is close to a 64% chance that the project will be completed in less than 21 days.

To summarize what we have obtained,

1. The expected completion time of the project is 20 days.
2. There is a better than 60% chance of finishing before 21 days. *Note:* We can also obtain the chances of meeting any other deadline if we wish. All we need to do is change the delivery time and recalculate the z value.
3. Activities B-D-G are on the critical path; they must be watched more closely than the others, for if they fall behind, the whole project falls behind.
4. If extra effort is needed to finish the project on time or before the deadline, we have to borrow resources (such as money and labor) from any activity not on the critical path.

SUMMARY OF PERT PROCEDURE
In analyzing any project using PERT, we perform the following steps:

Step 1: Develop a list of activities that make up the project, including immediate predecessors and draw a network corresponding to the activity list developed.
Step 2: Estimate the expected activity time and the variance for each activity.

Step 3: Using the expected activity time estimates, determine the earliest start time and the earliest finish time for each activity. The earliest finish time for the complete project corresponds to the earliest finish time for the last activity. This is the expected project completion time.

Step 4: Using the project completion time as the latest finishing time for the last activity, work backward through the network to compute the latest start and latest finish time for each activity.

Step 5: Compute the slack associated with each activity. The critical path activities are the activities with *zero* slack.

Step 6: Use the variability in the activity times to estimate the variability of the project completion date; then, using this estimate, compute the probability of meeting a specified completion date.

STEPS TO BE FOLLOWED IN DETERMINING THE CRITICAL PATH

When the network is large and complex, it is tedious to find the critical path by listing all the paths and picking the longest one. We need a more systematic and efficient approach, which is explained below.

Step 1: Find the earliest start (ES) and earliest finish (EF) times for the activities. This is done by assigning a start time (usually zero) for the initial job (s) and determining the earliest possible start time for each of the activities in the network. The rule is: since a job cannot be started until all preceding jobs have been finished, the earliest start time of an activity is the maximum of the earliest finish times of the immediate predecessors. The earliest finish time for an activity is its earliest start time plus the activity duration time (t). $EF = ES + t$.

Step 2: Compute the latest start (LS) and latest finish (LF) times for the activities. This is done by what is called a backward pass. We begin this time at the completion point. The latest finish time is the latest time at which an activity can be completed without extending the completion time of the network. The rule is: the latest finish time for an activity is the minimum of the latest start time of the immediately succeeding activities. The latest start time is the latest at which an activity can begin without extending the completion time of the project. It is the latest finish time minus the activity duration, $LS = LF - t$

FIGURE 4
NETWORK DIAGRAM

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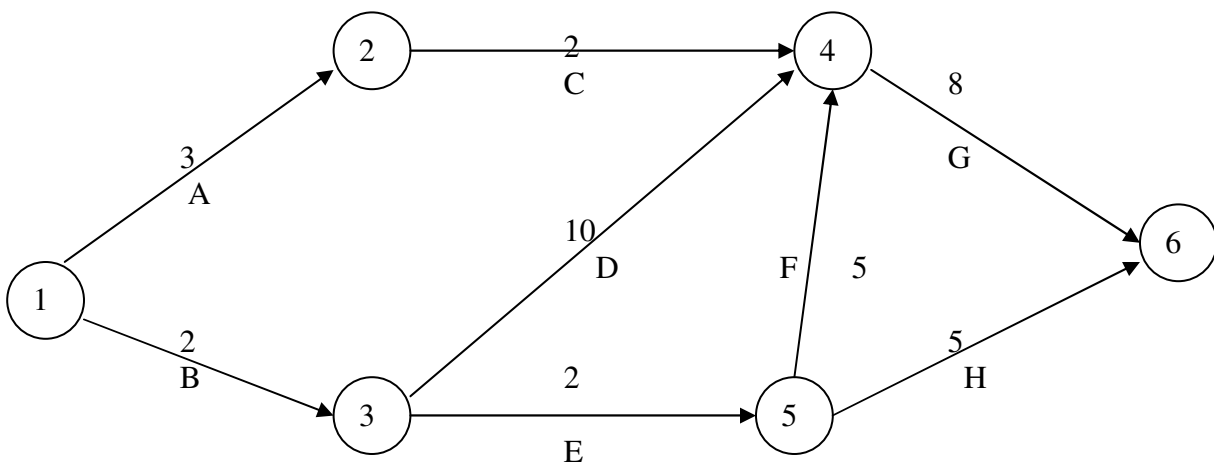
Step 3: Compute slack times for the activities. The critical path of the project is made up of those activities with zero slack. The slack is the length of the time we can delay an activity without interfering with the project completion. Any delay in completing activities on the critical path will result in a lengthening of the project duration.

$$\text{Slack} = \text{ES - LS or EF - LF}$$

In other words, we compare the earliest start time with the latest start time for any activity, i.e., we look at when it *can* be started and when it *must* be started to see how much free time, or slack, that activity has.

Table 3 illustrates how the critical path is determined using this approach.

TABLE 3
DETERMINATION OF THE CRITICAL PATH

Activity	ES	EF	LS	LF	Slack =ES - LS or EF - LF	Activity on Critical Path
A	0	3	7	10	7	
B	0	2	0	2	0	Yes
C	3	5	10	12	7	
D	2	12	2	12	0	Yes
E	2	4	5	7	3	
F	4	9	7	12	3	
G	12	20	12	20	0	Yes
H	4	9	15	20	11	

The critical path with zero slacks (double lines) is shown in Figure 5.

FIGURE 5
CRITICAL PATH
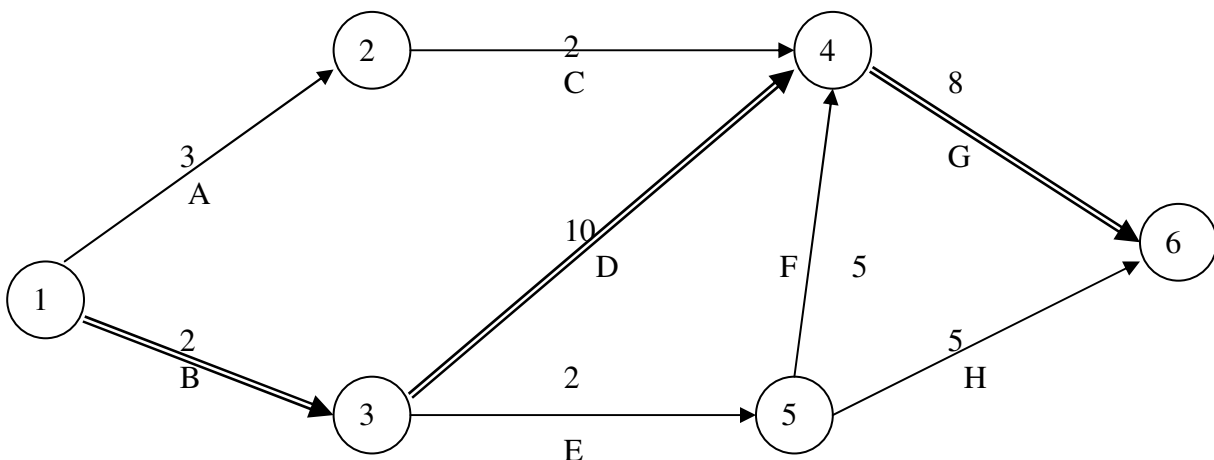
NOTE:
    It should be noted that PERT is a technique for project management and control. It is not an optimizing decision model since the decision to undertake a project is initially assumed. It will not evaluate an investment project according to its attractiveness or time specifications.

It is possible to reduce the completion time of one or more activities, which will require an extra expenditure of cost. The benefit from reducing the total completion time of a project by accelerated efforts on certain activities must be balanced against the extra cost of doing so. A related problem is to determine which activities must be accelerated to reduce the total project completion time. The *Critical Path Method (CPM),* also known as *PERT/COST*, is widely used to deal with this subject.

THE CRITICAL PATH METHOD (CPM) MODEL: PERT/COST

If the project duration (length of critical path) exceeds the allowable deadline, options include (1) changing the deadline or (2) "crashing" the project. Crashing means speeding up one or more activities along the critical path. This may involve shifting more resources (money) to those activities or perhaps outsourcing some of the work.

The critical path method (CPM) model, also known as PERT/COST, argues that most activities can be reduced in duration if extra resources (men, machines, money, and so on) are assigned to them. The cost for getting the job done may increase, but if other advantages outweigh this added cost, the job should be expedited or crashed. The CPM model attempts to solve (1) which jobs to crash and (2) by how much. The *normal time* is similar to the most likely time estimate in PERT. This could be viewed as the most efficient time to complete the project.

The *crash time* is the time required when extra resources are added to complete the project in the minimum possible time. Use of the crash time results in added costs for the project. A simplified view of the relationship between the normal and the crash times is seen in Figure 8. This represents a linear cost-time relationship. A nonlinear relationship is also possible, and may be more realistic. However, to illustrate the model, only the simplified linear relationship will be used. The slope of the cost-time line for any activity can be determined by the following:

$$\text{Slope} = \text{cost per day} = \frac{\text{Crash cost - Normal cost}}{\text{Normal time - Crash time}}$$

The slope of these lines actually measures the increase in cost per unit increase in time. Therefore, all such slopes are negative. The minus sign can be ignored and only absolute values considered, however.

To illustrate the CPM model, assume a simple project, as represented by the network diagram in Figure 6. The time, cost, and cost slope data for this project are shown in Table 4.

FIGURE 6
NETWORK DIAGRAM FOR CPM ILLUSTRATION
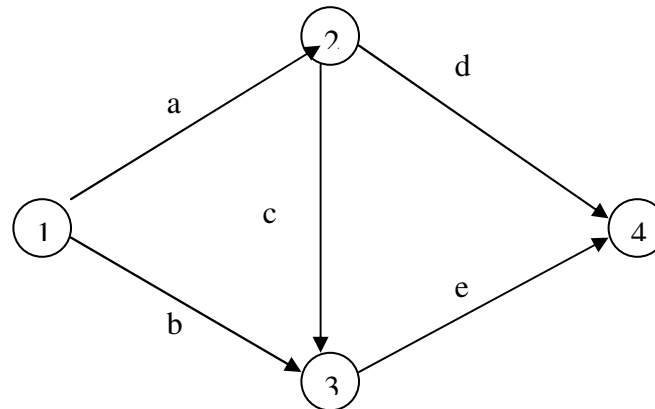
NORMAL SOLUTION

From the foregoing information, the normal time solution can be developed. This solution is shown in Figure 7, with the appropriate normal time estimates indicated on the activity arrows. The critical path for this solution, as indicated by the heavy arrows, is a-c-e = 15 days. The total cost of the normal time solution is $3,900.

TABLE 4
CPM PROJECT TIME AND COST DATA

| Activity | Time/Days | | Cost | | Slope |
	Normal	Crash	Normal	Crash	
a	4	3	$ 400	$ 800	400
b	8	5	600	2,400	600
c	6	5	1,000	1,200	200
d	9	8	700	1,400	700
e	5	2	1,200	2,700	500
Total cost			$3,900	$8,500	

CRASH SOLUTION

The crash time solution can also be determined from the information in the same way. This solution is found in Figure 8. The critical path can be determined as a-d = 11 days, with a cost of $8,500.

FIGURE 7
NORMAL TIME SOLUTION CPM NETWORK
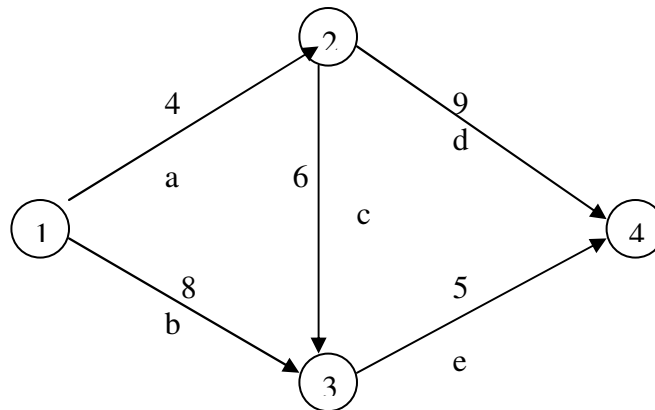
FIGURE 8
CRASH TIME SOLUTION CPM NETWORK
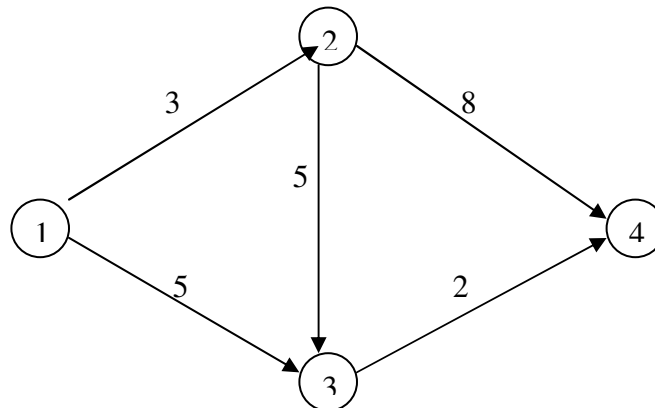
DETERMINATION OF MINIMUM-COST CRASH SOLUTION

The crash solution set forth above indicated that this project can be completed in 11 days at a cost of $8,500. The next question for management to answer is whether the project can be completed in this same period of time for a lower cost.

The CPM (PERT/COST) model involves the following steps:

1. Find the *critical path*.
2. Look at all the slopes (crash costs per unit of time) for all activities on the critical path.
3. Pick the activity on the critical path with the lowest cost increase per unit of time. If there is a tie, pick one of the ties activities at random.
4. Use crash time on this activity, compute the expected total time, the total cost, and determine the new critical path.
5. Repeat the process until either the expected total time is equal to or less than the required time, there are no more possible time savings, *or* the total cost exceeds available funds.

Now we apply these steps to the example. First, we list all paths:

Path	Length
a-c-e	15 ← critical path
b-e	13
a-d	13

Next, we determine the critical path activities in the order of lowest crashing cost and the number of days that can be crashed.

Activity	Slope	Available days
c	200	1
a	400	1
e	500	3

Shorten c and a one day a piece at a cost of $600 ($200 +$400). The length of the path a-c-e becomes 13 days, which is the same as the length of paths b-e and a-d. Since all three paths are now critical further improvements will necessitate shorting one activity on each.

Path	Length	
a-c-e	13	critical path
b-e	13	critical path
a-d	13	critical path

Path	Activity	Slope
a-c-e	a	No reduction possible
	c	No reduction possible
	e	$500
b-e	b	$600
	e	No reduction possible
a-d	a	No reduction possible
	d	$700

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The following three activities can be crashed:

Activity	Slope	Available days
e	500	3
b	600	3
d	700	1

Shortening activity e two days for $1,000 ($500 x 2) and d one day ($700) would lead to the critical paths a-c-e and a-d of 11 days for $6,200. While activity b can be crashed, their crashing does not reduce project duration. The minimum time of the project is 11 days at a cost of $6,200. At this point, no additional improvement is possible.
To summarize,

Project Time	Crashing Options	Least Cost Option	Project Cost	Critical Paths
15 days			$3,900	a-c-e
13	-1 at c & a ($200 + 400)	c & a	$4,500	a-c-e; b-d; a-d
11	-2 at e ($500 x 2) & -1 at d ($700)	e & d	$6,200	a-c-e; a-d

MANAGEMENT USE OF CPM

The CPM network has the primary goal of aiding management in the control of costs as well as of time. In these models, this goal is accomplished by providing management with a technique whereby the various time-cost trade-offs in a project can be evaluated. The process involves the determination of the lowest cost, longest completion time solution; and the shortest time, highest cost solution. From these two solutions, various alternatives can be established. For example, the lowest cost possible for the shortest completion time can be found. In addition, a variety of alternatives involving reduction in completion time and the added cost of each can be ascertained. Thus, the time and cost of completing the project under normal conditions, and the amount of time that can be saved by the expenditure of more money on various activities are determined. Management can then make a decision about the project after a consideration of all of the time-cost options. The lowest cost option, the shortest time option, and the interim alternatives with the appropriate cost and schedule data will be available.

COMPUTER SOFTWARE FOR PROJECT MANAGEMENT

Most project management applications today use computers extensively. The management of projects is enhanced by tools such as *Gantt* charting, the *Program Evaluation and Review Technique (PERT)*, and *Critical Path Method (CPM)*. These tools are easily computerized and indeed there are dozens of commercial packages on the market. The user inputs activity time estimates and procedure information, program output slack for each activity, duration and variance for critical paths, and other useful project management information.

Popular packages are listed below.

AllFusion Process Management Suite
Computer Associates International

iPlan Enterprise 4.3; iPlan Web 1.3
Integrated Strategic Information Systems, Ltd.
www.iPlanEnterprise.com

Microsoft Project 2003
Microsoft Visio Standard 2003
Microsoft Corp.
www.microsoft.com

The Edge Solution w/Portfolio Edge & Project Office
Serena Software
www.pacificedge.com

PlanView
PlanView
www.myplanview.com

Primavera TeamPlay
Primavera Systems
www.primavera.com

Cobra 3.5
Open Plan 2.6
WelcomHome 2.5
Welcom
www.welcom.com

QUESTIONS
1. Define *project management*.
2. Describe the key elements of the project-planning process.
3. Why is a network diagram used in project management?
4. Differentiate between an event and an activity.
5. Discuss why Gantt charts are a useful aid to an operations manager.
6. What options are available if the project duration (length of critical path) exceeds the allowable deadline?
7. What is the difference between the normal time and the crash time?
8. Briefly describe PERT/COST? What is it also known as?

PROBLEMS
1. Laurie, operator at Charles Speedy print shop, has three jobs that she must get out today. Each job must be type set, printed, then folded, and the jobs must be done in the order shown below.

Job	Type setting	Printing	Collating

X	1 hour	3 hr.	1.5
Y	4	3	.5
Z	2.5	2	1

Construct a Gantt chart of her day's work.

2. Given the project below,
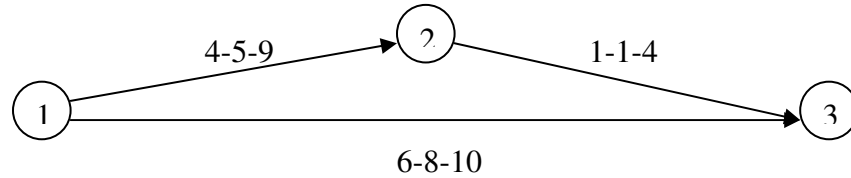
What probability would you assign to a project duration of more than 8.5 weeks?

3. Given the network diagram below,
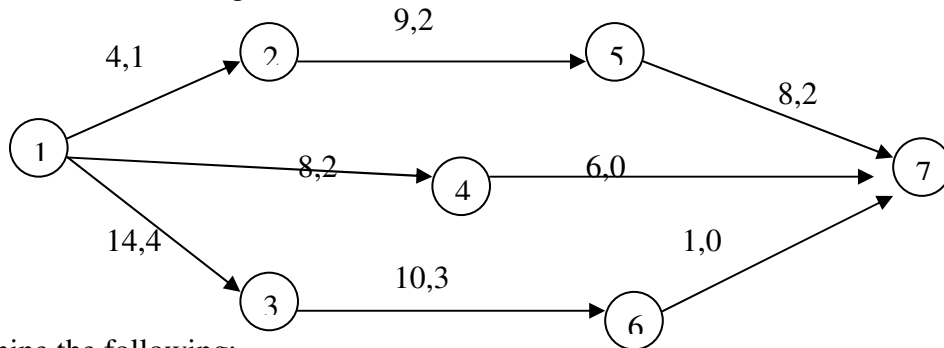
Determine the following:
   (a) The activities on the critical path.
   (b) The expected project duration
   (c) The probability that the project will be completed in 29 weeks or less.

4. Consider the following:

Activity	Immediate Predecessor	a	m (in weeks)	b
A	None	2	4	6
B	None	6	8	10
C	A	1	5	15
D	C	1	5	9
E	B	6	8	10

   (a) Compute the expected time and standard deviation of the time required to complete each activity.
   (b) Find the critical path by computing earliest start (ES), latest start (LS), and slack. What is the expected length of the critical path?
   (c) Assume the time required to complete the project is normally distributed. Compute the probability that path ACD will be completed in less than 16 weeks.
   (d) What is the probability that the project will be completed in less than 16 weeks?

5. Given the following network of a project:
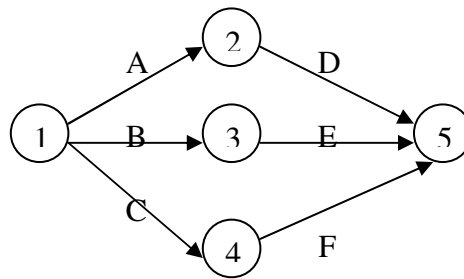
(a) Determine the critical path of the network by enumerating all paths.
(b) Determine the critical path of the network by computing the slacks of the activities.

6. Using the information below, develop an optimum time-cost solution.
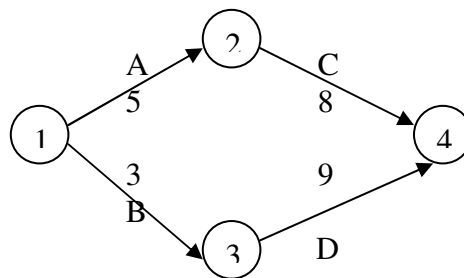
Activity	Normal time (day)	Crash time (day)	Crash cost per day
A	5	3	2.5
B	3	2	4
C	8	6	3.5
D	9	7	1

ANSWERS
1. Project management involves the planning, directing and controlling of resources (people, equipment, material) to meet the technical cost, and time constraints of the project.
2. Project planning involves project definition, resource definition, project scheduling, and project control.
3. The network diagram provides an easily understood graphical description of the project and how activities must be sequenced.
4. Events correspond to points in time at which activities begin or end. Activities consume time and resources.
5. Gantt charts allow an operations manager to schedule activities over time in a graphical manner. A Gantt chart is readily understood and updated, and it is useful in determining the status of a project at any point in time.
6. If the project duration (length of critical path) exceeds the allowable deadline, options include (1) changing the deadline or (2) "crashing" the project.
7. The *normal time* is similar to the most likely time estimate in PERT. This could be viewed as the most efficient time to complete the project. The *crash time* is the time required when

extra resources are added to complete the project in the minimum possible time. Use of the crash time results in added costs for the project.

8. PERT/COST, also known as the *Critical Path Method (CPM)*, is a technique designed to assist in the planning, scheduling, and controlling of project costs.

PROBLEMS
1.

Activity	1	2	3	4	5	*Hours* 6	7	8	9	10	11	12
Type setting	[X]	[	Y		]	[	Z	]				
Printing		[	X	]		[	Y		]	[Z	]	
Collating				[X	]			[Y]		[Z	]	

2.

Path	t_e	σ	z	P(<8.5)
1-2-3	7	.972	+1.54	.9382
1-3	8	.667	+0.75	.7734

The probability of both less than 8.5 is (.9382)(.7734) = .7256. Thus, P(project < 8.5) = 1 - .7256 = .2744 = 27.44%

3.

Path	t_e	σ	z	P(<8.5)
1-2-5-7	21	3	+2.67	
1-4-7	14	2	+7.50	
1-3-6-7	25	5	+0.80	.7881

The critical path is 1-3-6-7.
Expected project duration is 25 weeks.
Except for the critical path, the project will easily finish on time due to their large z values. The probability of critical path completion by week 29 is .7881 = 78.81 percent.

4.
(a)

Activity	t_e	σ	ES	LS	Slack
A	4	.67	0	1	1
B	8	.67	0	0	0
C	6	2.33	4	5	1
D	5	1.33	10	11	1
E	8	.67	8	8	0

(b)
The critical path is B-E and the expected length is 8 + 8 = 16 days.
(c)
The path A-C-D = 4 + 6 + 5 = 15 days

$\sigma_{ACD} = \sqrt{(.67)^2 + (2.33)^2 + (1.33)^2} = \sqrt{7.6467} = 2.76$

To find the probability that path ACD will be completed in less than 16 weeks, define Z = (16 - 15)/2.76 = .36

From the normal distribution in the Appendix, we get .6406 or 64. 06%.

(d)

$\sigma_{BE} = \sqrt{(.67)^2 + (.67)^2} = \sqrt{.8978} = .947$

 Define Z = (16 - 16)/.947 = 0

From Table 1 (normal distribution) in the Appendix, we get .50 or 50%, which is the probability the project will be completed in less than 16 weeks.

5.

(a)

Path	Duration	Remark
A-D	3 + 2 = 5	
B-E	1 + 7 = 8	Critical path
C-F	4 + 3 = 7	

(b)

Activity	Duration	Immediate Predecessor	ES	EF	Predecessor of	LS	LF	Slack (LF - EF)
A	3	None	0	3	D	3	6	3
B	1	None	0	1	E	0	1	0
C	4	None	0	4	F	1	5	1
D	2	A	3	5	None	6	8	3
E	7	B	1	8	None	1	8	0
F	3	C	4	7	None	5	8	1

The critical path is B-E with zero slacks.

6.

Activity	Normal time (day)	Crash time (day)	Crash cost per day
A	5	3	2.5
B	3	2	4
C	8	6	3.5
D	9	7	1

Project Time	Crashing Options	Least Cost Option	Crash Cost	Critical Paths
13 days				A-C
12	-2 at A ($2.5 x 2)	A	$5	B-D
11	-2 at D ($1 x 2)	D	$7	A-C
10	-2 at C ($3.5 x 2)	C	$14	B-D
9	-1 at B ($4)	B	$18	A-C

CHAPTER 12
ANALYSIS OF WAITING LINES AND QUEUING

LEARNING OBJECTIVES:

After studying this chapter you will be able to:

1. Discuss the goal of the queuing (or waiting line) theory.
2. List some examples of waiting for service.
3. Classify the queue process.
4. Distinguish among various queuing models.
5. Calculate the measures of system performance for each model that are used in queuing, such as the mean number in system, mean time in system, and mean time waiting for service.
6. Distinguish between *finite* and *infinite* population sources.

Queuing (waiting line) theory investigates the everyday hassle of waiting in line. Operations managers may apply this tool in performing their functions where waiting time is involved. Retailers and manufacturers know that waiting customers are often lost customers. However, improvements in this aspect of customer service are expensive in terms of extra attendants hired, whose pay must continue during slack hours. Coupled with this trade-off problem of quick customer service versus expensive "standby" employees is the random nature of customer arrivals.

In this chapter, we describe how waiting-line models can provide information about the characteristics of a process. Results from queuing analysis can provide helpful process design and layout information that will insure proper operation when the new process is implemented.

QUEUING OR WAITING LINE

There are a number of situations in which a customer of some sort arrives at a service facility of some sort. The only reason that a customer ever needs to wait for service is that for the moment, at least, the ability to provide service is not sufficient to satisfy the demand for that service.

Some examples of waiting for a service are:

1. Out-of-service industrial equipment waiting for a repairman.
2. Patients waiting in clinics.
3. Computer jobs waiting for processing
4. Airplane waiting for a runway.
5. Cars waiting at toll booths.

More examples of waiting line (or queuing) situations are given in Table 1.

TABLE 1
WAITING LINE (OR QUEUING) SITUATIONS

Types of Problem	Customer	Service	Service Facility	Queue Discipline
Teller windows	Person	Deposits and withdrawals	Teller & equipment	First-come, first served (FCFS)
Telephone exchange	Incoming calls	Makes call connection	Operator & switchboard	Random
Machine repair	Disabled machines	Repair of machines	Repair crew	Priority
Tool crib	Machinist	Issues tools	Tool crib & attendants	FCFS
Market checkout stand	Customers with purchases	Ring up, collect, & wrap	Clerk, cash register & wrappings	FCFS
Bus terminal	Buses	Arriving & departing	Loading area, dispatcher & driver	Schedule
Medical clinic	Patients	Medical treatment	Receptionist, nurse, doctor, equipment	FCFS or priority by appointment
Beauty shop	Patrons	Hair dressing	Beauty operator & equipment	FCFS or priority by appointment

GOAL OF QUEUING ANALYSIS

The goal of queuing is essentially to balance the cost of providing a level of service capacity and the customers waiting for service. Capacity costs relate to maintaining the ability to provide service. Examples include the number of repairmen to handle machine breakdowns, the number of checkouts in a retail store, the number of bays in an auto repair garage, and so on.

This notion is illustrated in Figure 1. We expect a trade-off between these two types of costs and total cost to be represented as a U-shaped curve. The optimal level of service capacity is the one in which total cost is minimized.

<div align="center">

FIGURE 1
OPTIMAL SERVICE CAPACITY DETERMINATION

</div>
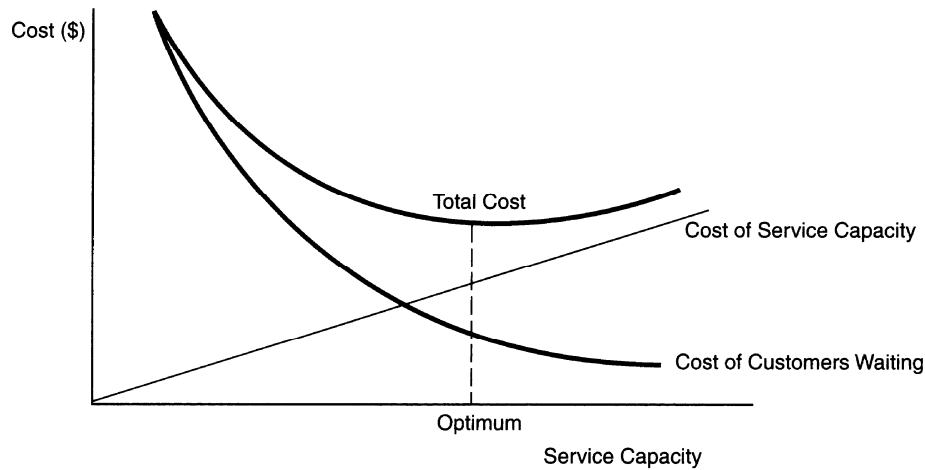
Many situations in productive systems are described conceptually by the general waiting line (queuing) model. How many shipping docks and receiving docks should be built for incoming and outgoing shipments? How many lift trucks should be provided to move products? How should machines be arranged to minimize waiting lines of products in process? How many teller windows should be open in a bank?

NOTE:

Unlike in the case of the *EOQ* inventory model, the minimum cost is *not* usually obtained at the point where two cost curves intersect.

<div align="center">

QUEUING (WAITING LINE) MODELS

</div>

There are four basic structures that describe the general conditions at the service facility:

1. The single-channel, single-phase case is the one in which arrival units form a waiting line and are serviced by a single service facility. The one-clerk parts department is illustrative.

<div align="center">

waiting line   service facility

</div>

2. The multiple-channel, single-phase case is illustrated by a two-or-more-clerks parts department since customers can be serviced by any of the clerks (channel).

waiting line   service facility
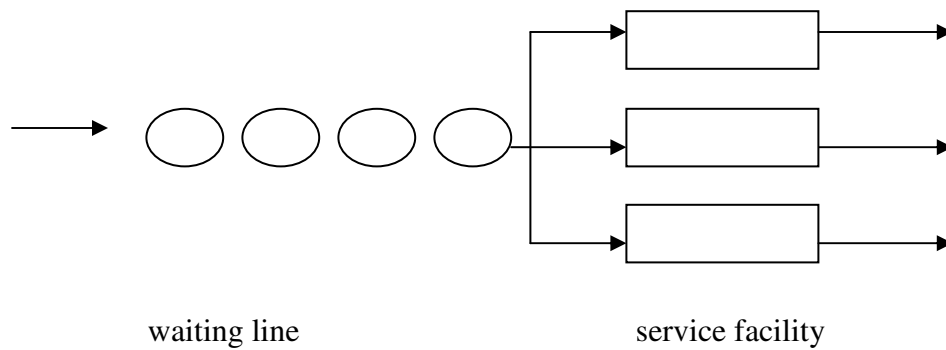
3. The single-channel, multiple-phase case is illustrated by a simple production line where there are a series of operations (phases) and the unit to be processed goes through the series for complete processing.

waiting line   service facility
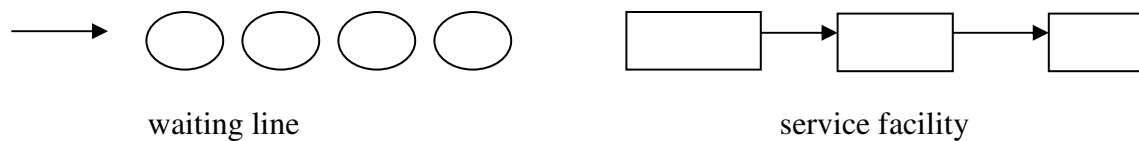
4. The multiple-channel, multiple phase case is illustrated by duplicate production lines in parallel

waiting line   service facility
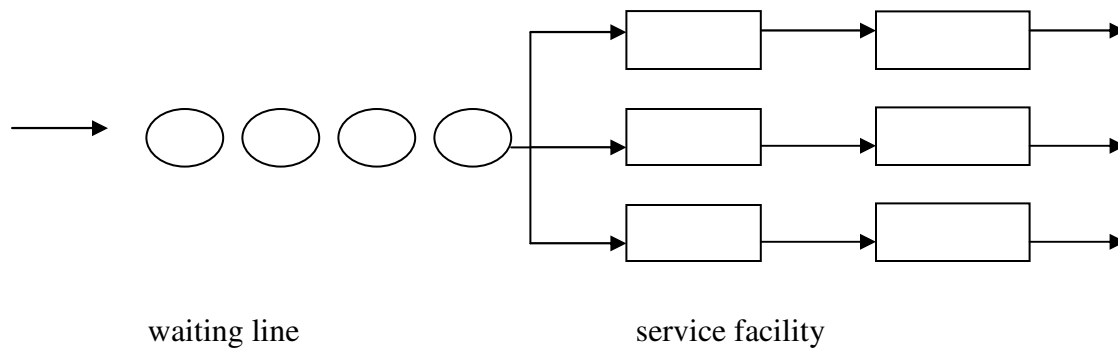
Of course, a complex network of waiting lines could involve combinations of any or all of the four basic structures.

NOTE:

        The layout analysis can effectively utilize queuing theory to find answers to such questions as the following:

        1.How many customers will be waiting in line?

        2.How long will these customers have to wait for service?

3.How many service facilities should be provided to minimize the costs and time involved?
4.How much idle time will the service facilities have?

ANALYTICAL MODELS FOR WAITING LINES

Depending on the size of source population of the inputs, waiting line models are based on whether the waiting line can theoretically become *infinite* or whether conditions limit the maximum waiting line to some *finite* value. Infinite waiting lines might be illustrated by automobile flow on a freeway. Finite waiting lines might be illustrated by the problem of a company with 10 machines, such as looms: a unit "arrives" for service when a thread breaks, or the machine must be stopped for some other reason. The operator gives the needed service and starts the machine again. However, if there are only 10 machines to be serviced, the maximum possible waiting line is 10.

Queue discipline, which is the order in which the units in the waiting line are selected for service, can be "*first-come, first-served (FCFS)* " or based on other priority rules. In a medical clinic, emergencies and patients with appointments are taken ahead of walked-in patients.

NOTE:
The "first-come, first-served" rule is assumed in all four basic models. Because of the mathematical complexity involved, the systems involving queue disciplines other than the FCFS rule are typically analyzed using *Monte Carlo simulation*.

The most common waiting line analyses are based on the assumptions that *arrival rates* are represented by the Poisson distribution and that *service times* are represented by the negative exponential distribution. The formula for the Poisson distribution is:

$$P(x) = \frac{e^{-\lambda}\lambda^x}{x!}$$

where x = the number of units arriving in one unit of time, P(x) = probability of x arrivals, e = a constant, equal to 2.71828, λ = the mean arrival rate, and x! = x(x-1)(x-2)…1. The Poisson is a discrete distribution . The example shown in Figure 2 is smoothed.

The negative exponential distribution corresponds very closely to the Poisson. It is the distribution of the time intervals between arrivals where arrival times are the reciprocal of the arrival rates, and indicates that the intervals of time are also random. The formula for the exponential distribution is:

$$P(t) = e^{-\lambda t}$$

where t = the time between arrivals. An example of a negative exponential distribution is indicated in Figure 3.

FIGURE 2
EXAMPLE OF TYPICAL POISSION DISTRIBUTION OF ARRIVALS

Frequency

Number of Arrivals Per Hour
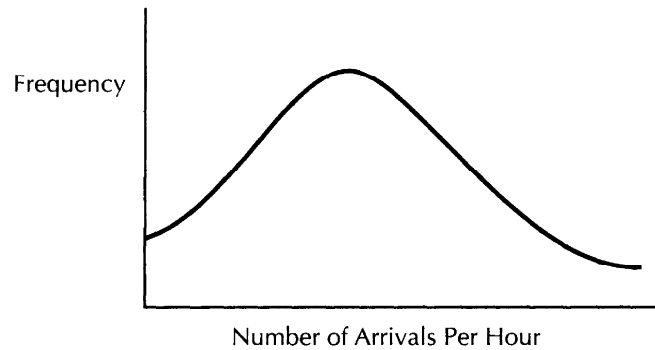
FIGURE 3
EXAMPLE OF TYPICAL NEGATIVE EXPONENTIAL DISTRIBUTION

Frequency

Service Time in Hours
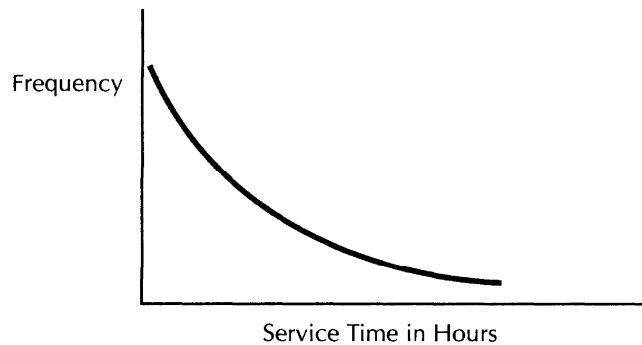
NOTE:
        There are a few other standard distributions for which analytical solutions have been developed. Again, when the distribution assumptions are not valid, it is common to use simulation as the necessary mode of analysis.

QUEUING NOTATIONS

        Define:

λ = the mean arrival rate
μ = the mean service rate
$1/\lambda$ = the mean time between arrivals
$1/\mu$ = the mean time for service
ρ = utilization rate = λ/μ = the expected number being served
P_0 = probability of none in the system = $1 - \lambda/\mu$
P_n = probability of n units in the system at any point in time

L_q = expected number in the waiting line = expected length of the waiting line

L = expected number in the system = expected number in the waiting line plus the expected number being served = $L_q + \lambda/\mu$

W_q = expected waiting time in the queue = $L_q \times 1/\lambda = L_q/\lambda$

W = expected waiting time in the system including service (i.e., total time in the system)
$$= L/\lambda = W_q + 1/\mu$$

The first three models are the case in which arrival units form a waiting line and are serviced by a single service facility. The population source being serviced is unlimited. Model 4 assumes multiple channels. The last model is appropriate when there exits a limited number of customers.

MODEL 1--THE SINGLE-CHANNEL WAITING LINE MODEL WITH POISSON ARRIVALS AND EXPONENTIAL SERVICE TIMES

> Assumptions:
1. Single-channel, single-phase case.
2. Poisson arrival rates.
3. Negative exponential service times.
4. First-come, first-served queue discipline.
5. Mean service rate is greater than mean arrival rate $\mu > \lambda$

Note: if $\mu < \lambda$, for example, 100 customers arrive in line per hour and only 60 are serviced per hour. Accordingly, the queue will expand to infinity during peak periods.

Under these conditions, the following formulas apply.
1. The probability of none in the system = percentage of idle time:

$$P_0 = 1 - \lambda/\mu$$

2. The probability of n units in the system at any point in time:

$$P_n = (\lambda/\mu)^n P_0 = (\lambda/\mu)^n (1 - \lambda/\mu)$$

3. The probability of having to wait = probability of more than zero units in the system:

$$P(w) = 1 - P_0$$

4. The average number of units in the system, including the one being serviced:

$$L = \lambda/(\mu - \lambda)$$

5. The average time a unit spends in the system (waiting time plus service time):

$$W = 1/(\mu - \lambda) = L/\lambda$$

6. The average number of units in the queue waiting for service:

$$L_q = \lambda^2/\mu(\mu - \lambda) = L - \lambda/\mu$$

7. The average time a unit spends in the queue waiting for service:

$$W_q = \lambda/\mu(\mu - \lambda) = L_q/\lambda = W - 1/\mu$$

NOTE:

Formulas used in *operations management* texts can be confusing. We also note the following relationships between W_q and W and L_q and L:

1. W_q =Mean waiting time = L_q/λ
2. L = Mean number in waiting line = $L_q + \lambda/\mu$
3. W = $W_q + 1/\mu = L/\lambda$

These relationships are intuitively obvious, however.

EXAMPLE 1

Downey Bank is contemplating opening a drive-in window for customer service. It is estimated that customers will arrive for service at a rate of 15 per hour. The teller at the service window can serve customers at the rate of one every three minutes. Assuming Poisson arrivals and exponential service the following can be computed:

The utilization rate of the teller = λ/μ = 15/20 = 75 percent

P_0 = probability of none in the system = 1 - λ/μ = 1 -(15/20) = 25 percent

P_n = probability of, say, 2 units in the system at any point in time = $(1 - \lambda/\mu)(\lambda/\mu)^2$ = .25(15/20)^2 = 0.14 = 14 percent L_q = Mean number in waiting line = $\lambda^2/\mu(\mu - \lambda)$ = (15)^2/20(20 - 15) = 2.25 customers

L = Mean number in system, including the one being serviced = $\lambda/(\mu - \lambda)$ = 15/(20 - 15) = 3 customers

W_q =Mean waiting time = $\lambda/\mu(\mu - \lambda)$ = 15/20(20 - 15) = 0.15 hour or 9 minutes

W = Mean time in system, including service = $1/(\mu - \lambda)$ = 1/(20 - 15) = 0.2 hours or 12 minutes

MODEL 2--THE SINGLE-CHANNEL WAITING LINE MODEL WITH POISSON ARRIVALS AND CONSTANT SERVICE TIMES

This model is appropriate for the case of an automobile car wash, an automatic coffee machine in an office building, or a machine-controlled manufacturing operation.

Assumptions:

1. Single-channel, single-phase case.
2. Poisson arrival rates.
3. *Constant* service times.
4. First-come, first-served queue discipline.
5. Mean service rate is greater than mean arrival rate $\mu > \lambda$.

Then the average number in waiting line

$$L_q = \lambda^2/2\mu(\mu - \lambda)$$

W_q =Mean waiting time = L_q/λ

L = Mean number in system, including the one being serviced = $L_q + \lambda/\mu$

W = Mean time in line and service = $W_q + 1/\mu = L/\lambda$

EXAMPLE 2

Rossmore Car Wash is an automatic, five-minute wash operation with a single bay. On a typical Sunday morning, cars arrive at a mean rate of 8 per hour, with arrivals to follow a Poisson distribution. Note that $\lambda = 8$ cars per hour and $\mu = 12$ cars per hour (1 per 5 minutes).

Then the average number in waiting line:
$L_q = \lambda^2/2\mu(\mu - \lambda) = (8)^2/[2((12)(12 - 8)] = .667$ cars

W_q =Mean waiting time = $L_q/\lambda = \lambda/2\mu(\mu - \lambda) = 8/[2((12)(12 - 8)] = .083$ hours or 4.98 minutes

L = Mean number in system, including the one being serviced = $L_q + \lambda/\mu$ = 7.5 + 8/12 = 8.167 cars

W = Mean time in system, including service = $W_q + 1/\mu$ = .083 + .083 = 0.166 hours or 9.96 minutes

MODEL 3--THE SINGLE-CHANNEL WAITING LINE MODEL WITH POISSON ARRIVALS AND SERVICE TIMES NOT SPECIFIED

Assumptions:
1. Single-channel, single-phase case.
2. Poisson arrival rates.
3. Service times not specified.
4. First-come, first-served queue discipline.
5. Mean service rate is greater than mean arrival rate $\mu > \lambda$.

Then the average number in waiting line
$$(\lambda\sigma)^2 + (\lambda/\mu)^2$$

$$L_q = \frac{\text{------------------}}{2(1 - \lambda/\mu)}$$

L = Mean number in system, including the one being serviced $= L_q + \lambda/\mu$

W_q =Mean waiting time $= L_q/\lambda$

W = Mean time in system, including service $= W_q + 1/\mu = L/\lambda$

EXAMPLE 3

Trucks arrive at the truck dock of a wholesale grocer at the rate of 8 per hour and the distribution of arrivals is Poisson. The loading and/or unloading time averages 5 minutes, but the estimate of the standard deviation of service time (σ) is 6 minutes. Truckers are complaining that they must spending more time waiting than unloading and the following information verifies their claim:

$\lambda = 8$ per hour; $\mu = 60/5 = 12$ per hour; $\sigma = 6/60 = 1/10$ per hour

$$L_q = \frac{(\lambda\sigma)^2 + (\lambda/\mu)^2}{2(1 - \lambda/\mu)} = \frac{(8 \times 1/10)^2 + (8/12)^2}{2(1 - 8/12)} = 1.63 \text{ trucks in line}$$

L = Mean number in system, including the one being serviced $= L_q + \lambda/\mu = 1.63 + 8/12 = 2.3$ trucks in the system

W_q =Mean waiting time $= L_q/\lambda = 1.63/8 = 0.204$ hours, or 12.24 minutes in line waiting for service

W = Mean time in system, including service $= L/\lambda = 2.3/8 = 0.288$ hours, or 17.28* minutes in the system. Note also that $W = W_q + 1/\mu = 0.204$ hours + 1/12 hours = 12.24 minutes + 5 minutes = 17.24* minutes.

Note: the discrepancy between 17.28 and 17.24 is due to rounding errors.

MODEL 4--THE MULTIPLE-CHANNEL WAITING LINE MODEL WITH POISSON ARRIVALS AND EXPONENTIAL SERVICE TIMES

The multiple-channel model is appropriate for the case of a toll road pay booth, bank teller window, and maintenance repair shop.

1. Multiple-channel.
2. Poisson arrival rates and exponential service times.
3. Services all work at the same rate.
4. Customers form a single waiting line in order to maintain first-come, first-served processing.

The utilization rate = the expected number being served:

$\rho = \lambda/M\mu$ where M = number of servers (channels)

$$L_q = \frac{\lambda\mu(\lambda/\mu)^M}{(M-1)!(M\mu-\lambda)^2} P_0$$

The computation is very complicated. The procedure is to go to Table 2 (Infinite-Source Values for L_q and P_0 given = λ/μ and M) with $\rho = \lambda/\mu$ and M.

EXAMPLE 4

Using the data from Example 2, consider the characteristics of the process if a second office is added. Each office can process 5 patients per hour, on average. Note $M = 2$ and λ/μ = .8. From the table we see L_q = .152 and P_0 = .429. We can determine the following:

W_q = Mean waiting time = L_q/λ = .152/4 = .038 hours

L = Mean number in system, including the one being serviced = $L_q + \lambda/\mu$ = .152 + .8 = .952 patients

W = Mean time in system, including service = $W_q + 1/\mu$ = L/λ = 0.952/4 = 0.238 hours

In Example 2, the expected time lost waiting one day with one office was 76.8 hours. With two offices, it is 3.65 hours (4 x 24 x .038). Again assuming a cost of $15 for each hour, the average cost of waiting per day is $54.75, which means a saving in expected cost of $1,097.25 ($1,152 - $54.75). If the cost of adding the second office is less than $1,097.25, then the decision should be to go from one to two offices.

QUESTIONS
1. How many waiting lines can be encountered during an airline flight?
2. List the most common measures of system performance in a waiting line analysis.
3. Waiting line can form even when a service system is underloaded. Do you agree?
4. Briefly describe the major cost trade-off that must be made in managing queuing situations.
5. List the assumptions underlying Queuing Model 1 - Single Channel, Exponential Service Time.
6. Give an example where the first-come, first-service rule would be unfair.
7. Explain what is meant by an exponential service time. Provide an example of each of an exponential service time and a constant service rate.
8. Give an example of Poisson arrival rates.
9. Distinguish between *finite* and *infinite* population sources.

PROBLEMS
1. On the average 100 students arrive at the cashier's office each hour; on the average the cashier's office can process 120 students per hour. Assume that arrivals are Poisson-distributed and service times are exponentially distributed.
    (a) What is the probability that the system will be idle?

(b) On the average, how many students will be waiting to be served?
(c) On the average, how long will a student wait in line before meeting the cashier?
(d) On the average, how much time will the student spend waiting and negotiating with the cashier?

TABLE 2
INFINITE-SOURCE VALUES FOR L_q AND P_0 GIVEN $= \lambda/\mu$ AND M

ρ	M	L_q	P_0	ρ	M	L_q	P_0	ρ	M	L_q	P_0
0.15	1	0.026	0.850		3	0.094	0.294		5	0.130	0.080
	2	0.001	0.860		4	0.016	0.300		6	0.034	0.082
0.20	1	0.050	0.800		5	0.003	0.301		7	0.009	0.082
	2	0.002	0.818	1.3	2	0.951	0.212	2.6	3	4.933	0.035
0.25	1	0.083	0.750		3	0.130	0.264		4	0.658	0.065
	2	0.004	0.778		4	0.023	0.271		5	0.161	0.072
0.30	1	0.129	0.700		5	0.004	0.272		6	0.043	0.074
	2	0.007	0.739	1.4	2	1.345	0.176		7	0.011	0.074
0.35	1	0.188	0.650		3	0.177	0.236	2.7	3	7.354	0.025
	2	0.011	0.702		4	0.032	0.245		4	0.811	0.057
0.40	1	0.267	0.600		5	0.006	0.246		5	0.198	0.065
	2	0.017	0.667	1.5	2	1.929	0.143		6	0.053	0.067
0.45	1	0.368	0.550		3	0.237	0.211		7	0.014	0.067
	2	0.024	0.633		4	0.045	0.221	2.8	3	12.273	0.016
	3	0.002	0.637		5	0.009	0.223		4	1.000	0.050
0.50	1	0.500	0.500	1.6	2	2.844	0.111		5	0.241	0.058
	2	0.033	0.600		3	0.313	0.187		6	0.066	0.060
	3	0.003	0.606		4	0.060	0.199		7	0.018	0.061
0.55	1	0.672	0.450		5	0.012	0.201	2.9	3	27.193	0.008
	2	0.045	0.569	1.7	2	4.426	0.081		4	1.234	0.044
	3	0.004	0.576		3	0.409	0.166		5	0.293	0.052
0.60	1	0.900	0.400		4	0.080	0.180		6	0.081	0.054
	2	0.059	0.538		5	0.017	0.182		7	0.023	0.055
	3	0.006	0.548	1.8	2	7.674	0.053	3.0	4	1.528	0.038
0.65	1	1.207	0.350		3	0.532	0.146		5	0.354	0.047
	2	0.077	0.509		4	0.105	0.162		6	0.099	0.049
	3	0.008	0.521		5	0.023	0.165		7	0.028	0.050
0.70	1	1.633	0.300	1.9	2	17.587	0.026		8	0.008	0.050
	2	0.098	0.481		3	0.688	0.128	3.1	4	1.902	0.032
	3	0.011	0.495		4	0.136	0.145		5	0.427	0.042
0.75	1	2.250	0.250		5	0.030	0.149		6	0.120	0.044
	2	0.123	0.455		6	0.007	0.149		7	0.035	0.045
	3	0.015	0.471	2.0	3	0.889	0.111		8	0.010	0.045
0.80	1	3.200	0.200		4	0.174	0.130	3.2	4	2.386	0.027
	2	0.152	0.429		5	0.040	0.134		5	0.513	0.037
	3	0.019	0.447		6	0.009	0.135		6	0.145	0.040
0.85	1	4.817	0.150	2.1	3	1.149	0.096		7	0.043	0.040
	2	0.187	0.404		4	0.220	0.117		8	0.012	0.041
	2	0.024	0.425		5	0.052	0.121	3.3	4	3.027	0.023
	4	0.003	0.427		6	0.012	0.122		5	0.615	0.033
0.90	1	8.100	0.100	2.2	3	1.491	0.081		6	0.174	0.036
	2	0.229	0.379		4	0.277	0.105		7	0.052	0.037
	3	0.030	0.403		5	0.066	0.109		8	0.015	0.037
	4	0.004	0.406		6	0.016	0.111	3.4	4	3.906	0.019
0.95	1	18.050	0.050	2.3	3	1.951	0.068		5	0.737	0.029
	2	0.277	0.356		4	0.346	0.093		6	0.209	0.032
	3	0.037	0.383		5	0.084	0.099		7	0.063	0.033
	4	0.005	0.386		6	0.021	0.100		8	0.019	0.033
1.0	2	0.333	0.333	2.4	3	2.589	0.056	3.5	4	5.165	0.015
	3	0.045	0.364		4	0.431	0.083		5	0.882	0.026
1.1	4	0.007	0.367		5	0.105	0.089		6	0.248	0.029
	2	0.477	0.290		6	0.027	0.090		7	0.076	0.030
	3	0.066	0.327		7	0.007	0.091		8	0.023	0.030
	4	0.011	0.367	2.5	3	3.511	0.045		9	0.007	0.030
1.2	2	0.675	0.250		4	0.533	0.074	3.6	4	7.090	0.011

2. A retailer is evaluating two alternative cash register systems. It is expected that the firm will have about 2,500 customers per hour to service, and that ill will caused by waiting costs is about $2 per hour per customer. Given:

System I	System II
$\mu = 2,800$ per hour	$\mu = 3,500$ per hour
Operating costs: $100 per hour	Operating costs: $125 per hour

Which system should be recommended?

3. Demands on a fork lift truck are considered to be Poisson, with an average time of 10 minutes between one arrival and the next ($1/\lambda = 10$). The length of time a truck is used is assumed to be distributed exponentially, with a mean of 3 minutes ($1/\mu = 3$).
(a) What is the probability that a person requiring a truck will have to wait?
(b) What is the average length of the queues that form from time to time?
(c) The company will buy a second truck when convinced that an arrival would expect to have to wait at least 3 minutes for the truck. By how much must the flow of arrivals be increased in order to justify a second truck?

4. A company wishes to hire a repairman to service its machines which beak down at an average rate of 3 per hour. Breakdowns occur at random times which are distributed Poisson. Downtime on any one machine costs the company $30 per hour. The choice of a repairmen has been narrowed to two men--one slow but cheap, the other fast but expensive. The slow, cheap repairman will repair the broken-down machines exponentially at an average rate of 4 per hour; he asks for wages of $10 per hour. The fast, expensive repairman will repair broken-down machines exponentially at an average rate of 6 per hour, and demands $20 per hour. Which repairman should the company hire to minimize the average costs of downtime and repair on the machines?

5. You are planning to construct an automatic car wash. The traffic count and market study suggest that a mean arrival rate of 6 cars per hour can be expected. You can buy either of two automatic washers: one with a constant service time of 5 minutes (12 washes per hour) and a more expensive one with a constant service time of 4 minutes (15 washes per hour). You have established a criterion that the mean waiting time to get into the wash area should not be more than 2 minutes and will buy the slower machine if it meets this criterion. Which machine should you buy?

6. A community hospital is served by a single ambulance based at the hospital. During peak periods the call rate averages 3 per hour (Poisson distribution) and the average service time is 15 minutes with a standard deviation of 5 minutes. Compute: (a) the average number of emergencies waiting during peak demand. (b) the average number of emergencies in the

system. (c) the average time waiting for service. (d) the average waiting time, including service.

7. Customers filter into Tour Records at an average of 1 per minute (Poisson) where the service rate is 15 per hour. Determine the following:
   (a) The average number of customers in the system with 8 servers.
   (b) The minimum number of servers needed to keep the average time in the system to under 6 minutes.

ANSWERS

1. Baggage check-in at the ticket counter, security check, check-in at gate, at boarding, and baggage pickup.
2. Common system performance measures include: the average number waiting, either in line or the system and system utilization rate. Furthermore, total cost of waiting time and facility expansion is important.
3. Yes. It may be due to variations in service and/or arrival rates which creates situations in which demand temporarily exceeds capacity.
4. The trade-off is between the cost of waiting for service and the cost of providing additional service capacity.
5. The assumptions are Poisson arrival rates and exponential service rates.
6. The first-come, first-served rule would be the exception rather than the rule in an emergency room at a hospital. This rule would be unfair when a patient with a minor problem is treated before another experiencing severe pain or wounds.
7. An exponential service time implies that most of the time the service requirements are of short duration with only occasional long ones. It also means that the chance that a service will be complete in the next instant of time is not dependent on the time at which it entered the system. Buying an airline ticket at the airport is an example of an exponential service time. Riding a merry-go-round at a theme park is an example of a constant service rate since it has a fixed cycle.
8. In a marathon, the arrival pattern typically shows a few runners arriving "early," the majority arriving in a bunch, and the remainder spreading out along the tail of the distribution.
9. A finite source exists when the system caters to a small, limited number of potential customers. An infinite source model applies when system entry is unrestricted, or when the potential number of arrivals exceeds the system capacity.

PROBLEMS

1.
(a) $P_0 = 1 - \lambda/\mu = 1 - 100/120 = 0.167 = 16.7$ percent of the time
(b) $L_q = \lambda^2/\mu(\mu - \lambda) = (100)^2/120(120 - 100) = 10,000/2,400 = 4.17$, or 4 students
(c) $W_q = \lambda/\mu(\mu - \lambda) = 100/120(120 - 100) = 100/2,400 = 1/24$ hour, or 2.5 minutes
(d) $W = 1/(\mu - \lambda) = 1/(120 - 100) = 1/20$ hour, or 3 minutes
2.
For System I:
$\lambda = 2,500$ and $\mu = 2,800$ per hour
$W = 1/(\mu - \lambda) = 1/(2,800 - 2,500) = 1/300$ hour, or 0.0033 hours (0.2 minutes or 12 seconds)
The average hourly cost of ill will = 2,500 (0.0033) ($2) = 16.50

Operating cost =   100.00
          Total System I cost $116.50
For System II:
No need to calculate cost of ill will since operating costs alone for System II are already greater than total costs for System I ($130 vs. $116.50). So System I should be recommended.

3.
$\lambda = 6$ per hour and $\mu = 20$ per hour
     (a)   The probability of having to wait = probability of more than zero units in the system:
$P(w) = 1 - P_0 = \lambda/\mu = 6/20 = 0.3$
     (b)   The average number of units in the system, including the one being serviced:
$L = \lambda/(\mu - \lambda) = 6/(20 - 6) = 0.43$ units
     (c)   Given average waiting time of at least 3 minutes or 1/20 hour., solve for λ
$W_q = \lambda/\mu(\mu - \lambda)$
$1/20 = \lambda/20(20 - 6)$
$\lambda = 10$ arrivals per hour. Arrival rate must increase from 6 to 10.

4.
$\lambda = 3$ per hour = arrival (breakdown) rate
$\mu_s = 4$ per hour = service (repair) rate, slow repairman
$\mu_f = 6$ per hour = service (repair) rate, fast repairman
Wages, fast repairman = $15 per hour
Wages, slow repairman = $10 per hour
Downtime cost, machines = $20 per hour
The average number of units in the system, including the one being serviced:
Slow repairman: $L_s = \lambda/(\mu - \lambda) = 3/(4 - 3) = 3$ units
Fast repairman: $L_f = \lambda/(\mu - \lambda) = 3/(6 - 3) = 1$ unit
Average hourly cost = wages plus downtime
Slow repairman: $10 + 3($30) = $100
Fast repairman: $20 + 1($30) = $50
Fast repairman should be hired to minimize costs of downtime and repair on the machines.

5.
For the slower washer the mean waiting time in the queue will be
$W_q = L_q/\lambda = \lambda/2\mu(\mu - \lambda) = 6/[2(12)(12 - 6)] = 6/24(6) = 0.0417$ hour or 2.5 minutes
For the faster washer the waiting time in the queue will be
$W_q = 6/[2(15)(15 - 6)] = 6/30(9) = 0.0222$ hour or 1.33 minutes
Therefore, you should buy the faster washing equipment.

6.
$\lambda = 3$ per hour; $\mu = 60/15 = 4$ per hour; $\sigma = 5/60 = 1/12$ per hour
(a)
$$L_q = \frac{(\lambda\sigma)^2 + (\lambda/\mu)^2}{} = \frac{(3 \times 1/12)^2 + (3/4)^2}{} = 1.25 \text{ emergencies in line}$$

$$\frac{}{2(1 - \lambda/\mu)} \qquad \frac{}{2(1 - 3/4)}$$

(b) L = Mean number in waiting line = $L_q + \lambda/\mu$ = 1.25 + 3/4 = 2 emergencies in the system

(c) W_q =Mean waiting time = L_q/λ = 1.25/3 hours, or 25 minutes in line waiting for service

(d) W = Mean time in system, including service = L/λ = 2/3 hours, or 40 minutes in the system. Note also that W = $W_q + 1/\mu$ = 1.25/3 hours + 1/4 hours = 25 minutes + 15 minutes = 40 minutes.

7.

(a) λ = 60 per hour; μ = 15 per hour.

With $\rho = \lambda/\mu$ = 60/15 = 4 and M= 8

From Table 2 (infinite-Source Values) we see L_q = 0.059.

L = Mean number in system, including the one being serviced = $L_q + \lambda/\mu$ = .059 + 4 = 4.059 customers

(b)

M	Average time in system	
8	4.059	
7	4.180	
6	4.570	(6 servers needed)
5	6.216	

CHAPTER 13
QUALITY CONTROL AND CONTINUOUS IMPROVEMENT

LEARNING OBJECTIVES:

After Studying this chapter you will be able to:

1. Conduct a Pareto analysis.
2. Initiate a statistical control analysis.
3. Develop a control chart.
4. Compute the means and the range.
5. Distinguish between the producer's risk and the consumer's risk.
6. Explain the Operating Characteristic (OC) curve.
7. Develop a sampling plan.
8. Discuss the acceptance sampling technique.
9. Calculate the average outgoing quality (AOQ)
10. Compute the average outgoing quality limit (AOQL).
11. Determine the acceptable quality level (AQL).
12. Explain and discuss the lot tolerance percent defective (LTPD).

In Chapter 1 we discussed the importance of quality and outlined the role of quality assurance in productions/operations management. Designing quality into products or services is an important strategic aspect in P/OM. Quality assurance involves all of the activities necessary to ensure that the customer receives satisfactory performance, including assurance that the product or service is adequately designed and conforms to the design.

Inspection is the major means of determining quality of conformance. In general, sampling, either by variables or by attributes, may be employed in situations that are less critical or where testing is expensive or destructive. Statistical sampling or statistical quality control may be used for acceptance sampling or for process control. Acceptance sampling is used to infer the acceptability of the particular lot or batch from which the sample was extracted. Process control applications are employed to infer whether the process or operations are being performed adequately. In this chapter, we discuss several quality-control techniques and address the operational aspect of quality control.

PARETO ANALYSIS
Pareto analysis is used to differentiate between *the vital few* and *the trial many*. It is based on the concept that about 80 percent of the problems come from 20 percent of the items. We would expect to find *a few vital sources* that primarily contribute to costs, rather than the *many trivial sources* that contribute much less to costs. Quality costs are not uniformly distributed. Almost without exceptions, only a few of the sources account for the bulk of the costs. This "misdistribution" of quality costs is often referred to in quality diagnosis as a Pareto analysis.

Under Pareto analysis, a bar chart is constructed, with bar height representing frequency as a percentage (see Figure 1). The bars are arranged in descending order by weight (importance). Pareto analysis shows where process improvements should begin--those problem areas with the greater frequency.

STATISTICAL QUALITY CONTROL

The statistical control chart has been developed in the field of statistical quality control (SQC). The control charts use samples as a way of isolating operating situations that need managerial investigation. A control chart is illustrated in Figure 2. Assume that average performance for assembling a finished unit is 10.5 minutes, that the upper control limit (UCL) is 13 minutes, and that the lower control limit (LCL) is 8 minutes.

The control charts help distinguish between chance variances (also called *random causes*) from variances that need investigation (often called *assignable causes*). The analysis of the latter helps to obtain improvements in products and processes. The identification of chance variances avoids unnecessary investigations of variances and eliminates frequent changes (for example, machine settings) that may tend to increase rather than decrease the variability of the process.

FIGURE 1
PARETO CHART: OCCURRENCE OF ERRORS

FIGURE 2
CONTROL CHART

Upper Control Limit
(13 minutes)

Average Performance
(10.5 minutes)

Lower Control Limit
(8 minutes)

Sample Number

"Out of Control"—
Abnormal performance

"In Control"—Band of
Acceptable performance

"Out of Control"—
Abnormal performance
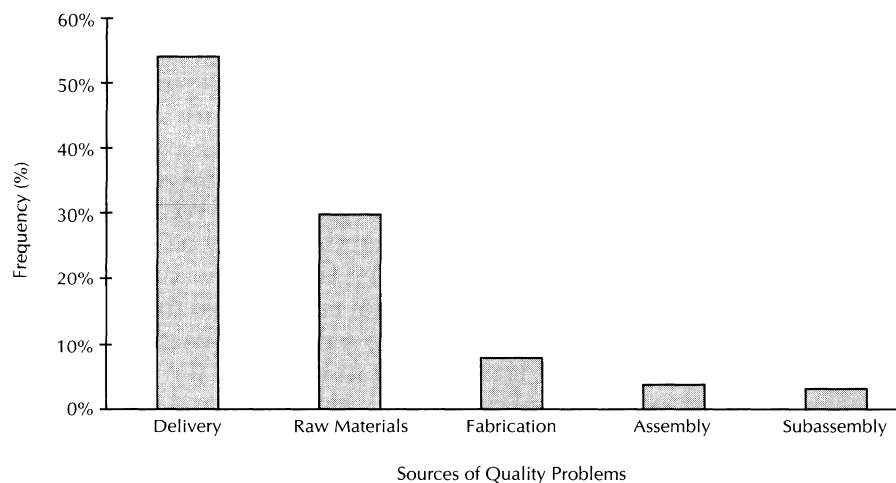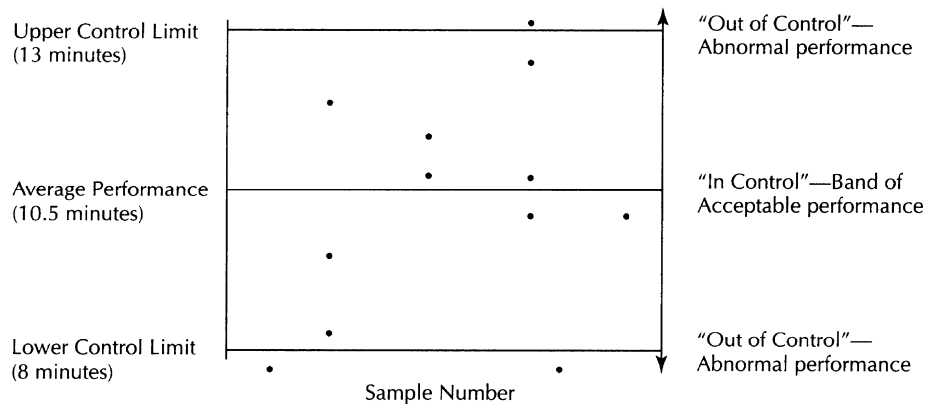
Statistical control charts are applicable to any repetitive manufacturing or nonmanufacturing operations. Examples include billing, filling containers, boring, turning, stamping, using materials and supplies, printing, customer complaints, sales returns, orders received, travel expenses, and the like. The intent of quality control is to ensure that goods and services conform to the design specifications. Whether the focus is on feedforward, feedback, or concurrent control, the emphasis is on ensuring product or service conformity.

Note that the control chart is very crude. The chart suggests that the manager do either something or nothing. It does not tell the manager what to do about the nonrandom variances or how to investigate them. A major deficiency of the traditional control process is that it does not focus on improving the entire production process.

STATE OF STATISTICAL CONTROL

The control chart helps to decide whether a process (operation) is in a *state of statistical control. A process is said to be in a state of statistical control if the variation is such as would occur in random sampling from some stable population*. If this is the case, the variation among the items is attributable to chance—it is inherent in the nature of the process. There is no point in seeking special causes for individual cases, because random variations are beyond management's ability to regulate or eliminate. With a given process and a given state of knowledge about the process, this chance variation is either impossible or impracticable to reduce. If the performance of a process is considered to be unsatisfactory even though it is statistically in control, the only remedy is some change in the process.

The probability is small that a point will fall outside the control limits from chance causes alone; so it is concluded that the process is out of control when this occurs. When the process is out of control, it is often possible to locate specific causes for the variation. Removal of these causes improves the future performance of the process.

CONTROL CHARTS FOR MEANS

The sample mean can be an indicator of a shift in the pattern of variations. As long as the sample means remains within the control limits, the process is assumed to be in control. The distribution is continuing to show only the normal variations which result from chance causes.

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It is necessary to select a variable to sample that will give the best indication of the effects of an out-of-control condition. The variable selected (usually a specific dimension from among many for a product) is the one that management believes will have the most direct cost relationship to the level of quality. The determination of the frequency and size of the sample is also an important consideration. In constructing control charts for variables, the initial samples used for setting the control limits should be selected at the outset of the run from items produced consecutively. The following samples should be taken at random intervals from items produced consecutively just prior to their selection.

The determination of the control limits is a simple process. The UCL and the LCL can be computed from equations that require little calculation. The equations for the mean or X (X bar) control chart are as follows:

$$UCL\overline{X} = \overline{\overline{X}} + A_2 \overline{R} \qquad (1)$$

$$LCL\overline{X} = \overline{\overline{X}} - A_2 \overline{R} \qquad (2)$$

Where:
$\overline{\overline{X}}$ = the grand mean. This is the mean of the means of the preliminary samples
A_2 = a constant
$\overline{R}$ = the average range of the preliminary samples

The value of A_2, and other applicable constants used for X and R charts are found in Table 1.

TABLE 1
TABLE OF CONSTANTS FOR X AND R CHARTS

n	A_2	D_3	D_4
2	1.880	0	3.268
3	1.023	0	2.574
4	.729	0	2.282
5	.577	0	2.114
6	.483	0	2.004
7	.419	.076	1.924
8	.373	.136	1.864
9	.337	.184	1.816
10	.308	.223	1.777

To illustrate, the data in Table 2 are from ten samples of three pieces each. The values are the deviations from a selected dimension of .990 inches.
From these data the control limits for this process can be computed and a control chart constructed. The computations follow:

$$\overline{\overline{X}} = 103.00/\ 10 = 10.30$$

and:

$$\overline{R} = 88/10 = 8.80$$

TABLE 2
RESULTS OF TEN SAMPLES OF THREE EACH
TAKEN FROM OUTPUT
(VALUES IN .001" DEVIATIONS FROM .990")

Sample	Values			Mean	Range
1	4	6	5	5.00	2
2	9	13	5	9.00	8
3	6	11	15	10.67	9
4	18	10	7	11.67	11
5	19	15	21	18.33	6
6	9	6	19	11.33	13
7	18	12	2	10.67	16
8	9	8	10	9.00	2
9	6	17	7	10.00	11
10	6	3	13	7.33	10
Totals				103.00	88

The control limits are then:

$$UCL\overline{X} = \overline{\overline{X}} + A_2\overline{R}$$
$$= 10.30 + (1.023)(8.80)$$
$$= 19.30 \qquad \text{and}$$

$$LCL\overline{X} = \overline{\overline{X}} - A_2\overline{R}$$
$$= 10.30 - (1.023)(8.80)$$
$$= 1.30$$

FIGURE 3
CONTROL CHART FOR SAMPLE MEANS

```
Sample No. 1    2   3   4   5   6   7   8   9   10
       20.00  ─────────────────────────────────   UCL = 19.30
                                •


                        •
                             •      •   •
       11.00  ──────────•──────────•────────────   X̄ = 19.30
                    •                  •
                        •                •
                                        •



        5.00    •



        2.00  ─────────────────────────────────   LCL = 1.30
        1.00
```
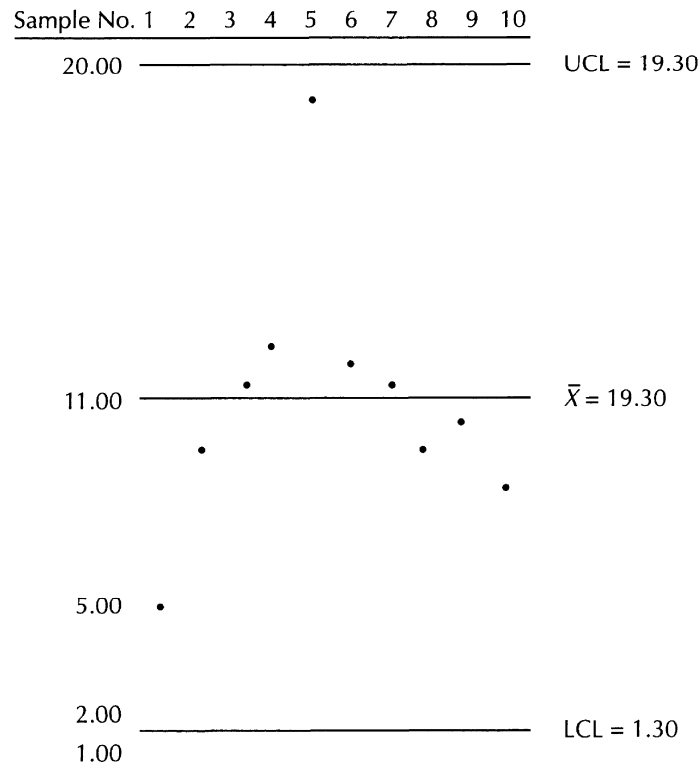
It is now possible to draw the control chart for the means of these samples. This control chart is shown in Figure 3. As can be seen, at this stage the process is under control. If one of the sample means was outside of the control limits this would not be true. Note that the control limits in the chart are not the limits permitted by the designer's specifications or tolerances. The control limits established for the mean are narrower than the tolerance limits.

CONTROL CHARTS FOR RANGES

This form of control chart can be used to determine any shift in the amount of variation which may take place. The range chart or R chart is used to plot the difference between the highest value and the lowest value in each sample. The plot of the range is made at the same time as the sample mean is plotted on the X chart. If the sample ranges stay within the control limits, the process is considered to be in control as far as the variability is concerned. The control limits here are the upper range limit (URL) and the lower range limit (LRL). They are also identified as UCL_R and LCL_R. The LRL is often identified as 0 (zero) since for sample sizes of six or fewer it is always zero. This value results from the fact that the value of the constant used is zero for these sample sizes.

The computation of the range chart control limits is accomplished in a similar fashion to that which was used for the mean chart. The equations are:

$$URL = D_4 \overline{R} \qquad\qquad (3)$$

$$LRL = D_3 \overline{R} \qquad\qquad (4)$$

The symbols D_3 and D_4 are constants whose values are found in Table 1. Note the values for D_3 are zero for sample sizes of six or fewer. This accounts for the zero value of the LRL in such instances.

The computation of the control limits for an R chart and the construction of such a chart can be illustrated with the data found in Table 2. The mean range was computed in the illustration for the X chart. It is:

$$\overline{R} = 88/10 = 8.80$$

The computations for the establishment of the control limits are as follows:

$$URL = D_4 \overline{R}$$
$$= (2.574)(8.80)$$
$$= 22.65$$

$$LRL = D_3 \overline{R}$$
$$= (0)(8.80)$$
$$= 0$$

The sample ranges can now be plotted on the control chart in Figure 4. The process is also found to be in control as regards to variability since none of the sample ranges is outside of the control limits.

These types of process control charts supply instantaneous information about the expected pattern of variation. When a point is beyond the control limits, it is a signal that a problem may be present. Since all of the points in the example used were inside of the limits for both the means and the ranges, it can be assumed that these limits are suitable for control purposes.

Additional samples can be taken and plotted at the desired time intervals. If there is a change in the processing methods, in the material, in the design specifications, or some other variable in the system, it would be necessary to compute new limits.

Had there been some points beyond the control limits in these initial samples, it would have been necessary to find the cause. Once found and eliminated (this assumes they can be eliminated economically), proper new limits would have to be established. Only then can management presume that the process is in control.

FIGURE 4
CONTROL CHART FOR SAMPLE RANGES

```
Sample No. 1   2   3   4   5   6   7   8   9   10

    20.00  ─────────────────────────────  URL = 22.65

    15.00

    10.00  ─────────────────────────────  R̄ = 8.80

     5.00

     0.00  ─────────────────────────────  LRL = 0
```
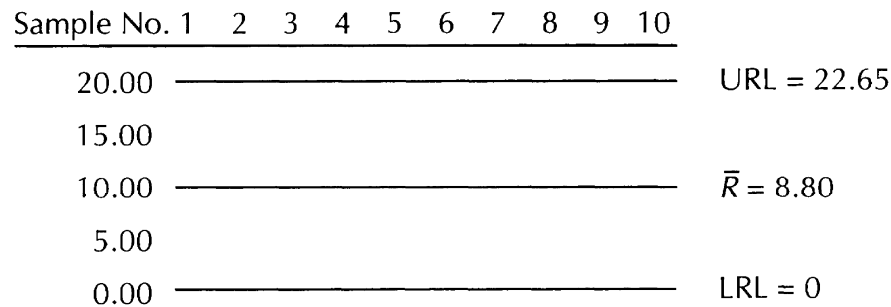
ACCEPTANCE SAMPLING FOR ATTRIBUTES

Acceptance sampling for attributes deals with inspection for the purpose of determining whether a unit of output is defective or nondefective. The unit selected may be anywhere from a single item, some portion or component of the item of output, the entire order, the output of some period of time, or a total shipment.

Design of Acceptance Sampling Plans

The prime purpose of an acceptance sampling plan is to determine the extent of nonconformity which is acceptable for the unit of output of concern. This nonconformity is usually expressed as a proportion of defectives in the unit: most frequently, the percent defectives, using the equation:

$$\text{Percent defectives} = \frac{\text{Number of defectives}}{\text{Number of units}}$$

A distinction is sometimes made between defectives and defects. A unit is defective if it has one or more defects. When a sampling plan is designed to determine defects, the proportion of nonconformity is stated as the defects-per-hundred units, expressed as:

$$\text{Defects-per-hundred units} = \frac{\text{Number of defects}}{\text{Number of units}}$$

Any acceptance sampling plan should be designed to avoid two basic errors. The first error to be avoided is the acceptance of output as satisfactory when in fact it is unacceptable. The second error to avoid is the rejection of a lot as unacceptable which is of an acceptable quality.

OPERATING CHARACTERISTIC (OC) CURVE

We may find the probability of acceptance for every possible value of the true percentage of defective items and plot the curve. This is called an *operating characteristic curve* (OC curve). OC curves are unique for a specific sampling plan and enable us to determine the producer's and consumer's risks. To do this, we need to specify an *acceptable quality level*

(AQL) and *lot tolerance percent defective* (LTPD). The AQL is the maximum percent defective that is considered acceptable. For example, a company may be willing to accept lots with 2 percent defective. The LTPD is the percent defective associated with what is considered to be a bad lot. For example, 10 percent defective may be considered "bad" for a particular application. Not all lots with AQL values will be accepted, nor will all lots with LTPD values be rejected every time. The producer would like good lots accepted with a high probability. The consumer would like to reject bad lots most of the time; thus the consumer wishes to have a low probability of accepting bad lots.

Suppose a company specifies AQL = 2 percent and LTPD = 10 percent. From the OC curve in Figure 5 we see that if the percent defective is actually 2 percent, the probability of acceptance is approximately .82. Thus the probability of rejecting this good lot is 1 - .82 = .18. This is the producer's risk. On the other hand, if the actual percent defective is 10 percent (LTPD), then the probability of acceptance is about .35. This represents the consumer's risk.

The *producer's risk* (α) is identified as the probability that output of the level of AQL will be rejected. The probability that a bad lot of the level of LTPD will be accepted is identified as *the consumer' risk* (β). The terms defined above and general relationships among them can be seen in the operating characteristic curve illustrated in Figure 5.

As AQL decreases, so does α the probability of rejecting a good lot. Similarly, as LTPD increases, then β--the probability of accepting a bad lot—decreases. The AQL is mutually agreed between the producer and consumer and is a useful negotiating tool in purchase contracts. A smaller AQL reduces the producer's risk but also requires tighter control in manufacturing. Thus economic analysis is important in determining quality specifications and contracts.

How is a sampling plan actually chosen? Note that there is a unique OC curve for every value of the size of the sample (n) and the value of the acceptance number (c). Therefore, to determine an appropriate plan, the quality-control supervisor must choose AQL, LTPD, α, and β. For Figure 5, we see that these values specify two points on the graph, i.e., (AQL, 1 - α) and (LTPD, β). There is a unique OC curve that passes through these two points. The value of n and c for this curve determine the sampling plan.

FIGURE 5
OPERATION CHARACTERITIC CURVE FOR SAMPLING PLAN
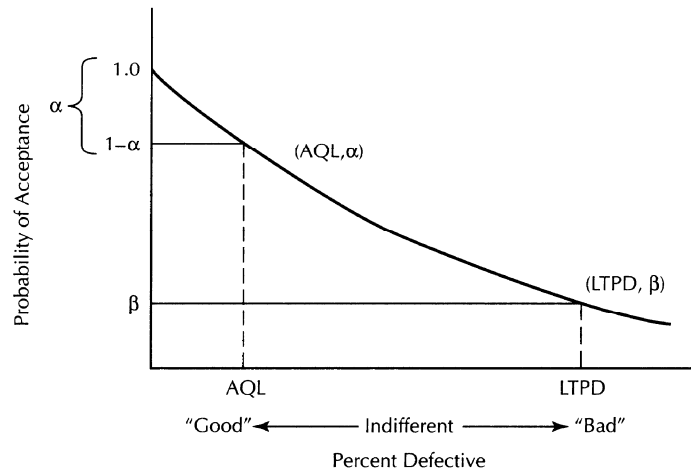
EXAMPLE 1

Suppose a quality control manager specifies AQL = 3%, LTPD = 15%, α = .25 (1 - α = .75), and β = .2. Finding the two points (3%, .75) and (15%, .2) in Figure 6, we see that the OC curve corresponding n = 10, c = 0 passes through these points. Thus n = 10, c = 0 is the appropriate sampling plan to choose.

Note: Fortunately, there is no need to plot all possible OC curves to select a sampling plan. Published tables are available to choose one. Refer to MIL-STD-105D, Sampling Procedures and Tables for Inspection by Attributes published by the Office of the Assistant Secretary of Defense, 1963 for government contract work.

Portion of a Cumulative Binomial Distribution Table (Table 5 from the Appendix)						
Sample size =10				*Sample size = 15*		
Number of defectives = c						
p	0	1		p	0	1
0.000	1.000	1.000		0.000	1.000	1.000
0.050	0.599	0.914		0.050	0.463	0.829
0.100	0.349	0.736		0.100	0.206	0.549
0.150	0.197	0.544		0.150	0.087	0.319
0.200	0.107	0.376		0.200	0.035	0.167
0.250	0.056	0.244		0.250	0.013	0.080
0.300	0.028	0.149		0.300	0.005	0.035
0.350	0.014	0.086		0.350	0.002	0.001
0.400	0.006	0.046		0.400	0.001	0.005

0.450	0.003	0.023		0.450	0.000	0.002
0.500	0.001	0.011		0.500	0.000	0.001
0.550	0.000	0.005		0.550	0.000	0.000
0.600	0.000	0.002		0.600	0.000	0.000
0.650	0.000	0.001				

FIGURE 6

ALTERNATE SAMPLING PLANS
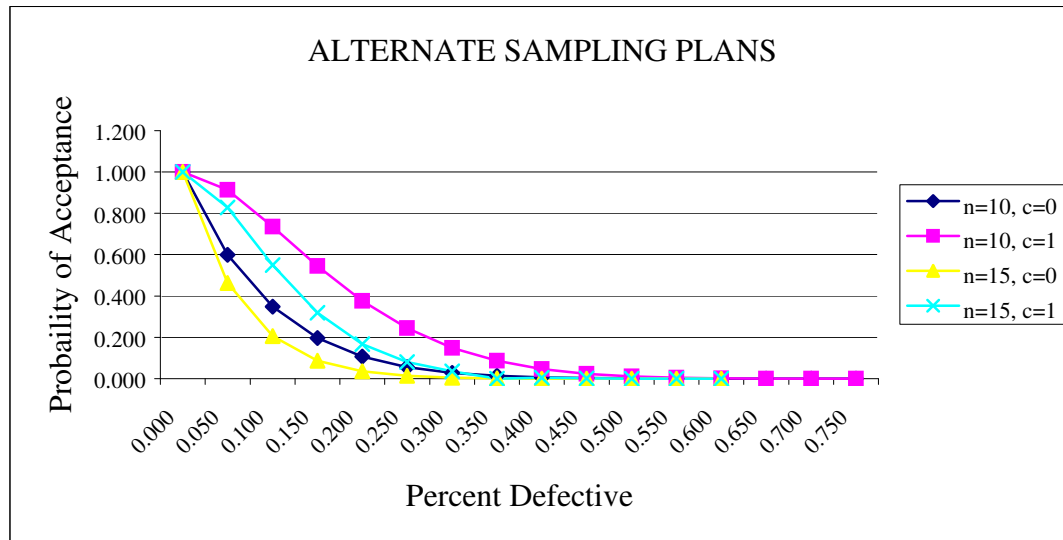
NOTE:
Four important definitions which in fact are the bases for specifying a given sampling plan. They are as follows:
1. AQL = Acceptable quality level. Lots at this level of quality are regarded as good, and we wish to have a high probability of acceptance.
2. α = Producer's risk—the probability that lots of the quality level AQL will be rejected. Usually, α = 1-5 percent. If a good lot is rejected, we refer to this as a type I error.
3. LTPD = Lot tolerance percent defective—the dividing line selected between good and bad lots. Lots at this level of quality are regarded as poor, and we wish to have a low probability for their acceptance.
4. β = Consumer's risk—the probability that lots of the quality level LTPD will be accepted. Usually, β = 10 percent. If a bad lot is accepted, we refer to this as a type II error.

The mechanics of actually finding specific plans that fit can be accomplished by using standard tables, charts, or formulas, all of which result in the specification of a combination of sample size n and acceptance number c which closely approximates the requirements for AQL, α, LTPD, and β.

AVERAGE QUALITY OF OUTGOING LOTS

An important feature of acceptance sampling is that the level of inspection automatically adjusts to the quality of lots being inspected, assuming rejected lots are subjected to 100 percent inspection. The OC curve shows that the greater the fraction of defectives in a lot, the less likely the lot is to be accepted.

If all lots have some given percentage of defectives, p, the average outgoing quality (AOQ) of the lots can be computed using the formula:

$$AOQ = P \times p \left(\frac{N-n}{N} \right)$$

where P = probability of accepting the lot
       p = percentage defective
       N = lot size
       n = sample size

In practice. the last term is often dropped since it is typically close to 1. The formula then becomes:

$$AOQ = P \times p$$

By allowing p to vary, a curve for AOQ can be developed . The curve illustrates the point that if lots are very good or very bad, the AOQ will be high.

EXAMPLE 2

We will develop the AOQ curve for N = 500, n =10, and c =1. From Table 5 (Cumulative Binomial Distribution) in the Appendix, we tabulate the probabilities of acceptance, P, for various values of fraction defective, p, as follows:

Portion of a Cumulative Binomial Distribution Table					
(Table 5 from the Appendix)					
n =10, c=1					
p	*P*	*AOQ*			
(1)	*(2)*	*(3) = (1) x (2)*	*AOQL*		
0.0	0.0	0.0			
0.05	0.9139	0.046			
0.1	0.7361	0.074			
0.15	0.5443	0.082	=Maximum AOQ = AOQL		
0.2	0.3758	0.075			
0.25	0.244	0.061			
0.3	0.1493	0.045			
0.35	0.086	0.030			
0.4	0.0464	0.019			

0.45	0.0233	0.010			
0.5	0.0107	0.005			
0.55	0.0045	0.002			
0.6	0.0017	0.001			
0.65	0.0005	0.000			
0.7	0.0001	0.000			
0.75	0	0.000			

The AOQ curve is shown in Figure 7.

FIGURE 7

AOQ Curve
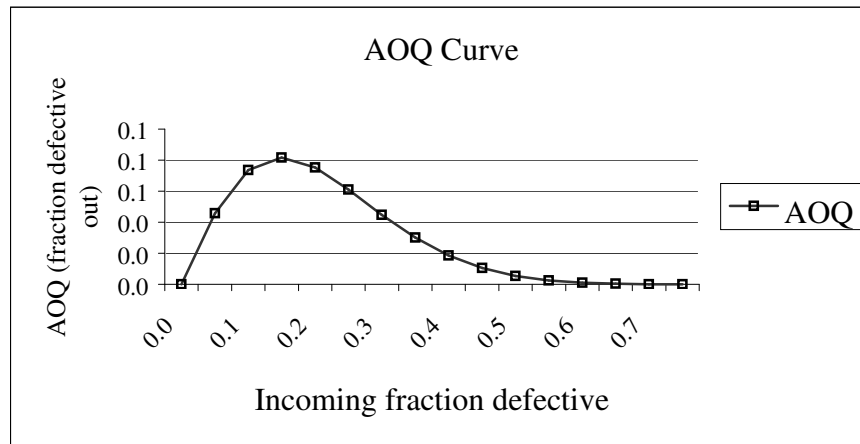
Note that the maximum point on the curve, often called the *average outgoing quality limit* (AOQL) is 0.082 for p = 0.15. Figure 9 illustrates that as the percentage of defectives I lots coming into inspection increases, the percentage of defectives in lots leaving inspection deteriorates at first, then peaks at the AOQL, and then improves. The improvement in quality occurs since as the acceptance plan rejects lots, the rejected lots are 100 percent inspected and the defectives are replaced with nondefectives. The net effect of rejecting lots is therefore an improvement in the quality of lots leaving inspection.

NOTE:
1. AOQ is the average outgoing quality. In a given case, it depends on the sampling plan and the lot quality.
2. AOQL is the average outgoing quality limit. It refers to the worst possible outgoing quality and occurs at an intermediate quality level, which is neither very good nor very bad.

TYPES OF SAMPLING PLANS

To this point the examples regarding acceptance sampling plans have dealt with the taking of only a single sample. This is the simplest type of sampling plan since the decision as to whether to accept or reject is made on the basis of what the one sample indicates. When the number of defectives in the sample is less than or equal to the acceptance number, the lot is accepted. If, on the other hand, the number of defectives is greater than the rejection number, the lot must be rejected. It is possible, however, to design sampling plans which utilize more than one sample. The major objective of such plans is to get the same assurance of quality with a

reduction in the amount of inspection. While such plans may result in a reduction in inspection time and consequent cost, this is not a certainty. A drawback of sampling plans that require more than one sample is the increased difficulty in designing them. The most frequent types of these sampling plans are double, multiple, and sequential sampling plans.

Double Sampling

These plans provide for the use of a second sample when the first sample is not conclusive enough to make a decision. If the number of defectives in the first sample is less than or equal to the acceptance number specified, the lot may be accepted. As in single sampling plans, if the number of defectives is larger than the rejection number, the lot is rejected. In double sampling plans the range between the acceptance number and the rejection number for the first sample is greater than one. Thus, when the number of defectives in the first sample is between the acceptance and rejection numbers, a second sample must be taken because the results of the first sample in this case are not conclusive.

After the second sample is drawn, the cumulative number of defectives from both samples is compared with the second acceptance and rejection numbers. For the second sample the range between these numbers is one, as in single sampling plans. The decision to accept or reject is then made as in the case of a single sampling plan.

Multiple Sampling

Multiple sampling plans are essentially the same as double sampling plans with the exception that the number of samples required for a decision may be more than two.

Sequential Sampling

This type of sampling plan provides for the taking of an unspecified number of samples. If the lot quality is either very good or very bad, a small sample will suffice. It is only when the quality is between these two levels that a larger sample is required. The range between the acceptance and rejection numbers remains constant and greater than one. The sampling process is carried on until either the acceptance or the rejection level is reached. A sequential sampling plan is illustrated in Figure 8. The design of a sequential sampling plan can be accomplished by determining the appropriate acceptance and rejection limits. Tables are available to determine the proper limits for specified values of AQL, LTPD, α, and β.

Double, multiple, and sequential sampling plans should typically result in less inspection than is required for single sampling plans for a given level of protection. However, the amount of inspection required will vary widely from lot to lot.

FIGURE 8
SEQUENTIAL SAMPLING PLAN
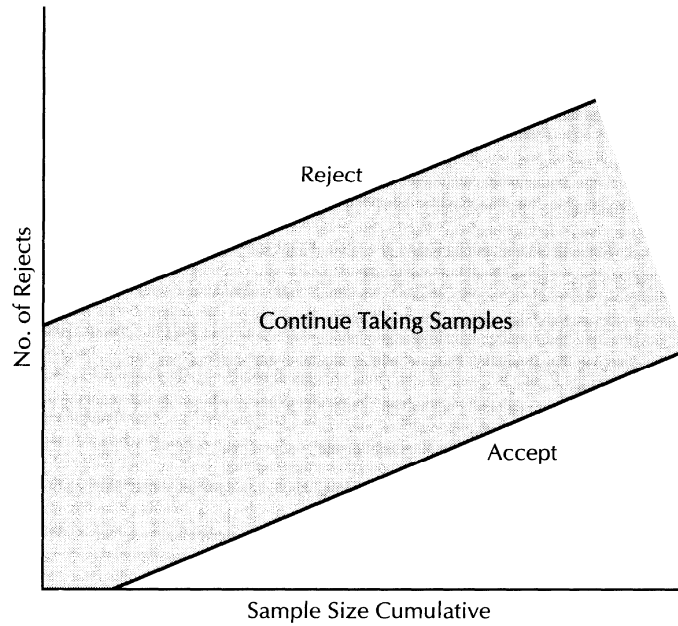
CONTROL CHARTS FOR ATTRIBUTES

Control charts can be utilized in attribute inspection as well as in variable control. The major difference in the control charts is that, in the case of attributes, the unit of measurement used is a distinct value while for variables it is a computed measure of central tendency; i.e., mean or range. The two types of attributes control charts are concerned with the percentage defective (*p*-chart) or with the defects per unit (*c*-chart).

Percentage Defective Charts

When control is concerned with attributes, a determination is made as to the acceptance or rejection of the output units. For each sample the percentage of defective units can be determined. The *p*-chart can be utilized to record the variations in the percentage defective in the lots sampled. Control limits are computed in the same way they are computed for variable control charts. As long as the points remain within the control limits, the quality is assumed to be in control. The control limits for a *p*-chart, based on three standard deviations, are computed as follows:

$$UCL_P = \bar{p} + 3 \quad \sqrt{\frac{p(1-\bar{p})}{n}} \qquad (5)$$

$$LCL_P = \bar{p} - 3 \quad \sqrt{\frac{p(1-\bar{p})}{n}} \qquad (6)$$

250

Where: $\overline{p}$ = the mean of the percentage defective in a series of initial samples

EXAMPLE 3

ABC City's department of public works is concerned about public reaction to a sewer project that is currently in progress. Each week, a sample of 100 residents are questioned on their feelings toward the project. The department wishes to analyze the survey data using an appropriate control chart to determine if the community sentiment is stable.

<div align="center">Week</div>

	1	2	3	4	5	6	7	8	Total
Number opposed	3	2	4	1	0	5	2	3	20
Fraction defective	.03	.02	.04	.01	0	.05	.02	.03	.2

Since the sample size is 100, the fraction defective is 20/100 = .20. Thus,

Assume that the average defective percent ($\overline{p}$) is .11. Then $\overline{p}$ = .20/8 = .025.

$$\sqrt{\frac{p(1-\overline{p})}{n}} = \sqrt{\frac{.025((1-.025)}{100}} = .0156$$

Control limits are:

$$UCL_P = \overline{p} + 3\sqrt{\frac{p(1-\overline{\overline{p}})}{n}} = .025 + 3(.0156) = .025 + .047 = .072$$

$$LCL_P = \overline{p} - 3\sqrt{\frac{p(1-\overline{\overline{p}})}{n}} = .025 - 3(.0156) = .025 - .047 = 0$$

It appears that the community sentiment is stable.

Defects Per Unit Charts

If output is such that defects can occur at a variety of points within the unit of output, the control of the number of defects may be more useful. Examples of processes where this type of control might be valuable are:

    a.   Electronics equipment in which a variety of defects can occur.
    b.   Textiles which may contain numerous defects per yard.
    c.   The number of improper medications issued in a hospital for some unit of time.
    d.   The number of incorrect orders sent out by the audiovisual service of a school district.

The cases where this type of control is useful may be generalized as those where the possibility of defects is high, but is in fact small. This condition is found to approximate the Poisson distribution for fluctuations in the number of defects. Using $\overline{c}$ as the average number of defects per unit of output, again based on three standard deviations, the control limits are determined by:

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}} \qquad\qquad (7)$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}} \qquad\qquad (8)$$

The value of $\bar{c}$ is an estimate, as was $\bar{p}$, based on past accumulated data. The c-chart has many uses other than for quality purposes. Examples are found in the area of inventory control for controlling the number of stockouts, in equipment maintenance for the number of breakdowns, and for accident statistics.

EXAMPLE 4

The OK City Transit Authority receives complaints from customers about the way drivers drive, their lack of courtesy, and the like. The manager wants to construct a control chart for defects per unit, c. In this case, a complaint is a defect and a unit of work is 500 fares collected on the bus. The manager intends to post the c-chart and complaints reported each week for each group of 500 fares that the driver collected. An average of 28.2 defects per unit occurred before the chart is posted. Control limits on the chart are:

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}} = 28.2 + 3\sqrt{28.2} = 44.13$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}} = 28.2 - 3\sqrt{28.2} = 12.3$$

COMPUTER SOFTWARE FOR QUALITY CONTROL

Computer software can relieve most of the tedious calculations formerly required to install and maintain a quality control system. Some popular packages, developed by TIME/WARE Corp, are listed with a brief description.

1. *ML105$:* Determines sampling plan to fit combinations of AOPL, lot size, etc., and randomly determines which parts to sample according to military standard.
2. *MLBIN$:* Evaluates multiple level sampling plans where users inspect a number of parts from a large lot and accepts, rejects, or resamples based on the number of defectives found (binomial distribution).
3. *OCBIN$:* Plots the OC curve. User supplies the sampling size and number of defectives required to reject the lot.
4. *CONLM$:* Determines confidence limits and sample statistics on a process average.

QUESTIONS
1. Describe the primary goal of quality assurance.
2. Define assignable causes in quality control.
3. Differentiate between variable and attribute measurement.
4. What is sampling plan, what is an operation characteristic curve (OC), and how is an OC curve used in sampling?
5. Discuss the concept of *in control*.
6. Describe the various types of control, charts and their applications.
7. Explain the purposes and differences between p-charts and $\bar{\bar{X}}$ and R charts.
8. How does producer and consumer risk relate to errors in statistics?

9. What is the objective of acceptance sampling?
10. Briefly explain AOQ and AOQL.

PROBLEMS

1. A sample study was made of hand assembly operation on a transistor radio. Samples of the time spent to assemble one unit were taken twice a day, in mid-morning and mid-afternoon. Four units are included in each sample. Observations were continued for two weeks, so that 20 samples were collected. The results are shown below. Each figure in a sample is the actual time taken to assemble one unit.

Measurement of Time Spent per unit (Two Samples Taken Daily for 10 Days)						
Sample Number	Time Spent on Each of Four Items within Samples				Arithmetic Mean	Range R
	12	11	10	9	10.5	3
2	10	10	9	11	10	2
3	13	11	10	9	10.75	4
4	10	9	8	11	9.5	3
5	12	11	10	10	10.75	2
6	11	11	14	9	11.25	5
7	10	9	12	10	10.25	3
8	11	12	10	11	11	2
9	13	9	10	10	10.5	4
10	11	9	10	10	10	2
11	11	11	11	10	10.75	1
12	8	14	10	10	10.5	6
13	10	11	9	11	10.25	2
14	12	10	9	10	10.25	3
15	8	10	10	12	10	4
16	11	10	10	9	10	2
17	13	10	9	11	10.75	4
18	11	8	10	13	10.5	5
19	10	9	13	12	11	4
20	13	12	8	13	11.5	5
				Totals	210	66
				Grand arithmetic mean	10.5	3.3

(a) Compute $\overline{\overline{X}}$ and $\overline{R}$, and the upper and lower control limits for each.

(b) Prepare a control chart for $\overline{\overline{X}}$ and $\overline{R}$.
(c) Comment on the charts.

2. Jeannie wants to use a p-chart to control the proportion of defective units coming from Final Assembly. She samples 50 units each hour and tested each unit to see if it works. The

number of defective units in her first 8 samples and the proportion defective (p) are given below.

Sample Number	n	Number Defective	P
1	50	3	0.06
2	50	2	0.04
3	50	0	0
4	50	1	0.02
5	50	1	0.02
6	50	7	0.14
7	50	2	0.04
8	50	0	0
	Totals	<u>16</u>	<u>0.32</u>

3. Steve Bono, the safety manager, recorded the number of injuries each week and uses a *c*-chart to detect changes in the injury rate. Over the next 8 weeks, injuries per week were 6, 5, 3, 8, 2, 6, 9, and 5. Construct the *c*-chart and determine if the process is in control.

4. Shipments of bowling balls are sampled before delivery to a warehouse. Lots of 600 balls are checked, using 10 observations from each lot. Any lot with more than one defective is rejected. Determine values for the operating characteristic (OC) curve for this sampling plan.

5. Ron Jaffe Industries, Inc., a maker of plastic wrapping material, takes a random sample of 50 items from each lot before it is sent to a customer. Lots contain 2,000 items each. Any lot with more than one defective is subjected to 100 percent inspection, and any defectives are replaced with good ones.
   (a) Develop the table for the OC curve for this sampling plan.
   (b) Construct the AOQ curve for this plan. What is the approximate average outgoing quality (AOQ) limit?

ANSWERS
1. The primary objective of quality assurance is to ensure that products and services conform to specifications of design and customer satisfaction by preventing defects, detecting them when they occur, and taking remedial action.
2. Causes that are not due to chance and can be controlled, such as materials, equipment, labor, and personnel.
3. Variables are measured on a continuous scale of measurement such as means and ranges; attributes assume only two values such as good or bad.
4. A sampling plan is a plan that discriminates between lots of various qualities (i.e., percent defectives). An OC curve is the relationship between lot quality (or percent defective) and the probability of lot acceptance given a sampling plan. It attempts to determine the producer's and consumer's risk for a given sampling plan. The curve is used to select a plan having a specified risk profile.
5. "In control" means that any variation in quality is due solely to chance; no assignable causes are present.

6. $\overline{\overline{X}}$ chart: used for averages
   R-chart: used for ranges or spread
   p-chart: used for fraction defective
   c-chart: used for defectives
7. p-charts are used to monitor the process for attribute data. These are typically binomial "go, no-go" data. An example of a p-chart is percent of pieces nonconforming. $\overline{\overline{X}}$ charts are used for charting population values for continuous measurement. $\overline{\overline{X}}$ charts are used when the process is too slow to produce enough measurements for an $\overline{X}$ chart. An example of an $\overline{\overline{X}}$ chart is average time to complete a mile run for one person. R charts are used to compute process ranges for variable data. R charts are used in concert with $\overline{\overline{X}}$ charts.
8. Producer's risk (consumer's risk) is equivalent to the probability of a Type I (Type II) error.
9. The objective of acceptance sampling is to make a decision as to whether to accept or reject a lot. It is *not* to estimate the quality of a lot.
10. AOQ is the average outgoing quality. In a given case, it depends on the sampling plan and the lot quality. AOQL is the average outgoing quality limit. It refers to the worst possible outgoing quality and occurs at an intermediate quality level, which is neither very good nor very bad.

PROBLEMS

1.
(a) For $\overline{X}$: Control limits are

$$UCL\overline{X} = \overline{\overline{X}} + A_2\overline{R}$$
$$= \quad 60.02 + (.729)(0.17)$$
$$= \quad 60.144$$

and:

$$LCL\overline{X} = \overline{\overline{X}} - A_2\overline{R}$$
$$= \quad 60.02 - (.729)(0.17)$$
$$= \quad 59.896$$

For $\overline{R}$:

$$URL = D_4\overline{R} = 2.282\,(0.17) = 0.388$$
$$LRL = D_3\overline{R} = 0(0.17) = 0$$

(b)
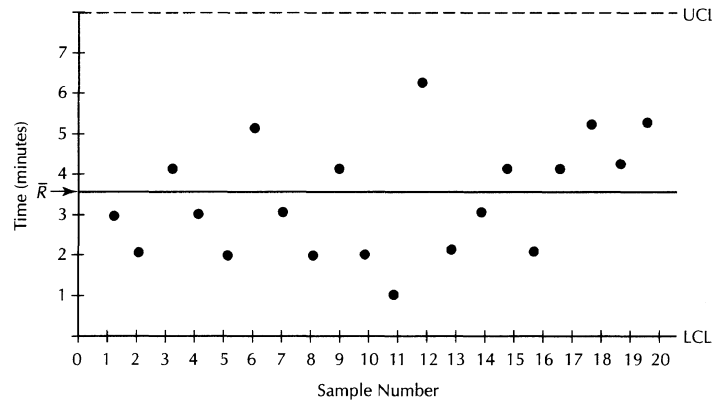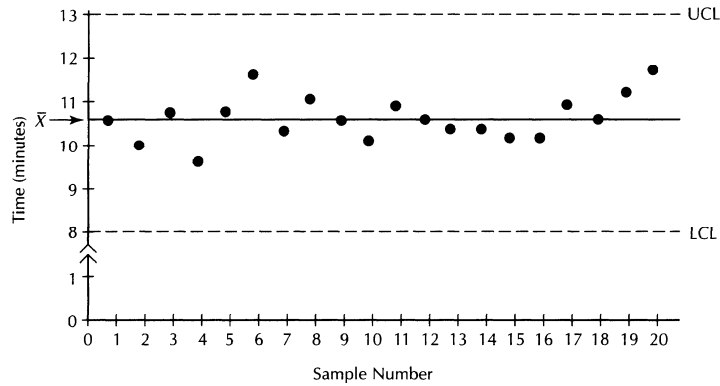
(c) No observations are outside the control limits, so the process is apparently in control as far as the sample means are concerned. The process also seems to be in control as far as the range is concerned. Caution is needed here. Given certain men, materials, machines, and methods, the process or operation may be statistically in control. However, this does not mean that the process or operation is beyond change or improvement.

2.

The fraction defective is $16/50 = .32$. So $\bar{p} = .32/8 = .4$

The control limits for a p-chart, based on three standard deviations, are computed as follows:

$$UCL_P = \bar{p} + 3 \sqrt{\frac{p(1-\bar{p})}{n}} = .04 + 3 \frac{(.04)(.96)}{50} = .123$$

$$LCL_P = \bar{p} - 3 \sqrt{\frac{p(1-\bar{p})}{n}} = \frac{.04 - 3\,(.04)(.96)}{50} = -.043$$

(because LCL cannot be negative) $= 0$

The defective rate was "out of control" when sample #6 was taken. The problem must be investigated and the cause eliminated. When the cause is determined and eliminated, she can recalculate $\bar{p}$ and the control limits.
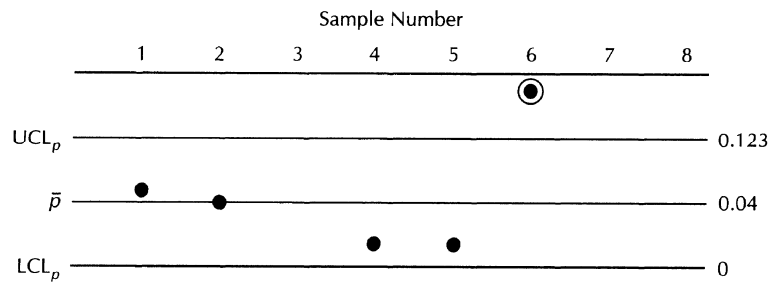
3.

The average number of injuries per week is $\bar{c} = 44/8 = 5.5$

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}} = 5.5 + 3\sqrt{5.5} = 12.54$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}} = 5.5 - 3\sqrt{5.5} = -1.54 = 0$$

All of the samples are "in control."
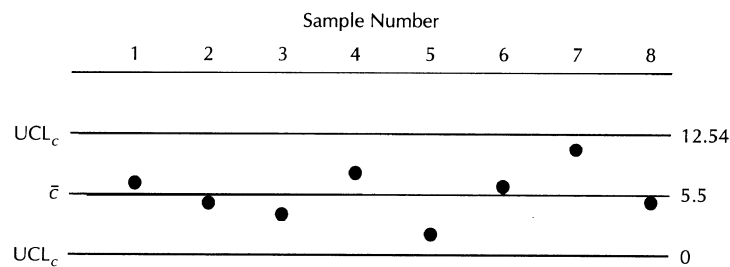
4.

n = 10, c = 1. Using Table 5 (Binomial Distribution) in the Appendix, we obtain

Fraction defective	Cumulative probability
.05	.9139
.10	.7361
.15	.5443
.20	.3758
.25	.2440
.30	.1493
.35	.0860
.40	.0464
.45	.0233

5.

Note that n =50 and c = 1. Using Table 6 (Poisson Distribution) in the Appendix, we get

p (1)	$\lambda=np$	Cumulative probability (2)	AOQ (1)x(2)
.002	.10	.995	.00199
.004	.20	.982	.00393
.008	.40	.938	.00750
.012	.60	.878	.01054
.016	.80	.809	.01294
.020	1.00	.736	.01472
.024	1.20	.663	.01591
.028	1.40	.592	.01658
.032	1.60	.525	.01680
.036	1.80	.463	.01667

AOQ limit =AOQL = maximum AOQ

APPENDIX

TABLE 1
NORMAL DISTRIBUTION TABLE

Areas under the normal curve

Z	0	1	2	3	4	5	6	7	8	9
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7703	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9278	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9430	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9648	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9700	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9762	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9874	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9990	0.9993	0.9995	0.9997	0.9998	0.9998	0.9999	0.9999	1.0000

TABLE 2
LEARNING CURVE COEFFICIENTS

	70%		75%		80%		85%		90%	
Unit Number	Unit Time	Total Time	Unit Time	Total Time	Unit Time	Total Time	Unit Time	Total Time	Unit Time	Total Time
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.700	1.700	0.750	1.750	0.800	1.800	0.850	1.850	0.900	1.900
3	0.568	2.268	0.634	2.384	0.702	2.502	0.773	2.623	0.846	2.746
4	0.490	2.758	0.562	2.946	0.640	3.142	0.723	3.345	0.810	3.556
5	0.437	3.195	0.513	3.459	0.596	3.738	0.686	4.031	0.783	4.339
6	0.398	3.593	0.475	3.934	0.562	4.299	0.657	4.688	0.762	5.101
7	0.367	3.960	0.446	4.380	0.534	4.834	0.634	5.322	0.744	5.845
8	0.343	4.303	0.422	4.802	0.512	5.346	0.614	5.936	0.729	6.574
9	0.323	4.626	0.402	5.204	0.493	5.839	0.597	6.533	0.716	7.290
10	0.306	4.932	0.385	5.589	0.477	6.315	0.583	7.116	0.705	7.994
11	0.291	5.223	0.370	5.958	0.462	6.777	0.570	7.686	0.695	8.689
12	0.278	5.501	0.357	6.315	0.449	7.227	0.558	8.244	0.685	9.374
13	0.267	5.769	0.345	6.660	0.438	7.665	0.548	8.792	0.677	10.052
14	0.257	6.026	0.334	6.994	0.428	8.092	0.539	9.331	0.670	10.721
15	0.248	6.274	0.325	7.319	0.418	8.511	0.530	9.861	0.663	11.384
16	0.240	6.514	0.316	7.635	0.410	8.920	0.522	10.383	0.656	12.040
17	0.233	6.747	0.309	7.944	0.402	9.322	0.515	10.898	0.650	12.690
18	0.226	6.973	0.301	8.245	0.394	9.716	0.508	11.405	0.644	13.334
19	0.220	7.192	0.295	8.540	0.338	10.104	0.501	11.907	0.639	13.974
20	0.214	7.407	0.288	8.828	0.381	10.485	0.495	12.402	0.634	14.608
21	0.209	7.615	0.283	9.111	0.375	10.860	0.490	12.892	0.630	15.237
22	0.204	7.819	0.277	9.388	0.370	11.230	0.484	13.376	0.625	15.862
23	0.199	8.018	0.272	9.660	0.364	11.594	0.479	13.856	0.621	16.483
24	0.195	8.213	0.267	9.928	0.359	11.954	0.475	14.331	0.617	17.100
25	0.191	8.404	0.263	10.191	0.355	12.309	0.470	14.801	0.613	17.713
26	0.187	8.591	0.259	10.449	0.350	12.659	0.466	15.267	0.609	18.323
27	0.183	8.774	0.255	10.704	0.346	13.005	0.462	15.728	0.606	18.929
28	0.180	8.954	0.251	10.955	0.342	13.347	0.458	16.186	0.603	19.531
29	0.177	9.131	0.247	11.202	0.338	13.685	0.454	16.640	0.599	20.131
30	0.174	9.305	0.244	11.446	0.335	14.020	0.450	17.091	0.596	20.727
31	0.171	9.476	0.240	11.686	0.331	14.351	0.447	17.538	0.593	21.320
32	0.168	9.644	0.237	11.924	0.328	14.679	0.444	17.981	0.590	21.911
33	0.165	9.809	0.234	12.158	0.324	15.003	0.441	18.422	0.588	22.498
34	0.163	9.972	0.231	12.389	0.321	15.324	0.437	18.859	0.585	23.084
35	0.160	10.133	0.229	12.618	0.318	15.643	0.434	19.294	0.583	23.666
36	0.158	10.291	0.226	12.844	0.315	15.958	0.432	19.725	0.580	24.246
37	0.156	10.447	0.223	13.067	0.313	16.271	0.429	20.154	0.578	24.824
38	0.154	10.601	0.221	13.288	0.310	16.581	0.426	20.580	0.575	25.399
39	0.152	10.753	0.219	13.507	0.307	16.888	0.424	21.004	0.573	25.972
40	0.150	10.902	0.216	13.723	0.305	17.193	0.421	21.425	0.571	26.543

TABLE 3
CRITICAL VALUES FOR STUDENT'S T-DISTRIBUTION
Critical Values for the t Statistic

	Values of t					
d.f.	$t_{0.100}$	$t_{0.050}$	$t_{0.025}$	$t_{0.010}$	$t_{0.005}$	d.f.
1	3.078	6.314	12.706	31.821	63.657	1
2	1.886	2.920	4.303	6.965	9.925	2
3	1.638	2.353	3.182	4.541	5.841	3
4	1.533	2.132	2.776	3.747	4.604	4
5	1.476	2.015	2.571	3.365	4.032	5
6	1.440	1.943	2.447	3.143	3.707	6
7	1.415	1.895	2.365	2.998	3.499	7
8	1.397	1.860	2.306	2.896	3.355	8
9	1.383	1.833	2.262	2.821	3.250	9
10	1.372	1.812	2.228	2.764	3.169	10
11	1.363	1.796	2.201	2.718	3.106	11
12	1.356	1.782	2.179	2.681	3.055	12
13	1.350	1.771	2.160	2.650	3.012	13
14	1.345	1.761	2.145	2.624	2.977	14
15	1.341	1.753	2.131	2.602	2.947	15
16	1.337	1.746	2.120	2.583	2.921	16
17	1.333	1.740	2.110	2.567	2.898	17
18	1.330	1.734	2.101	2.552	2.878	18
19	1.328	1.729	2.093	2.539	2.861	19
20	1.325	1.725	2.086	2.528	2.845	20
21	1.323	1.721	2.080	2.518	2.831	21
22	1.321	1.717	2.074	2.508	2.819	22
23	1.319	1.714	2.069	2.500	2.807	23
24	1.318	1.711	2.064	2.492	2.797	24
25	1.316	1.708	2.060	2.485	2.787	25
26	1.315	1.706	2.056	2.479	2.779	26
27	1.314	1.703	2.052	2.473	2.771	27
28	1.313	1.701	2.048	2.467	2.763	28
29	1.311	1.699	2.045	2.462	2.756	29
Inf.	1.282	1.645	1.960	2.326	2.576	Inf.

Note:The t value describes the sampling distribution of a deviation from a population value divided by the standard error.

Degrees of freedom ($d.f.$) are in the first column. The probabilities indicated as subvalues of t in the heading refer to the sum of a one-tailed area under the curve that lies outside the point t. For example, in the distribution of the means of samples of size $n = 10$, $d.f. = n - 2 = 8$; then 0.0025 of the area under the curve falls in one tail outside the interval $t \pm 2.306$.

TABLE 4
RANDOM NUMBERS

03689	33090	43465	96789	56688	32389	77206	06534	10558	14478
43367	46409	44751	73410	35138	24910	70748	57336	56043	68550
45357	52080	62670	73877	20604	40408	98060	96733	65094	80335
62683	03171	77109	92515	78041	27590	42651	00254	73179	10159
04841	40918	69047	68986	08150	87984	08887	76083	37702	28523
85963	06992	65321	43521	46393	40491	06028	43865	58190	28142
03720	78942	61990	90812	98452	74098	69738	83272	39212	42817
10159	85560	35619	58248	65498	77977	02896	45198	10655	13973
80162	35686	57877	19552	63931	44171	40879	94532	17828	31848
74388	92906	65829	24572	79417	38460	96294	79201	47755	90980
12660	09571	29743	45447	64063	46295	44191	53957	62393	42229
81852	60620	87757	72165	23875	87844	84038	04994	93466	27418
03068	61317	65305	64944	27319	55263	84514	38374	11657	67723
29623	58530	17274	16908	39253	37595	57497	74780	88624	93333
30520	50588	51231	83816	01075	33098	81308	59036	49152	86262
93694	02984	91350	33929	41724	32403	42566	14232	55085	65628
86736	40641	37958	25415	19922	65966	98044	39583	26828	50919
28141	15630	37675	52545	24813	22075	05142	15374	84533	12933
79804	05165	21620	98400	55290	71877	60052	46320	79055	45913
63763	49985	88853	70681	52762	17670	62337	12199	44123	37993
49618	47068	63331	62675	51788	58283	04295	72904	05378	98085
26502	68980	26545	14204	34304	50284	47730	57299	73966	02566
13549	86048	27912	56733	14987	09850	72817	85168	09538	92347
89221	78076	40306	34045	52557	52383	67796	41382	50490	30117
97809	34056	76778	60417	05153	83827	67369	08602	56163	28793
65668	44694	34151	51741	11484	13226	49516	17391	39956	34839
53653	59804	59051	95074	38307	99546	32962	26962	86252	50704
34922	95041	17398	32789	26860	55536	82415	82911	42208	62725
74880	65198	61357	90209	71543	71114	94868	05645	44154	72254
66036	48794	30021	92601	21615	16952	18433	44903	51322	90379
39044	99503	11442	81344	57068	74662	90382	59433	48440	38146
87756	71151	68543	08358	10183	06432	97482	90301	76114	83778
47117	45575	29524	02522	08041	70698	80260	73588	86415	72523
71572	02109	96722	21684	64331	71644	18933	32801	11644	12364
35609	58072	63209	48429	53108	59173	55337	22445	85940	43707
73703	70069	74981	12197	48426	77365	26769	65078	27849	41311
42979	88161	56531	46443	47148	42773	18601	38532	22594	12395
12279	42308	00380	17181	38757	09071	89804	15232	99007	39495

TABLE 5
BINOMIAL DISTRIBUTION

P

n	x	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
1	0	0.9500	0.9000	0.8500	0.8000	0.7500	0.7000	0.6500	0.6000	0.5500	0.5000	0.4500	0.4000	0.3500	0.3000	0.2500	0.2000	0.1500	0.1000
	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0	0.9025	0.8100	0.7225	0.6400	0.5625	0.4900	0.4225	0.3600	0.3025	0.2500	0.2025	0.1600	0.1225	0.0900	0.0625	0.0400	0.0225	0.0100
	1	0.9975	0.9900	0.9775	0.9600	0.9375	0.9100	0.8775	0.8400	0.7975	0.7500	0.6975	0.6400	0.5775	0.5100	0.4375	0.3600	0.2775	0.1900
	2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0	0.8574	0.7290	0.6141	0.5120	0.4219	0.3430	0.2746	0.2160	0.1664	0.1250	0.0911	0.0640	0.0429	0.0270	0.0156	0.0080	0.0034	0.0010
	1	0.9928	0.9720	0.9393	0.8960	0.8438	0.7840	0.7183	0.6480	0.5748	0.5000	0.4253	0.3520	0.2818	0.2160	0.1563	0.1040	0.0608	0.0280
	2	0.9999	0.9990	0.9966	0.9920	0.9844	0.9730	0.9571	0.9360	0.9089	0.8750	0.8336	0.7840	0.7254	0.6570	0.5781	0.4880	0.3859	0.2710
	3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4	0	0.8145	0.6561	0.5220	0.4096	0.3164	0.2401	0.1785	0.1296	0.0915	0.0625	0.0410	0.0256	0.0150	0.0081	0.0039	0.0016	0.0005	0.0001
	1	0.9860	0.9477	0.8905	0.8192	0.7383	0.6517	0.5630	0.4752	0.3910	0.3125	0.2415	0.1792	0.1265	0.0837	0.0508	0.0272	0.0120	0.0037
	2	0.9995	0.9963	0.9880	0.9728	0.9492	0.9163	0.8735	0.8208	0.7585	0.6875	0.6090	0.5248	0.4370	0.3483	0.2617	0.1808	0.1095	0.0523
	3	1.0000	0.9999	0.9995	0.9984	0.9961	0.9919	0.9850	0.9744	0.9590	0.9375	0.9085	0.8704	0.8215	0.7599	0.6836	0.5904	0.4780	0.3439
	4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0	0.7738	0.5905	0.4437	0.3277	0.2373	0.1681	0.1160	0.0778	0.0503	0.0313	0.0185	0.0102	0.0053	0.0024	0.0010	0.0003	0.0001	0.0000
	1	0.9974	0.9185	0.8352	0.7373	0.6328	0.5282	0.4284	0.3370	0.2562	0.1875	0.1312	0.0870	0.0540	0.0308	0.0156	0.0067	0.0022	0.0005
	2	0.9988	0.9914	0.9734	0.9421	0.8965	0.8369	0.7648	0.6826	0.5931	0.5000	0.4069	0.3174	0.2352	0.1631	0.1035	0.0579	0.0266	0.0086
	3	1.0000	0.9995	0.9978	0.9933	0.9844	0.9692	0.9460	0.9130	0.8688	0.8125	0.7438	0.6630	0.5716	0.4718	0.3672	0.2627	0.1648	0.0815
	4	1.0000	1.0000	0.9999	0.9997	0.9990	0.9976	0.9947	0.9898	0.9815	0.9688	0.9497	0.9222	0.8840	0.8319	0.7627	0.6723	0.5563	0.4095
	5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
6	0	0.7351	0.5314	0.3771	0.2621	0.1780	0.1176	0.0754	0.0467	0.0277	0.0156	0.0083	0.0041	0.0018	0.0007	0.0002	0.0001	0.0000	0.0000
	1	0.9672	0.8857	0.7765	0.6554	0.5339	0.4202	0.3191	0.2333	0.1636	0.1094	0.0692	0.0410	0.0223	0.0109	0.0046	0.0016	0.0004	0.0001
	2	0.9978	0.9842	0.9527	0.9011	0.8306	0.7443	0.6471	0.5443	0.4415	0.3438	0.2553	0.1792	0.1174	0.0705	0.0376	0.0170	0.0059	0.0013
	3	0.9999	0.9987	0.9941	0.9830	0.9624	0.9295	0.8826	0.8208	0.7447	0.6563	0.5585	0.4557	0.3529	0.2557	0.1694	0.0989	0.0473	0.0159
	4	1.0000	0.9999	0.9996	0.9984	0.9954	0.9891	0.9777	0.9590	0.9308	0.8906	0.8364	0.7667	0.6809	0.5798	0.4661	0.3446	0.2235	0.1143
	5	1.0000	1.0000	1.0000	0.9999	0.9998	0.9993	0.9982	0.9959	0.9917	0.9844	0.9723	0.9533	0.9246	0.8824	0.8220	0.7379	0.6229	0.4686
	6	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
7	0	0.6983	0.4783	0.3206	0.2097	0.1335	0.0824	0.0490	0.0280	0.0152	0.0078	0.0037	0.0016	0.0006	0.0002	0.0001	0.0000	0.0000	0.0000
	1	0.9556	0.8503	0.7166	0.5767	0.4449	0.3294	0.2338	0.1586	0.1024	0.0625	0.0357	0.0188	0.0090	0.0038	0.0013	0.0004	0.0001	0.0000
	2	0.9962	0.9743	0.9262	0.8520	0.7564	0.6471	0.5323	0.4199	0.3164	0.2266	0.1529	0.0963	0.0556	0.0288	0.0129	0.0047	0.0012	0.0002
	3	0.9998	0.9973	0.9879	0.9667	0.9294	0.8740	0.8002	0.7102	0.6083	0.5000	0.3917	0.2898	0.1998	0.1260	0.0706	0.0333	0.0121	0.0027
	4	1.0000	0.9998	0.9988	0.9953	0.9871	0.9712	0.9444	0.9037	0.8471	0.7734	0.6836	0.5801	0.4677	0.3529	0.2436	0.1480	0.0738	0.0257
	5	1.0000	1.0000	0.9999	0.9996	0.9987	0.9962	0.9910	0.9812	0.9643	0.9375	0.8976	0.8414	0.7662	0.6706	0.5551	0.4233	0.2834	0.1497
	6	1.0000	1.0000	1.0000	0.9999	0.9999	0.9998	0.9994	0.9984	0.9963	0.9922	0.9848	0.9720	0.9510	0.9176	0.8665	0.7903	0.6794	0.5217
	7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

TABLE 6
POISSON DISTRIBUTION

λ\x	0	1	2	3	4	5	6	7	8	9
0.05	0.951	0.999	1.000							
0.10	0.905	0.995	1.000							
0.15	0.861	0.990	0.999	1.000						
0.20	0.819	0.982	0.999	1.000						
0.25	0.779	0.974	0.998	1.000						
0.30	0.741	0.963	0.996	1.000						
0.35	0.705	0.951	0.994	1.000						
0.40	0.670	0.938	0.992	0.999	1.000					
0.45	0.638	0.925	0.989	0.999	1.000					
0.50	0.607	0.910	0.986	0.998	1.000					
0.55	0.577	0.894	0.982	0.998	1.000					
0.60	0.549	0.878	0.977	0.997	1.000					
0.65	0.522	0.861	0.972	0.996	0.999	1.000				
0.70	0.497	0.844	0.966	0.994	0.999	1.000				
0.75	0.472	0.827	0.960	0.993	0.999	1.000				
0.80	0.449	0.809	0.953	0.991	0.999	1.000				
0.85	0.427	0.791	0.945	0.989	0.998	1.000				
0.90	0.407	0.772	0.937	0.987	0.998	1.000				
0.95	0.387	0.754	0.929	0.984	0.997	1.000				
1.0	0.368	0.736	0.920	0.981	0.996	0.999	1.000			
1.1	0.333	0.699	0.900	0.974	0.995	0.999	1.000			
1.2	0.301	0.663	0.880	0.966	0.992	0.998	1.000			
1.3	0.273	0.627	0.857	0.957	0.989	0.998	1.000			
1.4	0.247	0.592	0.833	0.946	0.986	0.997	0.999	1.000		
1.5	0.223	0.558	0.809	0.934	0.981	0.996	0.999	1.000		
1.6	0.202	0.525	0.783	0.921	0.976	0.994	0.999	1.000		
1.7	0.183	0.493	0.757	0.907	0.970	0.992	0.998	1.000		
1.8	0.165	0.463	0.731	0.891	0.964	0.990	0.997	0.999	1.000	
1.9	0.150	0.434	0.704	0.875	0.956	0.987	0.997	0.999	1.000	
2.0	0.135	0.406	0.677	0.857	0.947	0.983	0.995	0.999	1.000	
2.2	0.111	0.355	0.623	0.819	0.928	0.975	0.993	0.998	1.000	
2.4	0.091	0.308	0.570	0.779	0.904	0.964	0.988	0.997	0.999	1.000
2.6	0.074	0.267	0.518	0.736	0.877	0.951	0.983	0.995	0.999	1.000
2.8	0.061	0.231	0.470	0.692	0.848	0.935	0.976	0.992	0.998	0.999

GLOSSARY

ABC ANALYSIS inventory control system that divides the inventory into three classes.
A, B, and C depending on the value and importance of the item.

ACCEPTABLE OUTGOING QUALITY LEVEL (AOQL) average percentage of defectives in
lots leaving an inspection station.

ACCEPTABLE QUALITY LEVEL (AQL) quality standard that allows for a prespecified
number of defects.

AGGREGATE PRODUCTION PLANNING establishment of aggregate production and
inventory levels over a medium range time horizon.

ARRIVAL RATE number of customers or units arriving or entering the system in a given
period of time.

ASSEMBLY CHART graphical method for visualizing how the various parts and subassemblies
flow into the assembly process.

ASSIGNABLE CAUSES causes of poor quality that are due to problems with materials,
machines, or operators and that can be remedied.

ASSIGNMENT PROBLEM problem of determining how the assignments should be made in
order to minimize total costs.

BACKWARD PASS calculation procedure moving backward through the network that
determines the latest start and latest finish times for each activity.

BENCHMARKING searching for new and better procedures by comparing your own procedures
to that of the very best.

BETA DISTRIBUTION probability distribution often used to describe activity times.

BILL OF MATERIALS (BOM) structured parts list that shows the manner in which the product is actually put together.

BREAK-EVEN POINT level of sales revenue that equals the total of the variable and fixed costs for a given volume of output at a particular capacity use rate.

BUSINESS PROCESS REENGINEERING (BPR) approach aiming at making revolutionary changes as opposed to evolutionary changes by eliminating non-value added steps in a business process and computerizing the remaining steps to achieve desired outcomes.

CAPACITY rate at which work is capable of being produced.

CAPACITY REQUIREMENTS PLANNING (CRP) system for determining if a planned production schedule can be accomplished with available capacity and, if not, making adjustments as necessary.

CAPITAL BUDGETING process of making long-term planning and capital expenditure decisions.

CELLULAR MANUFACTURING groups of machinery that are closely associated with each family of parts.

CENTER-OF-GRAVITY METHOD quantitative approach to locating a facility that minimizes the distance or cost of transportation weighted by the volume of goods moved.

CHANNELS number of waiting lines in a service system.

CHASE PLAN aggregate production plan that adjusts capacity in response to seasonal demand.

CLASSICAL DECOMPOSITION approach to forecasting that seeks to decompose the underlying pattern of a time series into cyclical, seasonal, trend, and random sub-patterns.

COEFFICIENT OF DETERMINATION proportion of the total variation in the dependent variable that is explained by the regression equation.

COMPUTER-AIDED DESIGN (CAD) use of a computer to interact with a designer in developing and testing product ideas without actually building prototypes.

COMPUTER-AIDED DESIGN AND MANUFACTURING (CAD/CAM) computerized system to both integrate part design, as with CAD, and to generate processing or manufacturing instructions.

COMPUTER-AIDED MANUFACTURING (CAM) manufacturing system utilizing computer software that controls the actual machine on the shop floor.

COMPUTER-INTEGRATED MANUFACTURING (CIM) computer information systems utilizing a shared manufacturing database for engineering design, factory production, and information management.

COMPUTER-NUMERICALLY CONTROLLED (CNC) MACHINES stand-alone machines controlled by a computer.

CONSUMER SURVEYS method that involves interviewing potential customers to estimate demand relations.

CONSUMER'S RISK probability of accepting a bad lot.

CONTINUOUS IMPROVEMENT (CI) also called *Kaizen* in Japanese, never-ending effort for improvement in every part of the firm relative to all of its deliverables to its customers.

CONTROL CHART graphical means of depicting sample characteristics, such as means, ranges, and attributes, over time used for process control.

CORRELATION COEFFICIENT measure of the degree of correlation between two variables. The range of values it takes is between -1 and +1.

COST OF CAPITAL rate of return that investors expect to receive from the firm.

CRASHING process of reducing an activity time by adding resources and hence usually cost.

CRITICAL PATH longest sequence of activities in a project management network.

CYCLE TIME time required to produce one item on an assembly line; length of time between the placing of two consecutive orders.

DECISION MAKING UNDER RISK decision made when the probability of occurrence of the different states of nature is known.

DECISION MATRIX also called, payoff table, matrix consisting of the decision alternatives, the states of nature, and the decision outcomes.

DECISION THEORY systematic approach to making decisions especially under uncertainty.

DECISION TREE   graphical method of showing the sequence of possible decision alternatives.

DELPHI METHOD qualitative forecasting technique for arriving at group consensus in an anonymous fashion.

DESEASONALIZED DATA removal of the seasonal pattern in a data series. Deseasonalizing facilitates the comparison of month-to-month changes.

DISCOUNTED CASH FLOW (DCF) TECHNIQUES methods of selecting and ranking investment proposals such as the net present value (NPV) and internal rate of return (IRR) methods where time value of money is taken into account.

DUE DATE promised delivery date.

DUMMY ACTIVITY fictitious activity with zero activity time used to represent precedence or used whenever two or more activities have the same starting and ending nodes.

EARLIEST FINISH TIME earliest time at which an activity may be completed.

EARLIEST START TIME earliest time at which an activity may begin.

easier to use but limited to the LP problems involving two (or at most three) decision variables.

ECONOMIC ORDER QUANTITY (EOQ) amount that should be ordered to minimize the total ordering and carrying costs.

ECONOMIC PRODUCTION RUN SIZE amount that should be produced each production run to minimize the total setup and carrying costs.

EQUIVALENT UNIFORM ANNUAL COST annualized sum of all relevant costs. It is like the amount of an installment loan payment.

EXPONENTIAL DISTRIBUTION probability distribution used to describe the pattern or service times for some waiting lines.

EXPONENTIAL SMOOTHING forecasting technique that uses a weighted moving average of past data as the basis for a forecast.

FACTOR RATINGS procedure in which each alternative site is rated according to each factor relevant to the decision, and each factor is rated according to importance.

FISHBONE DIAGRAMS often called *cause-and-effect diagrams*, way of determining likely root causes of a problem.

FIXED-POSITION LAYOUT layout in which the construction of a large product is accomplished in one place.

FLEXIBLE MANUFACTURING SYSTEM (FMS) computer-controlled process technology suitable for producing a moderate variety of products in moderate, flexible volumes.

FLOW PROCESS CHART description of the sequence of operations in a production process. These generally are operation, inspection, movement, storage, and delay.

GANTT CHART graphical representation of a schedule used to plan or monitor progress.

GOODNESS-OF-FIT degree to which a model fits the observed data.

GPSS, SIMSCRIPT specially designed computer programming languages used for simulation.

GROUP LAYOUT layout in which machine groups are arranged to process families of parts with similar characteristics.

GROUP TECHNOLOGY concept for identifying and classifying part families to efficient mass-production-type layouts. It can be designed for items usually manufactured by a process layout.

HEURISTIC LINE BALANCING TECHNIQUE technique involving the generation of a precedence diagram (technological sequencing requirements) in a particular way, which indicates the flexibility available for shifting tasks from column to column to achieve the desired balance.

INDEPENDENT DEMAND demands for various items are unrelated to each other and therefore determined separately and independently.

INTERNAL RATE OF RETURN (IRR)   rate earned on a proposal. It is the rate of interest that equates the initial investment with the present value of future cash inflows.

INVENTORY STATUS FILE file indicating how much inventory is on hand or on order.

ISO 9000 certification standards developed by the International Organization for Standardization (ISO) that serve as a basis for quality standards for global manufacturers.

JIT MANUFACTURING manufacturing approach that produces only what is necessary to satisfy the demand of the preceding process (a demand-pull system).

JOB DESIGN determination of specific job tasks and responsibilities, the work environment, and work methods.

JOHNSON'S RULE technique that can be used to minimize the completion time for a group of jobs that are to be processed on two machines or at two successive work centers.

JUST-IN-TIME PRODUCTION   approach to manufacturing in which items are produced only when needed in production.

KANBAN   Japanese information system for coordinating production orders and withdrawals from in-process inventory to realize just-in-time production.

LATEST FINISH TIME latest time at which an activity must be completed without holding up the complete project.

LATEST START TIME   latest time at which an activity must begin without holding up the complete project.

LEAD TIME time between the placing of an order and its receipt in the inventory system.

LEARNING CURVE EFFECT reduction in labor hours as the cumulative production doubles, ranging typically from 10 percent to 20 percent.

LEAST-SQUARES METHOD statistical technique for fitting a straight line through a set of points in such a way that the sum of the squared distances from the data points to the line is minimized.

LEVEL PLAN aggregate production plan that maintains a uniform output rate.

LINE BALANCING process of distributing the workloads evenly.

LINEAR PROGRAMMING (LP) mathematical technique designed to determine an optimal decision (or an optimal plan) chosen from a large number of possible decisions.

LINEAR REGRESSION   regression that deals with a straight line relationship between variables.

LOADING allocating workloads to specific work.

LOCATIONAL BREAK-EVEN ANALYSIS technique that compares potential locations on an economic basis by estimating the variable and fixed costs and then graphing them for a representative sales or production volume at each location.

MAKE-BUY DECISION decision as to whether a given item should be manufactured internally or purchased outside.

MANUFACTURING RESOURCE PLANNING (MRP II) integrated information system that steps beyond first-generation MRP to synchronize all aspects (not just manufacturing) of the business.

MARGINAL APPROACH to inventory marginal analysis aiming at determining the optimal stock level.

MASTER PRODUCTION SCHEDULE (MPS) time-phased statement of how many finished items are to be manufactured. It is obtained by disaggregating the production plan and is the primary input to *material requirements planning (MRP)*.

MATERIAL REQUIREMENTS PLANNING (MRP) computerized data processing system whose function is to schedule production and control the level of inventory for components with dependent demand.

MATHEMATICAL MODELS quantitative representations of reality.

MEAN ABSOLUTE DEVIATION (MAD) mean or average of the sum of all the forecast errors with regard to sign.

MEAN SQUARED ERROR (MSE) average sum of the variations between the historical sales data and the forecast values for the corresponding periods.

MODEL representation of a real life system.

MODULAR DESIGN design of components that can be assembled in a variety of ways to meet individual consumer needs.

MONTE CARLO SIMULATION simulation using a random number procedure to create values for the probabilistic components.

MOTION STUDY analysis of a manual task in order to improve productivity.

MOVING AVERAGE   in a time series an average that is updated as new information is received.

MTM (METHODS-TIME MEASUREMENT)   system of predetermined motion-time data used to develop standards for highly repetitive tasks.

MULTIPLE REGRESSION ANALYSIS statistical procedure that attempts to assess the relationship between the dependent variable and two or more independent variables.

MULTIPLE-CHANNEL LINE waiting line with two or more parallel identical servers.

NET PRESENT VALUE (NPV) METHOD method widely used for evaluating investment projects. Under the net present value method, the present value of all cash inflows form the project is compared against the initial investment.

NODES intersection or junction points of a network.

OPERATING CHARACTERISTIC (OC) CURVE plot of the probability of acceptance of a lot as a function of the percent of defective items.

OPERATION CHART often called *right-handed, left-handed chart*, chart used to describe simultaneous motions of hands when performing a task.

OPERATIONS set of all activities associated with the production of goods and services.

OPERATIONS MANAGEMENT (OM) also called *production/operations management*, design, operation, and improvement of the productions/operations system that creates the firm's primary products or services.

OPERATIONS STRATEGY strategy specifying how the firm will employ its production capabilities to support its corporate strategy.

OPTIMIZATION MODELS prescriptive techniques for finding the best solutions to the problem at hand. Linear programming is an example.

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PAYBACK PERIOD length of time required to recover the amount of an initial investment.

PERT/COST also known as the *Critical Path Method (CPM)*, technique designed to assist in the planning, scheduling, and controlling of project costs.

POISSON DISTRIBUTION probability distribution used to describe the random arrival pattern for some waiting lines.

PRESENT VALUE ANALYSIS technique used widely to account for the timing of cash inflows and outflows.

PRIORITY RULES simple heuristics used to select the order in which the jobs will be processed.

PROCESS LAYOUT layout in which machines or activities are arranged by function.

PROCESS PLANNING planning involving a total analysis of the product and its processing requirements, decisions concerning the purchase of items outside versus their internal manufacture, and techniques for selecting among competing processes.

PROCESS SELECTION when operations can be performed by more than one process, an economic analysis should normally be made to determine which process should be chosen.

PRODUCER'S RISK probability of rejecting a good quality lot.

PRODUCT ANALYSIS analysis of product assembly. The early phases of product analysis may produce diagrams which "explode" the product into its various subassemblies and parts. These diagrams may be pictorial or schematic.

PRODUCT LAYOUT layout in which equipment is arranged based on the sequence of operations performed on a product or group of products.

PRODUCTION AND OPERATONS MANAGEMENT management of all activities directly related to the production of goods and services.

PRODUCTION DESIGN the conscious effort to design for low manufacturing cost.

PRODUCTION SYSTEM collection of inputs, conversion/.transformation processes, outputs, control mechanisms, and managers involved in production and operations.

PRODUCTIVITY ratio of outputs to inputs.

QUALITY measure of conformance of a product or service to certain specifications or standards.

QUALITY ASSURANCE all of the activities necessary to ensure that the customer receives satisfactory performance.

QUALITY FUNCTION DEPLOYMENT (QFD) system that uses interfunctional teams from marketing, design engineering, and manufacturing to translate the voice of the customer into the design specification of a product.

QUANTITY DISCOUNT MODEL inventory model that takes into account the price varying with the order size.

QUEUE waiting line that forms wherever there is more than one user of a limited resource.

QUEUE DISCIPLINE rules that determines the order in which arrivals are serviced.

QUEUING (OR WAITING LINE) THEORY operations research term for the study of waiting lines.

REGRESSION ANALYSIS statistical procedure for estimating mathematically the average relationship between the dependent variable (sales, for example) and one or more independent variables (price and advertising, for example).

RELIABILITY probability that a product or process will perform satisfactorily over a period of time under specified operating conditions.

REORDERT POINT inventory level that triggers a new order.

ROUGH-CUT CAPACITY PLANNING analysis of the *master production schedule* to determine the feasibility with respect to capacity limitations (warehouse facilities, equipment, labor, etc.).

r-SQUARED see *coefficient of determination*.

SAFETY STOCK inventory carried to assure that the desired service level is met.

SCHEDULING assignment of work to a facility and the specification of the sequence and timing of the work.

SEQUENCING determination of the order in which a facility is to process a set of jobs.

SERVICE LEVEL probability of no stockouts during the lead time.

SERVICE RATE number of customers or units that can be serviced by one server in a given period of time.

SIMPLE REGRESSION regression analysis which involves one independent variable.

SIMULATION technique to describe the behavior of a real-life system over time.

SINGLE-CHANNEL LINE waiting line with only one server.

SLACK length of time an activity can be delayed without affecting the project completion date.

SPT (SHORTEST PROCESSING TIME) scheduling rule that chooses jobs in order of shortest processing time first.

SUPPLY CHAIN MANAGEMENT management of the integration of the functions, information, and materials that flow across multiple firms in a supply chain-- i.e., buying materials, transforming materials, and shipping to customers.

SYSTEMATIC LAYOUT PLANNING generalized approach to layout that indicate nearness priorities, taking into account factors other than transportation cost.

TAGUCHI METHOD OF QUALITY CONTROL method of controlling quality that stresses robust product design and the quality loss function.

TARDINESS amount by which completion time exceeds the due date.

THE GRAPHICAL METHOD graphical approach to solving a linear programming (LP) problem. It is easier to use but limited to the LP problems involving two (or at most three) decision variables.

THE SIMPLEX METHOD linear programming algorithm, which is an iteration method of computation, to move from one corner point solution to another until it reaches the best solution.

THERBLIG one of 17 elementary human motions such as grasp, select, assemble, and so on.

THROUGHPUT rate at which money is generated by the system through sales.

TIME BUCKET term denoting a time period used in the master schedule.

TIME STANDARD amount of time required to perform a task by a trained operator working at a normal pace and using a prescribed method.

TIME STUDY development of standards through stopwatch observation.

TOTAL FIXED COSTS costs that remain constant in total regardless of changes in activity.

TOTAL QUALITY CONTROL (TQC) philosophy that aggressively strives for a defect-free manufacturing process.

TOTAL QUALITY MANAGEMENT (TQM) concept of using quality methods and techniques to strategic advantage within firms.

TOTAL VARIABLE COSTS costs that vary in total in direct proportion to changes in activity.

TRANSPORTATION LP PROBLEM problem of determining how much to ship from each origin to each destination in order to minimize total shipping costs.

TREND ANALYSIS special form of simple regression in which time is the independent variable.

UNIT CONTRIBUTION MARGIN selling price minus average variable cost.

VALUE ANALYSIS process of trying to reduce product costs by substituting less-costly materials, redesigning nonessential parts, and the like.

WORK MEASUREMENT process of estimating the amount of worker time required to generate one unit of output.

WORK SAMPLING work measurement technique involving the sampling of the nature of the activity in which the worker is involved; used for the broader problem of determining production standards.